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Intelligent Fixtures for the Manufacturing of Low Rigidity Components

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Preface

In the manufacturing industry, the machining of medium and big size parts within the required precision is a challenge, especially in high added value products manufactured in small or single-unit batches made of high-performance materials like in aeronautic, space or energy sectors, where conventional process engineering and test/error methods are not completely efficient.

The performance of the machining process is not only affected by direct factors like the machine tool behaviour or the process definition; other secondary factors are able to change the whole system behaviour and the result of the machining process.

One of these factors is the fixture, whose main and traditional functions are to securely hold and accurately locate the workpiece considered as an undeformable body. Nowadays, the volume of produced compliant thin-walled parts is increasing due to lightweight design of many sophisticated products. The increasing demand on the precision and the need of increasing the performance of the manufacturing processes drive to other important functions of the fixtures considering aspects like the deformations, vibrations and distortions of the workpiece during processing.

In this situation, the machining system consisting of the machine, fixture and workpiece cannot be considered as a stable unit due to its dynamic behaviour and geometrical shape variations along the process. So, it is reasonable to use the fixture to control and adapt the behaviour of machining systems to improve the performance.

New technologies—including sensors, actuators as well as Information and Communication Technology (ICT)—allow the development of intelligent fixture systems, enabling the monitoring, control and adaptation of the clamping and the process conditions to obtain suitable results according to precision, quality and cost requirements.

The INTEFIX project aimed to establish fixture design methodologies taking advantage of the available state-of-the-art software and hardware tools (e.g. sensors, actuators, CAD/CAM/CAE, CNC, PLC, process simulation tools) combined with ad hoc ICT tools (e.g. control algorithms, simulation tools) to control and adapt the behaviour of the fixture, resulting in the development of intelligent fixture systems.

The impact of the INTEFIX project is not only located in the field of machining processes, as the intelligent fixture concepts can be extended to other processes such as welding, repair or mechanical assembly.

The INTEFIX project was performed in a series of case studies divided into three parts oriented to obtain a solution to different problems associated to machining processes:

- Part I: Vibration. The intelligent fixture counteracts vibration problems during machining by changing the dynamic properties, stiffness, damping, etc.
- Part II: Deformation. The intelligent fixture counteracts the deformation or distortions of the workpiece associated to process/clamping forces or residual stress relieving.
- Part III: Positioning. The intelligent fixture produces small movements or corrections to counteract linear and angular positioning errors of the workpiece.

The developed solutions are validated in eleven real case studies from the aeronautic, railway, automotive and machine tool sectors covering different problems and requirements in the manufacturing industry.

Each case study established collaborations between different partners with supplemental capabilities needed to perform the required technological development. This includes an end user who defined the requirements and main objectives of the case study, different technology suppliers who provided base technologies used for the development of the solution, and a technology integrator who designed the fixture. Thus, bringing together the required critical mass in the entire value chain and connecting the end users in the manufacturing industry with the product innovators and the systems integrators.

The partners of the INTEFIX project are: IK4-TEKNIKER; IK4-IDEKO; OTTO-VON-GUERICKE-UNIVERSITAET MAGDEBURG; TECHNISCHE UNIVERSITÄT DORTMUND; RCMT OF THE CZECH TECHNICAL UNIVERSITY IN PRAGUE; CECIMO; BCT; COMPO TECH; INVENT; DR MATZAT & CO; ROEMHELD; GIGGEL; STERN HIDRAULICA; CEDRAT TECHNOLOGIES; ALAVA INGENIEROS; INDUSTRIA DE TURBO PROPULSORES; DEHARDE; SORALUCE; GOIMEK; STROJIRNA TYC; KALE HAVACILIK; TECNALIA; GAMESA ENERGY TRANSMISSION; MARPOSS; UNIVERSITA DEGLI STUDI DI FIRENZE; PARAGON; GIRARDINI; TECMA; BEREIKER; ZAYER; MESUREX; and WOELFEL.

The case studies treated in the project resulted in a series of specific solutions to improve the limitations presented by the end users, and several generic standalone products able to perform specific tasks in the fixture field or in general applications.

Eibar, Spain Oscar Gonzalo

Acknowledgements

The INTEFIX project (www.intefix.eu) was kindly funded in FP7 by the European Commission (Grant agreement No.: 609306).

The editors of the book sincerely thank all co-authors and all industrial and research partners of the INTEFIX project!

Contents

Abbreviations

3D	Three Dimensional
ANN	Artificial Neural Network
AVC	Active Vibration Control
BP	Backpropagation
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CFRP	Carbon Fibre Reinforced Polymers
CNC	Computer Numeric Control
DAQ	Data Acquisition
DoF	Degree of Freedom
DSP	Digital Signal Processing
FEA	Finite Element Analysis
FEM	Finite Element Method
FFD	Free-Form Deformation
FFT	Fast Fourier Transformation
FRF	Frequency Response Function
GA	Genetic Algorithm
HMI	Human–Machine Interface
HSK	Hollow Taper Shank (German: Hohlschaftkegel)
I/O	Input/Output
ICP	Iterative Closest Point
ICT	Information and Communications Technologies
IPC	Industrial Personal Computer
LVDT	Linear Variable Displacement Transducer
MLP	Multi Layer Perceptron
MOT	Minimum Overstock Transform
PLC	Programmable Logic Control

Ra	Arithmetic average of the surface roughness
TBH	Tail Bearing House
TCP	Tool centre point

Introduction

This book describes the developments, findings and research results that were achieved in the European INTEFIX project. Thus, this book can be regarded as the public project report which aims in the dissemination of the outcomes elaborated by the project partners. In this way, the project participants share the gained experiences with the reader.

Following the structure of the project, the main sections of the book deal with the parts of workpiece vibrations, workpiece distortions and the positioning of large workpieces. In each section, the book chapters introduce the different case studies of the project. The chapters begin with an abstract which briefly describes the background, tasks and content of the respective case study. At the end of each chapter, the results achieved regarding the case study are summarized. Furthermore, related references are provided which allow further studies of the subjects.

With respect to the three parts, within the case studies, various approaches and solutions to overcome the challenges of fixtures for low-rigidity components are explained. By this, the reader gets an overview of the ideas, technical possibilities, essential requirements, development methods and enabling technologies as well as limitations and drawbacks that were discovered in the INTEFIX project.

Before the specific case studies are presented, a general methodology is introduced. This methodology gives a structure and provides a systematic approach for the realization of intelligent fixtures. When reading the following chapters, the reader can retrace the different contributions to the overall systematics. Finally, the book ends with a summary and conclusion.

The editors of the book and all project partners sincerely thank the European Commission for the funding of the INTEFIX project (GA No.: 609306) within the Seventh Framework Programme (FP7). In the same way, the editors thank the authors of the book chapters, who are also the main responsible persons for the technical work in the respective case studies. Furthermore, the editors and the

project steering committee thank all the scientific and technical co-workers who contributed to the success of the project. Last but not least, the scientific institutions thank the industrial partners of the INTEFIX project for the intensive and essential collaboration.

Hans-Christian Möhring
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Methodology

Petr Kolar[1], Hans-Christian Möhring[2], Petra Wiederkehr[3]

Abstract

A fixture is an important part of the processing system which comprises the machine tool, the tools and tool holding clamping elements, the workpiece, and the workpiece holding 'fixture' system. Requirements on the fixture are similar as on the machine tool: it should ensure accurate and productive machining of a specific workpiece. To fulfil this, the fixture has to have high dynamic stiffness, thermal stability and geometric precision and accuracy to ensure the defined position and orientation of the workpiece within the workspace of the machine even under process loads.

An intelligent fixture is defined as a fixture with integrated sensors and actuators with feedback control of its function. Such sophisticated systems are equipped with a specific human–machine interface and also with an interface between the fixture control and the machine tool control system. Based on this, the intelligent fixture is an active component of the manufacturing system that is able to actively e.g. adjust the workpiece position, compensate the workpiece deformation or minimize the system vibration during the machining process.

The design of such complex systems needs a specific procedure. Although the intelligent fixtures are often developed as an original turn-key solution, the unified methodology described in this chapter is valid for various application cases. A simulation-aided design methodology combines the experimental and simulation approach for the integrated development of systems and processes. An application typology and solution synergies show cross-links between all presented specific

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case studies. The application of the methodology is presented for three typical parts in this book. Thus, the methodology can be used as a guideline for the design and development of other types of intelligent fixtures.

Introduction to Design Methods for Intelligent Fixtures

The fixture is a specific component performing the holding of a workpiece during manufacturing processes. Being a part of the system consisting of the workpiece, fixture, tool and machine tool, the fixture has to ensure a stiff, accurate and precise clamping of the part for the productive and accurate machining by improving the static and dynamic stiffness of the whole system and ensuring a right position of the part. In order to fulfil these requirements, a specific design and setup of the fixture is necessary.

An intelligent fixture is characterized by an integrated set of sensors and actuators. Also a feedback control is applied in the whole process: either the fixture can operate with the feedback control to ensure the specific requirements or the machining process works with the feedback control using the fixture or other system sensors. A specific software working as a HMI (Human–Machine Interface) and also an interface between the fixture control and the machine tool control system can be used in some cases.

An intelligent fixture system provides more functions, basically to shorten the workpiece setup time by assisted part positioning, to minimize the part deformation during clamping and machining using an active part deformation control, and to minimize vibrations during the machining process using passive or active damping. These mentioned functions are often combined in real cases.

In the design and layout of the intelligent fixtures, their mechanical structure and the functional performance of the sensor and actuator subsystems have to be optimized. This chapter presents a general approach of sensors and actuators integration, and introduces a principle design and layout methodology. Applications of this methodology on specific case studies are presented for three typical machining problems in the following chapters.

Simulation-Aided Design Methodology

Nowadays, virtual simulation techniques provide a powerful instrument for supporting the design of machine tools (including the related mechatronic subsystems and controls) [1–3] and for improving the layout and parameterization of machining operations [4–6]. By means of appropriate process simulations, a detailed consideration of the real functional environment of entire machine systems and their core components regarding loads, interactions and disturbing influences becomes possible already during the design and optimization phase. Thus, the performance of these systems can be assessed and verified before complex prototypes or (final) products are physically realized.

However, for enabling accurate process simulations, both representative process conditions and relevant system properties have to be identified and analysed in order to choose reasonable modelling approaches and to allow realistic model parameterization. For selected process parts (e.g. those which can be assumed to be the most critical regarding process stability or part quality) and dedicated representations of the mechatronic systems (e.g. defined by Finite Element (FE) models), simulation setups can be implemented by using analytically derived, experimentally obtained or estimated initial modelling parameter values. When coupling system models and process models using an exchange of simulation results, on the one hand, uncertainties in the system modelling significantly affect the quality of the process simulation results. On the other hand, the accuracy of the process simulation influences the validity of the optimization of the mechatronic system regarding its final performance. Nevertheless, the coupled virtual description of process and mechatronic machine system (or component respectively) can be used for improving the system design and process layout.

Consequently, a simulation-aided design methodology, which is described in detail in [7], can be proposed which combines the simulation-based process optimization (Fig. 1) with the simulation-based system design (Fig. 2) in one approach with two parallel 'layers' (Fig. 3) [7]. At first, at both layers, the application parts, requirements and boundary conditions have to be defined. Preparatory process analysis is necessary in order to obtain initial values for the process modelling and to provide meaningful process simulation results for the system development. In parallel, a decomposition of the mechatronic system regarding its relevant components, functions and process interactions has to be carried out. Based on the information of the preparatory process analysis and simulated system properties, a comprehensive process modelling can be conducted. Simulated process loads and excitations of the system by the process can be applied on the system model in order to investigate the performance of the system.

In an intermediate experimental testing step, simulation results should be verified in both, the process and the system layer. Based on first simulation results, specific

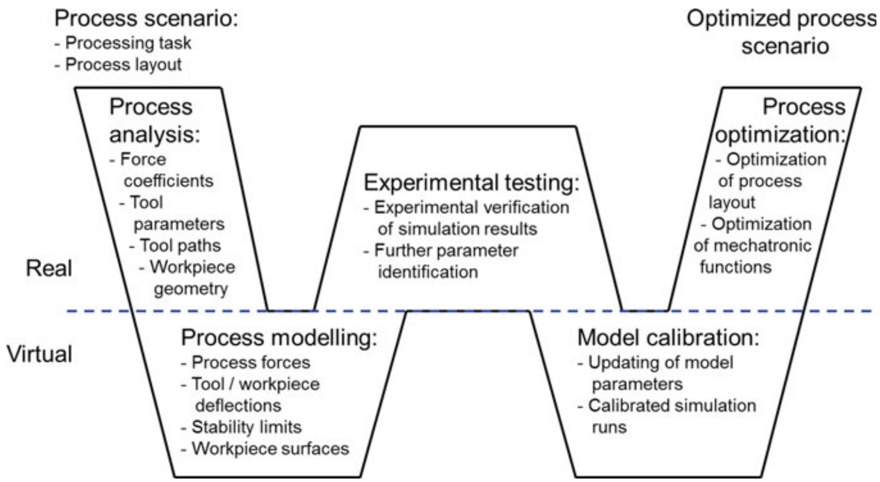

Fig. 1 Process-related simulation-aided design method [7]

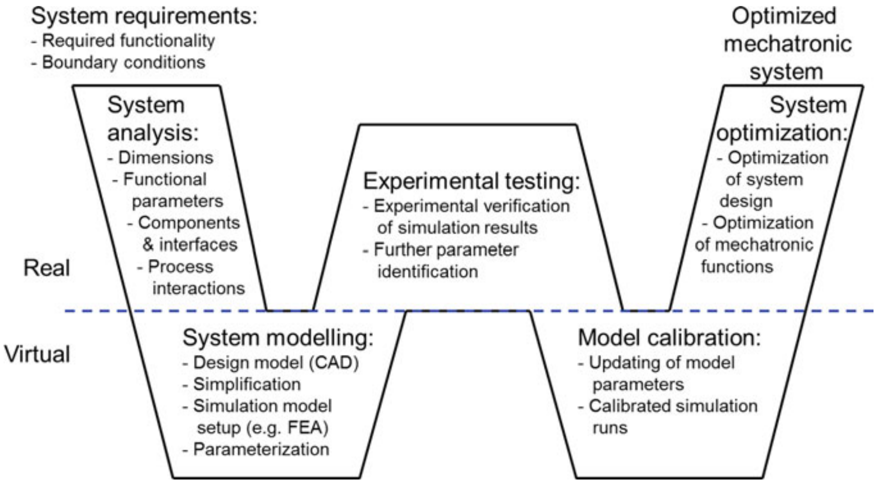

Fig. 2 System-related simulation-aided design method [7]

targeted test rigs can be defined and implemented which allow more detailed analyses and the identification of revised process and system parameters. In a model calibration step, the model parameter values are modified and adapted to the experimental results. The revised and updated models can then be utilized to optimize the processes taking the properties of the mechatronic system into account, and to optimize the mechatronic system in consideration of the realistic process conditions. Requirements and specifications as well as intermediate results and system properties are communicated at each step of the parallel design progress. This allows multiple iteration loops in each phase of the development, including, e.g. the consideration of parameter variations or of several constructive approaches, related test rigs and experiments.

Instead of only one system layer, for complex machine tools multiple system layers for each relevant mechatronic component must be considered. For each subsystem which interacts with the machining process—and, thus, in particular for intelligent fixtures—a similar structure as depicted in Fig. 3 can be established. Furthermore, interactions among the mechatronic components (e.g. the acceleration of a clamping system by a feed drive system) have to be taken into account. Certainly, the layer of the overall system, i.e. the entire machine tool, which comprises the functional properties of the subsystems, has a dominant role in the design concept hierarchy and it therefore summarizes the characteristics of the combined intelligent component.

Identification of an Application Typology and Solution Synergies

The procedure for developing intelligent fixtures is demonstrated on various case studies in the following chapters. Unless the types of the applications are different, functionally similar solutions can be successfully used. Various technical solutions

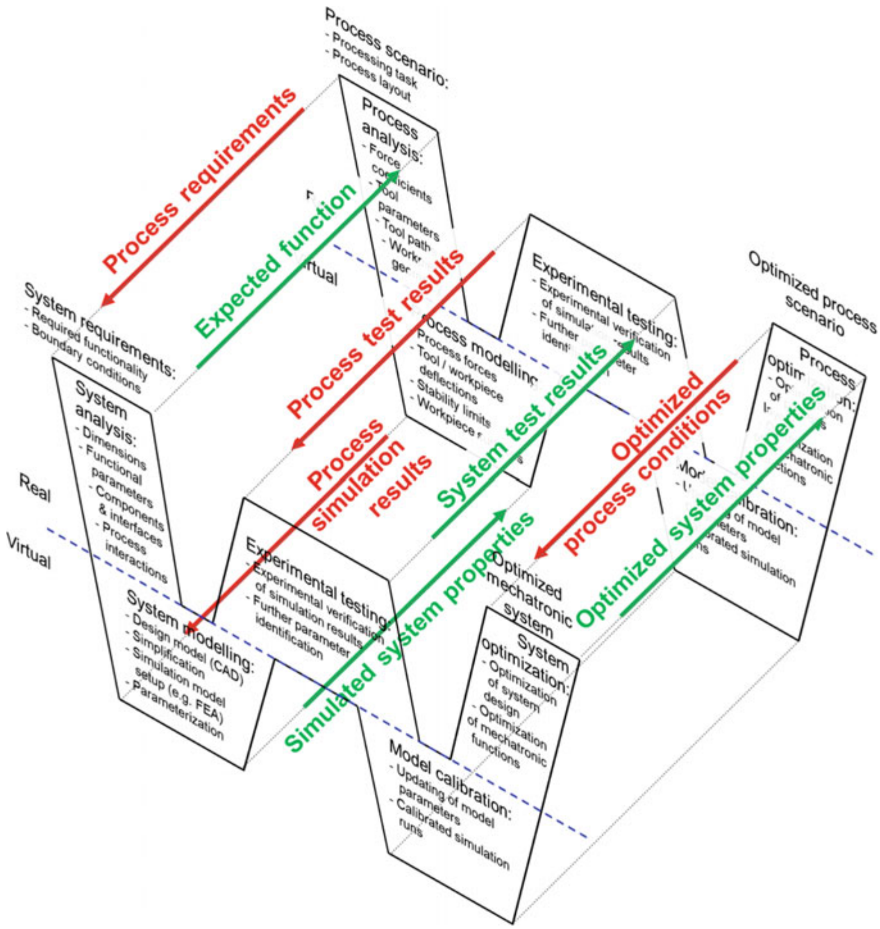

Fig. 3 Concept of the simulation-aided design method [7]

were developed to fulfil two main requests: to increase the machining productivity and accuracy. In order to improve both optimization criteria, different approaches were analysed in the described case studies, see Table 1.

An increase of the machining productivity can be achieved by minimizing the idle and process time. On the one hand, minimizing the idle time is carried out mainly using a high automation level for the workpiece setup (clamping of the raw part, workpiece inspection before machining) and for the workpiece reclamping. Several devices and their control were developed and are presented in the mentioned case studies. On the other hand, minimizing the process time is closely connected with the optimization of the cutting process with respect to the structural behaviour of the machine tool and the workpiece using an intelligent fixture. For all these purposes, experimental and simulation-based approaches can be used.

Table 1 Overview of approaches tested in the case studies.

Optimization criteria	Task	Approach	Case study
Machining productivity	Minimizing idle time (shorter workpiece setup time)	Shape adaptive part clamping	2.1, 2.2, 2.3, 2.4
		Contactless measurement and metrology	3.2
		Touch probe integration and metrology	3.1, 3.3
		Automatic workpiece alignment	3.1, 3.2, 3.3
	Minimizing process time (chatter avoidance)	Cutting conditions optimization to avoid chatter	2.1, 2.2
		Increase passive damping	1.1, 1.2
		Apply active damping	1.1, 1.2, 1.3
		Improve dynamic stiffness	1.1, 1.2, 1.3
		Disturb regenerative chatter effect	1.1, 1.3
Machining accuracy	In-process part dimension control	In-process part thickness measurement	2.2
	In-process part deformation control	Part reclamping and deformation measurement	2.1, 2.3, 2.4

Increasing the machining accuracy can be achieved by an in-process control of the part dimension or deformation. Dimension control is a direct approach where the critical dimension is directly measured for modifying subsequent machining processes. Deformation control is an indirect approach. The part deformation is checked and the dimensional corrections are computed using this information for the subsequent machining update.

Procedure for the Analysis and Design of the Complete Manufacturing Process

In the following, different case studies and their developed solutions including workpiece clamping, machining and quality control of the workpiece are presented. Some of these solutions are general and can also be used directly in other similar applications. Others were developed specifically for these case study experiments. However, they are good examples for the development of other dedicated solutions.

The schema of the manufacturing procedure using intelligent fixtures is presented in Fig. 4. It integrates three parts where applications of intelligent mechatronic fixture systems are useful. Approaches, e.g. related to a quick positioning of the part prior to the machining, to avoiding regenerative chatter during machining or to the machining of parts distorted due to residual stresses are combined in one flow chart. It can be used as an universal road map to check the

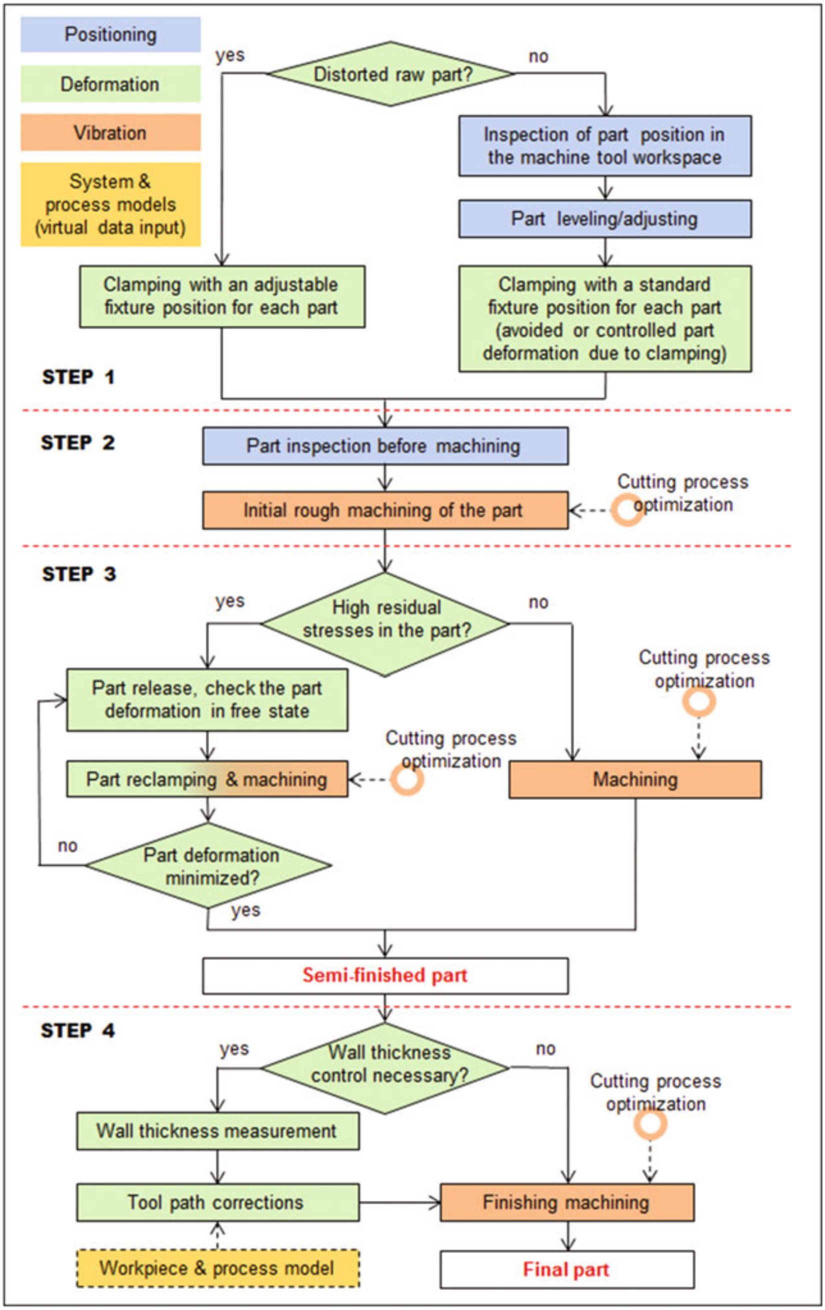

Fig. 4 General schema of the manufacturing procedure with integration of intelligent fixtures

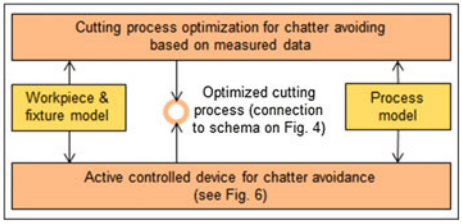

Fig. 5 Schema of two approaches for improving the performance of a machining process

fixture design for each specific application. The three addressed parts (positioning, vibration, deformation) are depicted in different colours. Decision points enable to skip some diagram parts if it is not relevant to the solved task. The comprehensive task of optimizing machining processes is described separately in Fig. 5. The connection to the main flow chart in Fig. 4 is marked by red circles.

The schema in Fig. 4 consists of four main steps. Step 1 includes the decision if the raw part is usually distorted or not. If the raw part is not distorted (as in case studies 2.1 and 2.2), it is possible to clamp all parts using a standard fixture system. The workpiece position should be inspected for part levelling using a touch probe (as in case studies 3.1 and 3.3) or using contactless methods (see case studies 3.2). Then the part is clamped. If the raw part is significantly distorted and the distortion is not repetitive, the fixture with adjustable jaws (as in case study 2.4) or adjustable fixture position (as in case study 2.3) should be used (as in case studies 2.3 and 2.4). The fixture adjustment has two main reasons in this case. Firstly, the workpiece load due to its clamping should be minimized and secondly, the workpiece should be clamped in a specific position. The appropriate machining strategy and the suitable zero point will be defined in the next step after the workpiece inspection prior to the machining process.

Step 2 starts with an initial part inspection. The part position and shape is checked and an appropriate machining zero point is defined. Afterwards, the first machining operation, which can be optimized as it is marked with a red circle and described below, can be conducted.

Step 3 covers actions for minimizing the workpiece distortion due to high residual stresses. The usual strategies for reducing these problems are the partial machining of the workpiece or the reclamping of the parts (see case studies 2.1, 2.3, 2.4). Typically, fixtures with floating jaws are used in these cases. The final workpiece deformation can be identified by deformation measurements (e.g. the measurement of the jaw movement or the part shape using a touch probe) or by measuring the workpiece reaction force by a force sensor integrated in the fixture system. In order to achieve a higher robustness of the part position analysis, both approaches can be used simultaneously. If the part deformation is still too large after the reclamping operation, this step should be repeated after the next partial machining.

The described procedure is part of the indirect accuracy check of the workpiece. The main goal is to reach a semi-finished workpiece with a minimum shape deformation. Also in this case, the semi-finishing machining can be optimized.

Step 4 involves the direct accuracy check of the workpiece. If there is a critical workpiece dimension affected by the workpiece deformation based on the clamping forces, the direct measurement of this dimension is recommended (example in case study 2.2). The tool path of the finish operation is modified using the measured data. Information about the structural properties of the workpiece and about the cutting process should be used in this step to ensure the requested accuracy of the workpiece after the finishing process.

As it was already mentioned, also the performance of the machining operation can be improved, see Fig. 5. In this case, the main influencing factor is the limited stiffness of the workpiece-tool-machine tool system, which can lead to regenerative chatter.

The self-excited vibrations can result in a bad workpiece surface, a higher tool wear or a damage of the milling tool. There are different approaches to avoid these chatter vibrations. A possible strategy is to optimize the cutting parameter values. This optimization can be based on measured data (case study 2.2) or on a complex simulation of process–machine interactions (as in case studies 1.1 and 2.1).

Another strategy is based on an active chatter avoidance using the controlled vibration of the workpiece (see case studies 1.1, 1.2, 1.3). A special design of the fixture and the integration of appropriate sensors and actuators are necessary in this case. Due to the complexity of the whole system, a special procedure for a successful application of the active device is necessary (Fig. 6).

In a first step, based on an initial process setup, an analysis of the machining process is carried out. This can be conducted either by means of experiments or by process simulations. For both, the experimental and the virtual process analysis, a selection of relevant sections of the machining operations (in terms of most likely critical operations regarding process performance and workpiece quality) is necessary. Furthermore, the experimental analysis requires an appropriate setup of reference measuring equipment and the implementation of the defined test process conditions. The virtual process analysis necessitates a detailed investigation of the boundary conditions. The implementation of the process models particularly demands the identification of characteristic parameters, e.g. process force coefficients.

If the process analysis reveals critical workpiece vibrations, compensating strategies can be applied in step 2. Basically, online approaches can be distinguished from offline approaches. In general, calibrated process simulations can be used offline in order to identify improved process parameter values that enable stable machining operations. If the vibrations involve mostly constant dominant frequencies, passive damping elements can be integrated into the fixtures which lead to diminished amplitudes of these dominant frequencies. The layout of the passive damping elements can also be supported by process simulations. If the dominant frequencies vary during the machining operations, either active damping or the application of counter excitations can be conducted. Active damping means that the actual vibration is observed by means of appropriate integrated sensors, that the vibration signals are analysed regarding dominant frequencies and phasing, and

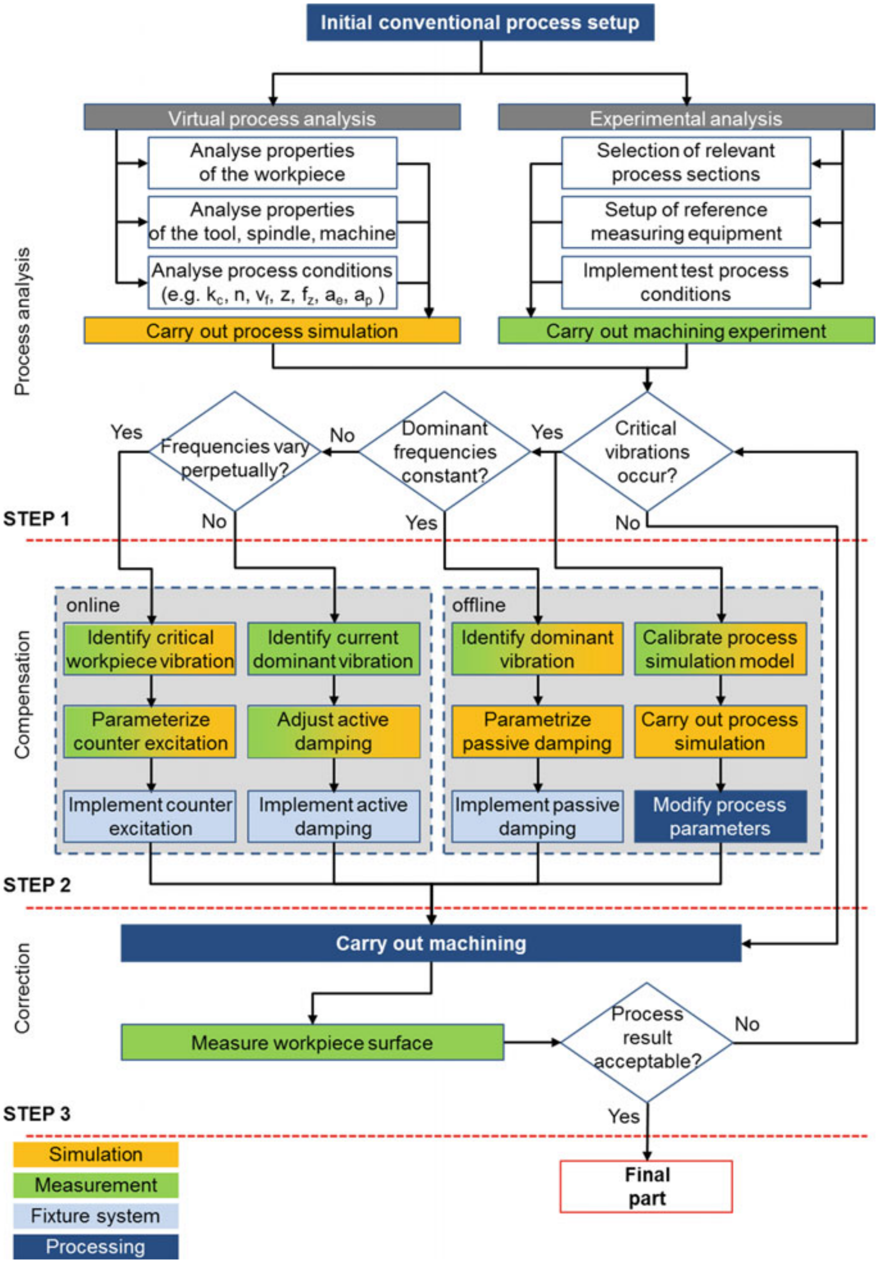

Fig. 6 Schema of machining with vibration compensation

that an active influencing of the process dynamics is realized by means of integrated controlled actuators. In principle, a closed loop active damping control can be implemented either to counteract the process and workpiece vibrations directly by a phase-delayed conscious excitation, or to detract vibration energy by means of a controlled spring-mass-damper system (see Chaps. 2 and 3). If the dominant vibration frequencies vary perpetually, the capability of active damping is limited because of the reaction time of the system. Furthermore, particularly if the dominant frequencies are relatively high, a controlled phase-delayed excitation becomes impossible due to the limited performance of available compact actuators. Another approach utilizes counter excitations without a controlled phase shift in order to disturb the regenerative chatter effect and, by this, to stabilize the machining process (see Chap. 1). Furthermore, also a combination of multiple compensation measures can be utilized for an improvement of the process performance and workpiece quality.

Especially for the adjustment of control settings and for the parameterization of counter excitations, process simulation results can be exploited. Whereas the active damping and application of counter excitations work online, the related process simulation has to be conducted offline due to the computational time.

In step 3, the machining operations are carried out and the resulting workpieces are analysed. If the process results are not acceptable, further compensation has to be achieved in iteration loops. Even if during the initial process analysis (step 1) no critical vibrations occur, this might be the case when the real production process is implemented due to additional effects (e.g. changing tool conditions) which were not considered accurately in step 1.

Summary

A principle design and layout methodology for intelligent workpiece fixtures was described in this chapter. Following the general methodology, various specific fixture systems can be developed and applied. Subsequently, the general schema of the manufacturing procedure integrating the intelligent fixtures for three typical issues was presented. The advanced mechatronic devices and comprehensive simulations can help to improve the machining results. However, the basic clamping rules are valid also in case of the intelligent fixture application:

- The fixture has to enable defined workpiece positioning by removing all six degrees of freedom of the part.
- The fixture has to ensure sufficient clamping forces with respect to the cutting forces and inertia forces due to machine movement for high process safety.
- The sources of workpiece deformation should be evaluated carefully before machining. This case analysis will enable to propose the manufacturing procedure for minimizing the part deformations according to Fig. 4.
- Optimal selection of cutting tools and cutting conditions can improve process productivity and accuracy without an expensive fixture redesign.

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Part I
Vibration

Chapter 1
Case Study 1.1: Identification and Active Damping of Critical Workpiece Vibrations in Milling of Thin Walled Workpieces

Hans-Christian Möhring, Petra Wiederkehr, Christoph Lerez, Tobias Siebrecht and Holger Schmitz

Abstract In milling of impellers and blisks (blade integrated disks), critical workpiece vibrations of thin-walled blade structures occur due to the excitation by the process forces and the dynamic compliance of the sensitive elements of the parts. Workpiece vibrations lead to inacceptable effects on the blade surfaces and thus to the production of defective parts. Also, these vibrations provoke an increased tool wear progress. Within the INTEFIX project, fixture solutions were developed which enable the detection and compensation of chatter vibrations during machining of thin-walled workpiece elements. This contribution introduces the development of an intelligent chuck for the clamping of impellers. The chuck exploits CFRP embedded piezo patch transducers for the identification of critical workpiece vibrations during milling. By means of an integrated piezo actuator, counter vibrations can be applied which disturb the regenerative chatter effect and lead to a decreased waviness of the workpiece surface. The development of the mechatronic clamping system is supported by innovative process simulation approaches.

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1.1 Introduction of the Case Study

During milling of thin-walled workpiece elements, such as the blades of impellers and blisks (blade integrated disks), vibrations especially of the tool and the workpiece occur [1–3]. The high vibration tendency results from the low dynamic stiffness of the thin workpiece structures and the high dynamic compliance of the mostly used slender and long milling tools which are necessary in order to reach all to be machined areas. The dynamic stiffness of the workpiece significantly depends on the current contact position of the tool and the progress of the material removal process which alters the actual thickness of the thin-walled structures and the related modal parameter values. Forced and self-excited vibrations lead to undesired surface effects and by this to the production of defective parts. Furthermore, process vibrations lead to an increase of the tool wear and, therewith, to increased tooling costs. In order to reduce this unstable dynamic process behaviour, in a conventional process layout the process parameter values are chosen carefully. Consequently, the material removal rates and productivity are limited.

In order to overcome this challenge, active fixtures can be applied which influence the process dynamics and diminish the tendency of regenerative chatter [4, 5]. In contrast to existing approaches, within the INTEFIX project, intelligent fixtures were investigated with a focus on minimizing process vibrations of thin-walled workpieces (see also Chaps. 2 and 3). In this case study, the machining of an exemplary impeller (aluminium Al7075) with a diameter of d = 200 mm and a height of h = 65 mm was analysed (Fig. 1.1). The milling process mainly comprises the three steps of roughing, pre-finishing and finishing in which different milling tools are used. Due to the shape of the final part, a complex 5-axes simultaneous motion of the machine tool is required.

The workpiece holding system has to provide an unaffected accessibility of the clamped part so that various relative orientations and engagement angles between the workpiece and tool can be realized (Fig. 1.2). Therefore, impellers are very often clamped by use of a clamping mandrel which exploits the centre bore hole of the part as clamping surface whereas the bottom of the workpiece is pulled against a reference planar surface which surrounds the mandrel.

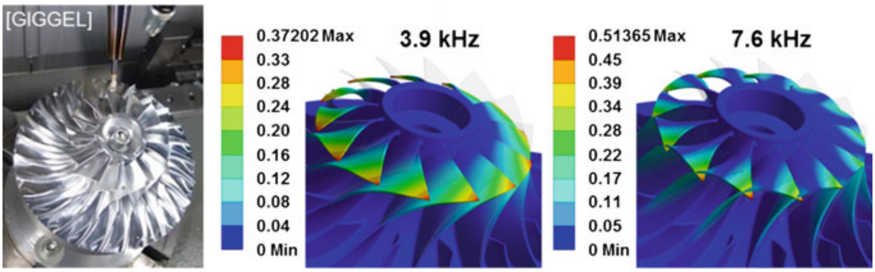

Fig. 1.1 Machining setup and first natural frequencies of impeller blades [6]

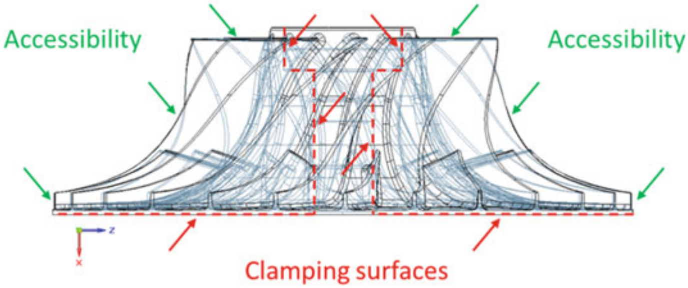

Fig. 1.2 Accessibility and clamping surfaces of the impeller

In this case study, two major tasks had to be fulfilled by the newly developed intelligent fixture:

- The integration of sensors which allow the detection of workpiece vibrations and regenerative chatter during the milling processes
- The integration of actuators which enable an active influencing of the workpiece vibrations so that regenerative workpiece vibrations can be diminished.

Considering the first natural frequencies of the regarded large impeller blades (Fig. 1.1) and the theorem of Shannon [7] for preventing aliasing effects, the sensor system bandwidth should exceed 15 kHz. In principle, the sensors for detecting workpiece vibrations could be integrated into the clamping mandrel. An integration into the clamping force flow of the mandrel would mean that high pre-stress loads act permanently on the sensor. An integration at the mandrel structure but outside the clamping force flow would mean that the sensor sensitivity is affected by the dynamic stiffness of the clamping mandrel and by the joint behaviour between the mandrel and the workpiece. Therefore, the prototypic intelligent fixture, which was developed in this case study, involves a designed sensory CFRP component which has a direct contact with the bottom surface of the clamped impeller (see Sect. 1.6).

In order to actively diminish workpiece vibrations, basically three strategies could be implemented:

- Applying counter excitations below the dominant workpiece vibration frequencies with the aim to disturb the regenerative chatter effect
- The reduction of workpiece vibrations by an actuation of the workpiece in the range of the dominant workpiece vibration frequencies applying a phase shift
- The active excitation of the workpiece above the dominant workpiece vibration frequencies (again) with the aim to disturb the regenerative effect.

In this case, due to the mass and inertial forces of the workpiece, an excitation in or above the first natural frequencies of the impeller blades (Fig. 1.1) can hardly be realized by a compact actuator or drive system which does not violate the requirement of accessibility of the workpiece. Basically, electromagnetic, hydraulic

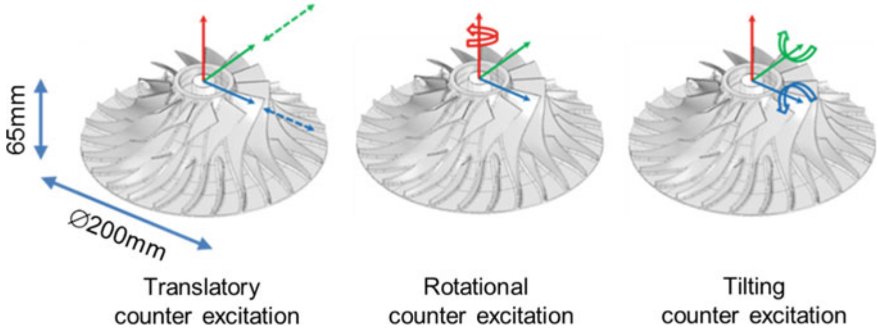

Fig. 1.3 Approaches to introduce counter excitations [8]

or piezo-electric actuators can be considered, of which piezo-electric actuators provide the most feasible combination of bandwidth and power density. In order to introduce counter excitations to blade vibrations, three fundamental approaches could be followed (Fig. 1.3):

- A translatory counter excitation in two degrees of freedom (DoF)
- A rotational counter excitation about the centre axis of the workpiece in one DoF
- A rotational counter excitation which tilts the workpiece in two DoF.

A major advantage of the rotational counter excitation about the centre axis of the workpiece is that it necessitates only one single actuator together with the related power electronics. Consequently, this approach implicates the lowest costs.

As a result of the discussed aspects, the developed intelligent fixture utilizes a piezo-electric actuator which excites the impeller in a single rotational DoF below the first natural frequencies of the large impeller blades. In a first step, a simplified translatory 1-DoF test rig was built and applied for basic experiments regarding the effect of counter excitation on the process stability (see Sect. 1.3). As the positive stabilizing effect of the counter excitation could be validated by the simplified test rig, a rotation intelligent fixture prototype was realized in a second development step (see Sect. 1.5). An important means for the development, validation and understanding of the functionality of the counter exciting fixture is provided by sophisticated process modelling and simulation (see Sects. 1.2 and 1.4).

1.2 Stability of Impeller Blade Machining Operations

When machining thin-walled workpieces for aerospace applications, e.g., blisks or turbine blades, high surface qualities have to be ensured by designing and parameterizing the manufacturing processes. During milling processes, chatter vibrations can result in chatter marks [9] and, thus, increased costs due to a higher

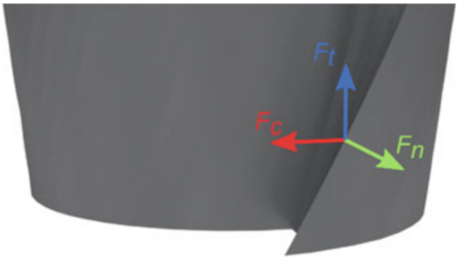

Fig. 1.4 Cutting force directions $\boldsymbol{F_n}$, $\boldsymbol{F_c}$, and $\boldsymbol{F_t}$

tool wear, additional process steps for repairing, or even waste. In order to apply active fixture systems for reducing workpiece vibrations, a process simulation system was extended to model the influence of an active excitation on the final surface topography of the workpiece.

The utilised simulation system is being developed at the Institute of Machining Technology for several years [9]. In this geometric physically-based process simulation, the milling tools and the workpieces are modelled using the Constructive Solid Geometry (CSG) [10] modelling technique [11]. The shape of the rotating tools is modelled by combining simple geometric primitives, e.g. cylinders or spheres, using union, intersection and difference operators. The workpieces are represented using the same modelling approach by subtracting the CSG model of the tool from the shape of the initial stock in each discrete simulation step, which corresponds to one feed per tooth. This way, the material removal and the changing shape of the workpiece are modelled. The intersection between the current tool shape and the workpiece corresponds to the undeformed chip shape, which can be analysed to calculate the undeformed chip thickness h, which varies during each cut. Using an empirical force model [12], the process forces in normal, cutting, and tangential direction F_n, F_c, and F_t, as shown in Fig. 1.4, can be calculated based on h. The parameter values of this force model can be estimated by conducting calibration experiments with the analysed workpiece material [13].

In order to optimize machining processes with respect to chatter vibrations, the dynamic behaviour of the tools and the workpieces has to be modelled as well [14]. This is achieved by representing the frequency response functions (FRFs) [15] of the tools and the workpiece using uncoupled damped harmonic oscillators, which are each described by their modal mass, damping coefficient and eigenfrequency. The FRFs can be obtained using impulse hammer tests, shaker measurements, or finite element analysis [15]. The parameter values of the oscillator models can be found by fitting their behaviour to the FRFs using evolutionary optimization algorithms. By exciting the oscillators by the calculated process forces, the deflections of the components can be simulated. When calculating the undeformed chip thicknesses, the deflections of the tool and the workpiece can be taken into account in order to model the regenerative effect and, thus, chatter vibrations. By combining the CSG-based model with an additional discrete representation with multi-dexel boards [16], surface location errors can be calculated and visualised efficiently [17].

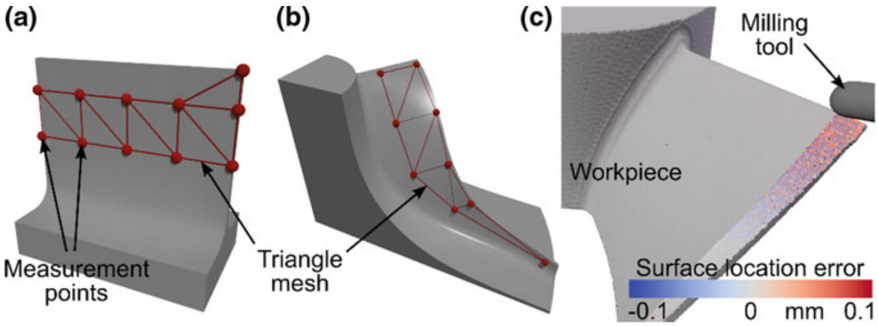

Fig. 1.5 Measurement points and triangle meshes for interpolating workpiece vibrations of a plate (**a**) and an impeller blade (**b**), and simulated surface location errors (**c**) (cf. [18, 23])

However, in case of workpieces vibrations, the dynamic behaviour at the engagement position of the tool varies during the machining process. On the one hand, this is caused by the local variation of the eigenshapes of the workpiece. On the other hand, the workpiece shape changes continuously due to the material removal process, which influences its dynamic properties and FRFs as well [2]. In many cases of finishing processes, which are most relevant for the final surface quality, the latter effect can be neglected since the amount of the removed material is low. In order to take the mode shapes in the simulation into account, a method for interpolating the dynamic compliance between multiple measurement points of the workpiece surface was developed. When measuring the FRFs using the impulse hammer test, the number of measurement points should be chosen to be as low as possible in order to reduce the amount of the required measurement work and costs. However, using a sparse distribution of measurement points, an interpolation between them becomes even more relevant. The FRFs are obtained by exciting the workpiece at a reference point while measuring the resulting deflections or accelerations at each measurement point. These FRFs can be used to calculate the transfer function between each pair of measurement points and each of these transfer functions is represented by an oscillator-based model [14].

The developed interpolation approach is based on a triangle mesh which spans the measurement points [18]. In each simulation step, the nearest neighbour of the position of the engagement situation between the tool and the workpiece on the triangle mesh is calculated. The barycentric coordinates of this nearest neighbour are used as weighting factors for distributing the process forces to the corners of the triangle. The same weighting factors can be used to calculate the deflection of the workpiece at the engagement position by interpolating the deflections calculated by the oscillator models at the measurement points at the corners of the triangle [14]. Exemplary measurement points and triangle meshes for the described interpolation approach are shown in Fig. 1.5 [18, 23].

The presented simulation approach can be applied to simulate the process dynamics and the resulting surface location error for, e.g., the finishing of an impeller blade, as shown in Fig. 1.5c. The highest deviations are present at the tip of the blade, where the workpiece is most susceptibility to vibrations.

1.3 Single Degree of Freedom Test Rig

In order to allow experimental studies of the effect of counter excitations on the chatter tendency during milling of thin-walled parts, a translatory 1-DoF test rig was developed and realized (Fig. 1.6).

A simple thin-walled test part is mounted on a movable translatory table which is guided by flexure hinges and which can be excited by a piezo actuator. The movement of the table is measured by an integrated eddy current sensor. By means of three laser triangulation sensors, the vibrations of the workpiece tip can be measured during the milling process.

In order to investigate the capability of CFRP integrated piezo patch transducers regarding the detection of workpiece vibrations during machining, a test specimen (produced by company INVENT) is located between the test part and the movable clamping table. The realized test rig is shown in Fig. 1.7.

Milling tests were conducted without and with the application of counter excitations. The sensitivity of the CFRP integrated piezo patch transducers with respect to the workpiece vibrations was validated and compared to the measurement data of the laser triangulation sensors (Fig. 1.8). The CFRP integrated sensors are capable to detect the workpiece vibrations up to the dominant frequency of approx. 2000 Hz. A smoother surface can be achieved by the application of counter excitations. Here, the measured surface roughness was reduced from Ra = 3.35 μm without a counter excitation to Ra = 0.68 μm with counter excitations (Fig. 1.8).

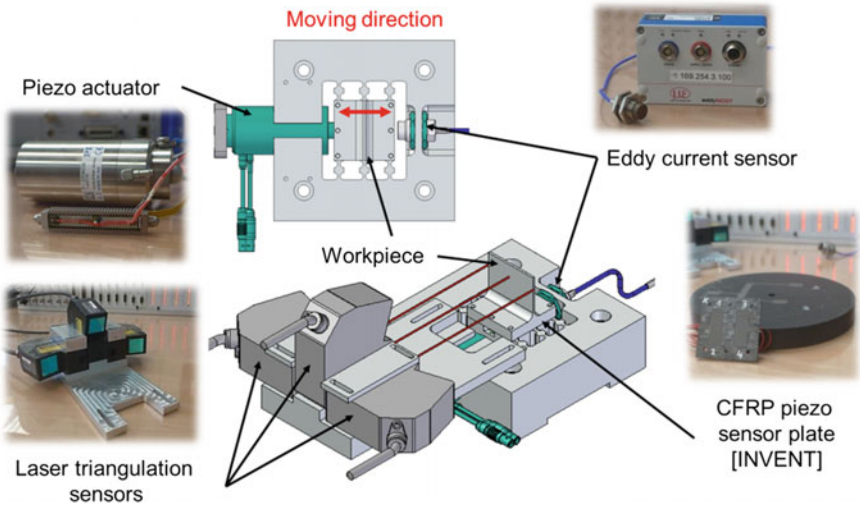

Fig. 1.6 Test rig with single translatory degree of freedom for counter excitation experiments [6]

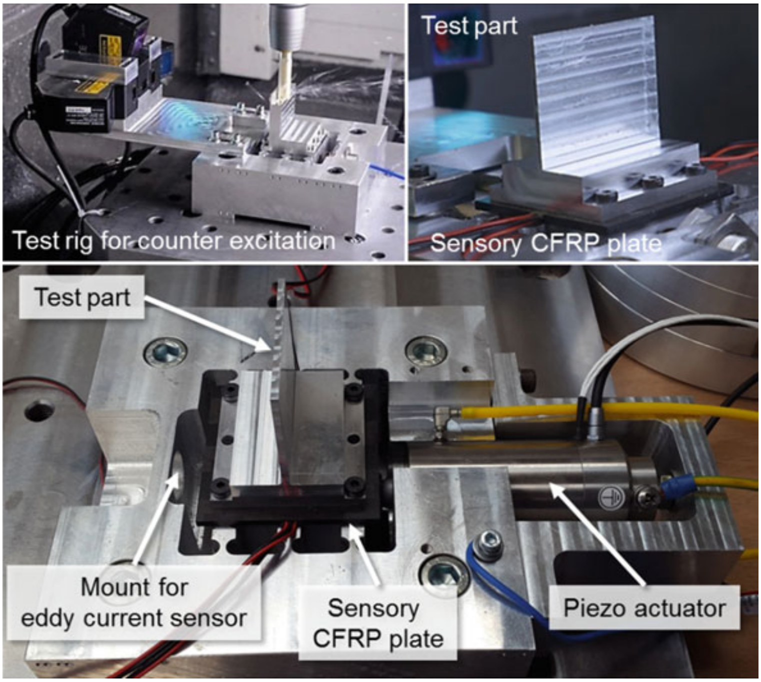

Fig. 1.7 Realized single degree of freedom test rig [6]

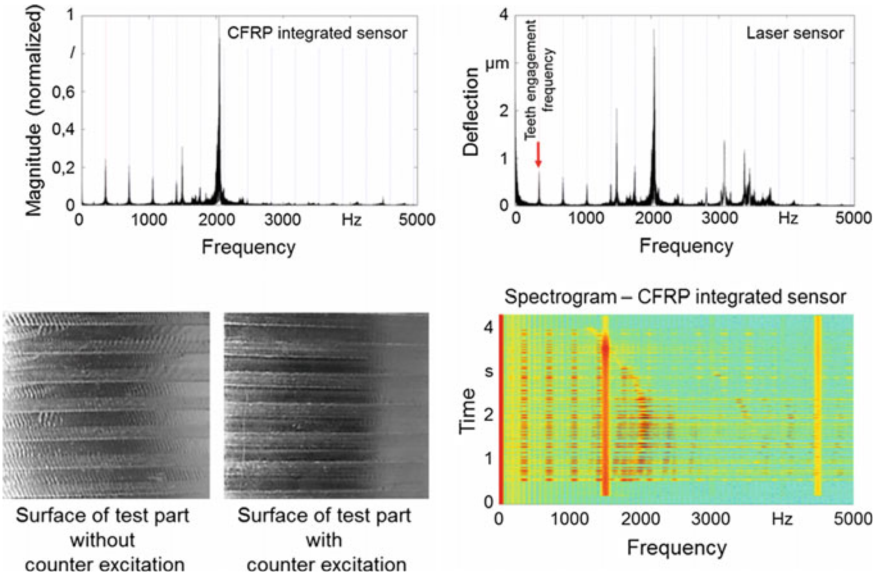

Fig. 1.8 Test results achieved with single DoF test rig [6]

1.4 Simulation of the Influence of a Counter Excitation

In order to evaluate different strategies for active excitations with, e.g., the test rig presented in Sect. 1.3, the simulation system presented in Sect. 1.1 was extended to simulate the influence of an active excitation on the resulting workpiece surface after the machining process [19, 22]. The additional vibration is modelled using uncoupled harmonic oscillators as well. These oscillator models can be calibrated in the same way as the model of the dynamic behaviour of the workpiece based on measured frequency response functions. Each of the FRFs represents the transfer behaviour from the actuator to one of the measurement points of the workpiece surface, which are already defined to simulate workpiece vibrations. Instead of exciting the workpiece with an impulse hammer, the actuator can be used directly for measuring the FRFs.

During the milling simulation, the oscillators which model the transfer behaviour of the actuator are excited based on a given strategy. In the simplest case, a sine force with a constant frequency and amplitude can be used. When calculating the deflection of the workpiece at the engagement position using the described interpolation approach, the deflections of the additional oscillators for the active excitation are added to the deflections of the workpiece oscillators. This way, the influence of the active excitation is taken into account in the calculation of the chip thickness and the resulting surface location errors.

Validation experiments for the presented modelling and simulation approach were conducted using the test rig with one translational degree of freedom, which is described in Sect. 1.3. The plate workpiece was mounted on the rig and machined with a toroidal cutter with a diameter of $d = 12\,\text{mm}$, a corner radius of $c_r = 1.5\,\text{mm}$, two cutting edges, and a helical angle of $\lambda = 30°$. The plate was machined from top to bottom with an axial depth of cut of $a_p = 0.6\,\text{mm}$, a radial depth of cut of $a_p = 1.0\,\text{mm}$, a feed velocity of $v_f = 3714\,\text{mm/min}$, and a spindle speed of 10600 RPM. Using these process parameter values, the machining process was simulated without an active excitation and with active excitation frequencies of 1200, 1500, and 1800 Hz [19]. The resulting surface topographies, which are depicted in Fig. 1.9, show that chatter marks, resulting from a torsion mode of the plate, are present in the corners when no active excitation is used. With the active excitation, the overall roughness is increased and for 1200 and 1800 Hz, the chatter marks are still present. However, using an active excitation at 1500 Hz, the chatter marks are almost completely avoided in simulation result.

In order to show the applicability of the simulation system for optimizing the active excitation strategy, machining experiments were conducted with the same process parameter values and excitation frequencies. Surface profiles of the resulting workpieces were measured. Figure 1.10 shows a comparison between these measured and the simulated profiles [19].

With an active excitation, the chatter marks in the corners are clearly visible in the measured and the simulated profiles. In addition to the position of the chatter marks, the magnitude of the deviations is similar. Comparing the surface profiles

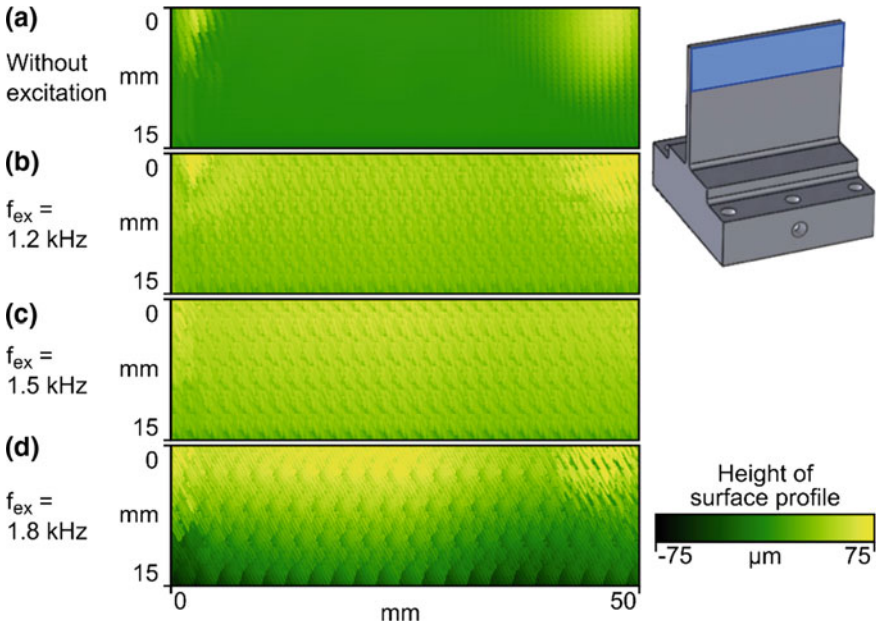

Fig. 1.9 Simulated surface location errors with different active excitation frequencies [19]

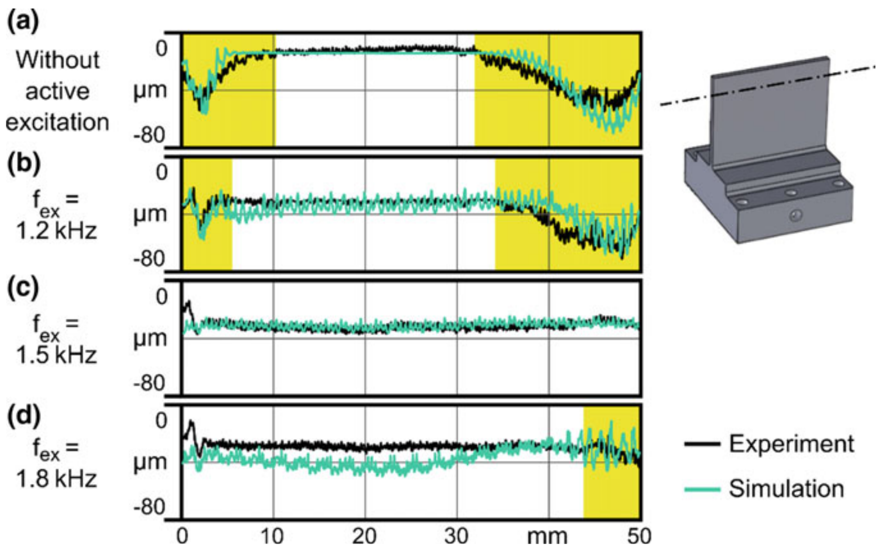

Fig. 1.10 Comparison of measured and simulated surface profiles for different active excitation frequencies [19]. Highlighted regions shows insufficient surface quality

for the three excitation frequencies, chatter marks are still present for 1200 and 1800 Hz in the experiment, as expected from the simulation results. Using an active excitation at 1500 Hz, a significant improvement of the surface quality could be observed as well. The correspondence between the results of the experiments and the simulations shows that the described modelling approach is applicable for the presented use case. However, the roughness of the simulated surfaces is slightly higher than the roughness of the surfaces after machining [19].

1.5 Preliminary Prototype of Rotational Intelligent Chuck

Based on the experiences made with the translatory single degree of freedom test rig, the prototype of the rotational intelligent chuck was developed. A challenging task regarding the realisation of a rotational counter excitation is the translation of the linear motion of the piezo-electric actuator to the rotating motion of the workpiece. To solve this problem, various designs of mechanisms were developed and studied by FE analysis (FEA). A first rotational actuation mechanism is presented in Fig. 1.11. In this approach, the piezo actuator applies dynamic forces on an outer ring element which is guided by flexure hinges around a static core (Fig. 1.11c). An additional elasto-kinematic rotational bearing (Fig. 1.11b) is combined with the drive structure so that the outer bearing ring is connected to the excited outer ring of the drive structure and the bearing core is connected to the core of the drive structure. The movable outer bearing ring on his part carries a clamping table (Fig. 1.11a) in which the clamping mandrel for the fixation of the workpiece can be integrated.

The results of the FEA of this mechanism show that a simulated linear elongation of the piezo actuator and resulting force leads to a rotational movement of the clamping table (Fig. 1.11e). However, due to the non-symmetrical torsional compliance of the mechanism, the centre of rotation does not coincide with the rotational axis of the table and workpiece. This means that the excitation is distributed unevenly and that additional superposed translational displacements occur. In a second improved design approach, these drawbacks were avoided by a modified and optimized mechanism (Fig. 1.12).

In the improved design concept, the actuator applies the excitation force on a movable core which is located in the centre of the fixture. This core is guided by flexure hinges inside a static frame. The drive structure (Fig. 1.12b) is again combined with rotational bearing elements which also carry the clamping mandrel (Fig. 1.12a). The dynamic behaviour and natural frequencies of the fixture mechanism can be adjusted by the arrangement and layout of the elasto-kinematic joints within the drive and bearing elements as well as by the combination of the drive element with one or two bearing elements. The FEA of the fixture mechanism shows that the centre of rotation now coincides with the rotational axis of the workpiece (Fig. 1.12d). The realized prototype of the intelligent rotational fixture is presented in Fig. 1.12e.

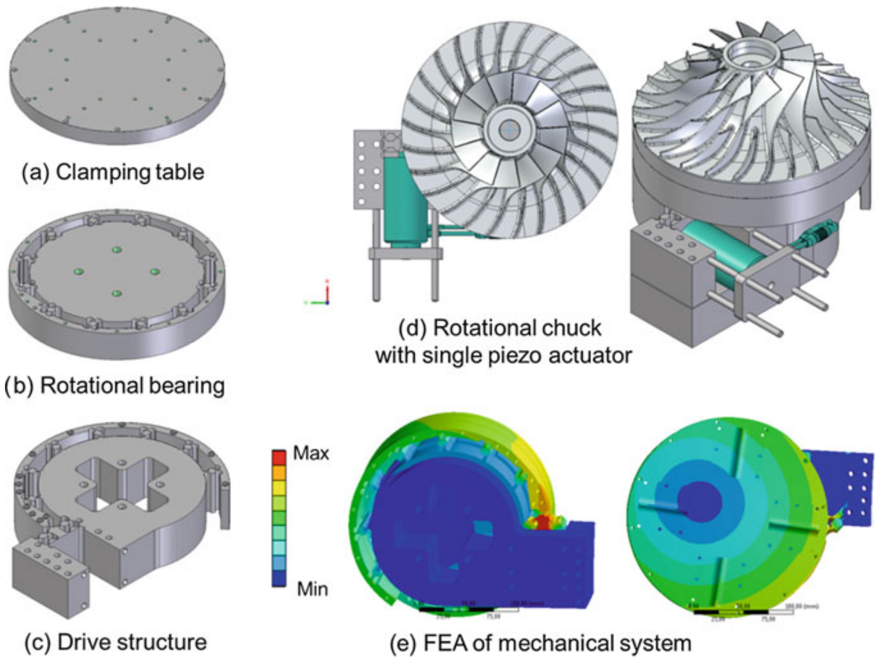

Fig. 1.11 Preliminary design of a rotational actuation mechanism [6]

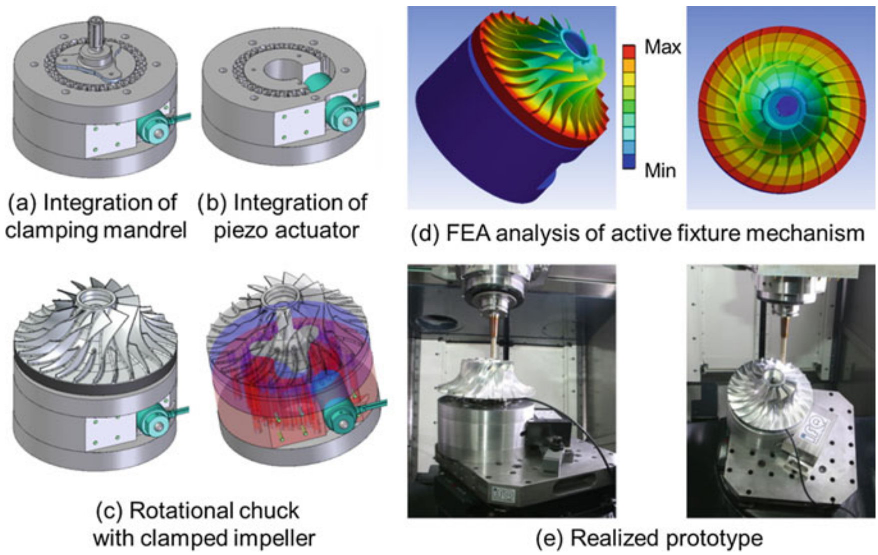

Fig. 1.12 Improved design of rotational actuation mechanism [6]

1.6 Sensor Integrated CFRP Structures

A sensitive easy-to-integrate sensor for the detection of workpiece vibrations during machining is a key component of the system. The principle approach of sensor integration is already mentioned in Sect. 1.3. In order to minimize the masses and inertial moments of the excited rotary movable part of the fixture system, a lightweight structure for the sensor integration approach is aspired. Therefore, a CFRP structure with integrated piezo patch transducers was developed as a sensory element of the intelligent chuck (Fig. 1.13).

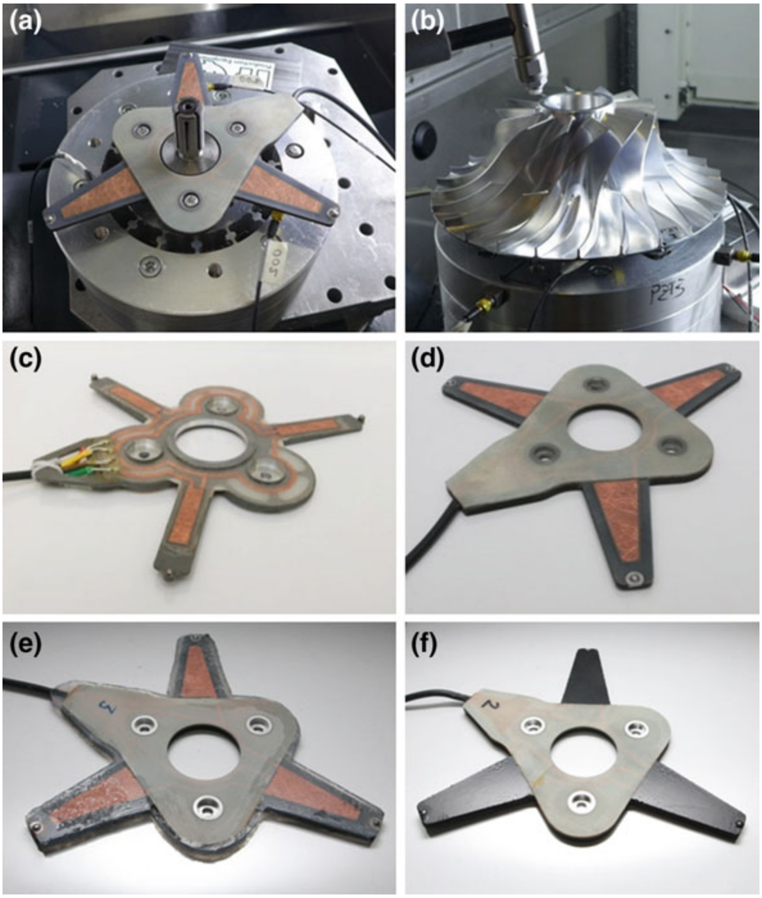

Fig. 1.13 Sensory CFRP structures for integration into the intelligent chuck: **a** integrated sensory CFRP structure, **b** testing of dynamic properties, **c** 3D printed sensory aluminium prototype, **d** sensory CFRP structure, **e** sensory CFRP structure with silicone cover, **f** sensory CFRP structure with EPDM cover [6]

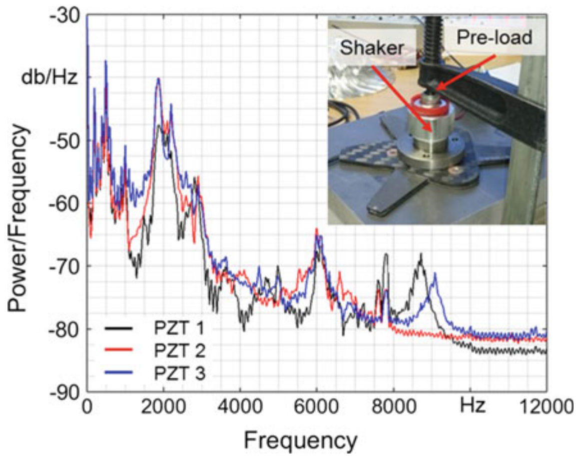

Fig. 1.14 Experimental test of sensory CFRP structure [6]

Whereas in the translatory test rig the CFRP integrated sensors are loaded by orthogonal forces between the workpiece and the movable table (see Figs. 1.6 and 1.7), in the rotational chuck the sensory element consists of three sensor equipped "fingers" which are pre-stressed against the bottom surface of the workpiece during the clamping procedure. Thus, bending loads are applied on each finger that can be detected by the integrated piezo patch transducers. The sensitivity and bandwidth of these sensory elements without and with workpiece was analysed by shaker and hammer excitation tests (Fig. 1.13b). In Fig. 1.14 a comparison of the frequency response of the three distributed piezo patch transducers (PZT 1–PZT 3) inside the sensory CFRP structure shown in Fig. 1.13d for an excitation by a miniature shaker is depicted. A comparable sensitivity of each of the sensors can be observed.

The symmetric arrangement of the distributed sensors allows the observation of workpiece vibrations independently from the point of excitation by the milling process. This aspect is important with respect to moving tool contact points during the overall machining process. Furthermore, sensor data fusion, e.g., by simply summing up the sensor raw signals, appears to be easily realizable without losing relevant frequency response information. A comparison of the dynamics characteristics of the different sensory structures shown in Fig. 1.13c–f is presented in Fig. 1.15. The first natural frequencies of the different CFRP components (represented by the first dominant peaks in the frequency response functions) are lower compared to the aluminium structure but nearly the same dynamic response amplitudes can be achieved. The results of the hammer excitation tests with a clamped impeller and the sensory CFRP element shown in Fig. 1.13d are illustrated in Fig. 1.16.

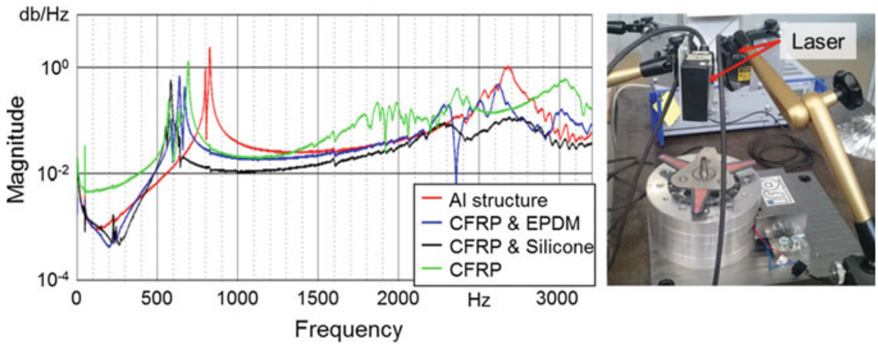

Fig. 1.15 Comparison of sensory structures [6]

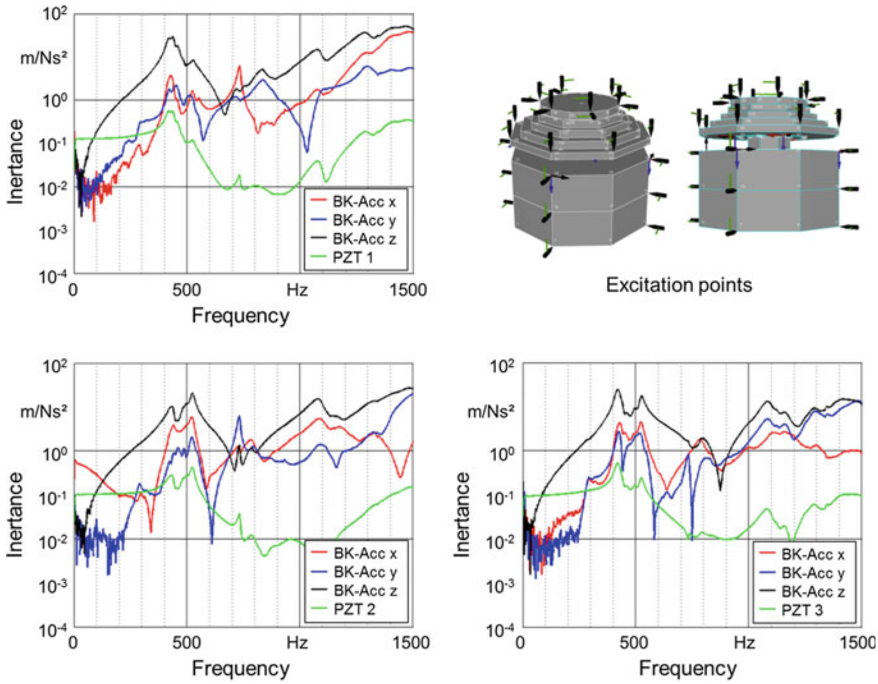

Fig. 1.16 Results of hammer excitation tests of the integrated sensory CFRP structure [6]

The integrated piezo patch transducers (PZT 1–PZT 3) are compared to triaxial reference sensors (BK-Acc) which were mounted at different components of the rotational chuck and the workpiece. The integrated sensory elements allow the detection of the first natural frequency of the assembled system. Due to the pre-stressed contact of the CFRP fingers at the bottom surface of the workpiece, vertical vibration motions are detected with a high sensitivity whereas other vibration modes are damped in the sensor signals. Since bending vibrations of the impeller blades also include vertical components as a result of the complex mode shapes, the integrated sensors possess the necessary sensitivity to observe these relevant blade vibrations.

1.7 Experimental Results

In order to validate the counter excitation strategy and to analyse the sensory capability of the rotational intelligent chuck, milling tests were conducted under the following process conditions: tool diameter $d = 12$ mm, tool rotational speed $n = 10{,}600$ min^{-1}, number of teeth $z = 2$, tool engagement parameters $a_e = 1$ mm, $a_p = 0.6$ mm, feed velocity $v_f = 3710$ mm/min. A milling setup comparable to the tests with the translatory single degree of freedom test rig was chosen. For this, straight thin-walled workpieces were mounted on top of a rotational plate which was clamped by the clamping mandrel of the fixture and which pre-stressed the integrated sensor system (Fig. 1.17).

The mass and inertia of the plate with mounted test workpieces was adapted to the properties of the reference impeller. Based on the results which were obtained with the translatory test rig, counter excitations with a frequency set value of $f_{ex} = 350$ Hz were applied and the machining results with and without counter excitation were compared with respect to the workpiece surface. The different workpiece surfaces were measured by an ALICONA InfiniteFocus device.[1]

As can be seen in Fig. 1.18, a smoother and more regular surface could be achieved when applying the counter excitation. The measured surface roughness could be reduced from $Ra = 1.806$ µm without counter excitation to $Ra = 0.562$ µm with counter excitation. However, more investigations regarding counter excitation strategies are necessary in order to further reduce the waviness of the parts.

[1]The surface measurements were conducted at the Institute of Mechanical Engineering of the University of Applied Science Magdeburg Stendal.

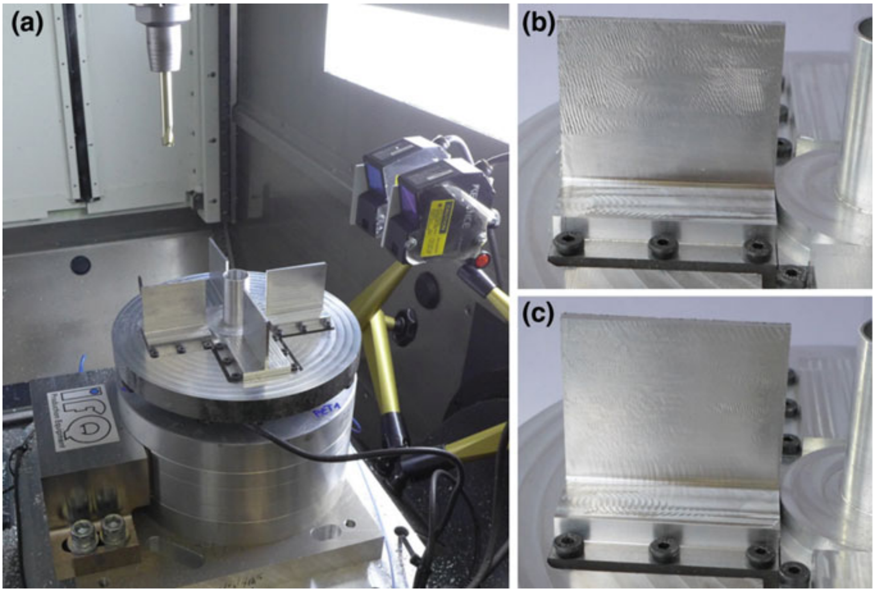

Fig. 1.17 Setup of machining tests with the intelligent chuck prototype (**a**), test workpiece after milling without counter excitation (**b**), test workpiece after milling with counter excitation (**c**) [20]

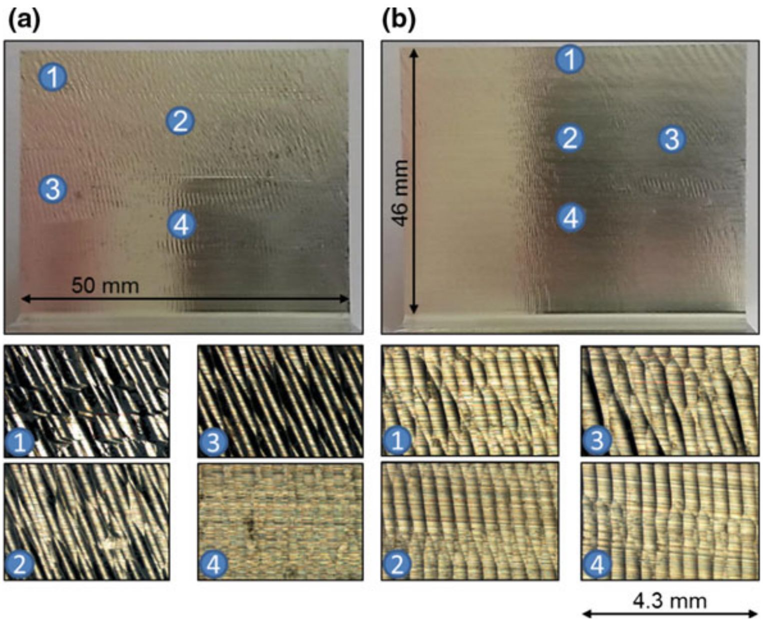

Fig. 1.18 Machining results without (**a**) and with (**b**) application of counter excitation [21]

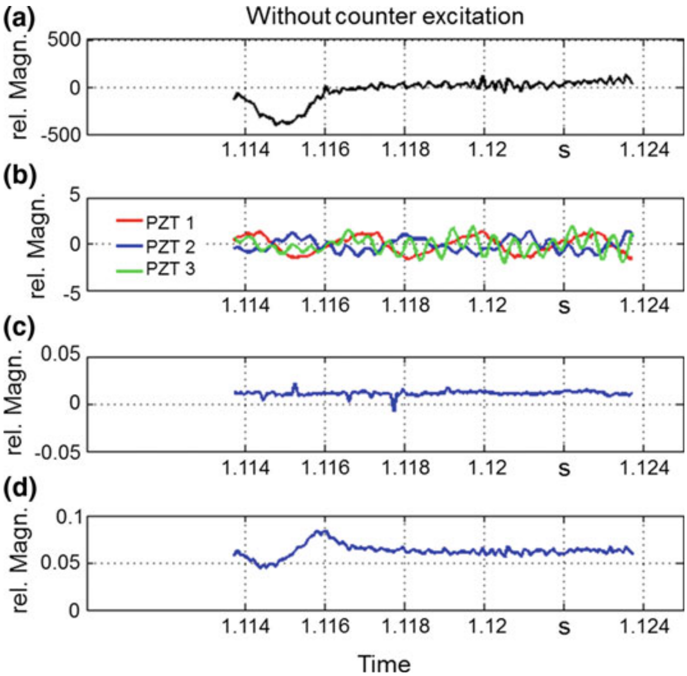

Fig. 1.19 Sensor signals during milling without counter excitation: **a** force at piezo actuator, **b** signals of integrated piezo sensors, **c** signal of laser sensor, **d** piezo actuator monitoring signal [6]

During the milling tests, the signals of the integrated piezo patch transducers, displacements of the tip of the test workpiece measured by laser triangulation sensors (see Fig. 1.17), the forces applied by the piezo actuator, and the elongation monitoring signals of the piezo actuator gathered by an attached strain gauge were collected.

In Figs. 1.19 and 1.20 these signals are depicted for a short time segment. In the signals of the integrated piezo sensors for the process without counter excitation (Fig. 1.19b), the tooth engagement frequency ($\sim$350 Hz) can be identified together with the first natural frequency ($\sim$2 kHz) of the simplified workpiece (see also Fig. 1.21a). In the process with counter excitation (Fig. 1.20b), the tooth engagement frequency diminishes in the signals of the piezo sensors PZT 2 and PZT 3 whereas the first natural frequency is increased (see also Fig. 1.21b). The counter excitation is visible in the signals of the laser sensor (Fig. 1.20c). This corresponds to the frequency of the waviness of the workpiece surface in Fig. 1.18b, which amounts to $\sim$174 Hz; that is approx. half of the tooth engagement frequency and counter excitation frequency. These interrelations have to be investigated in detail in future work.

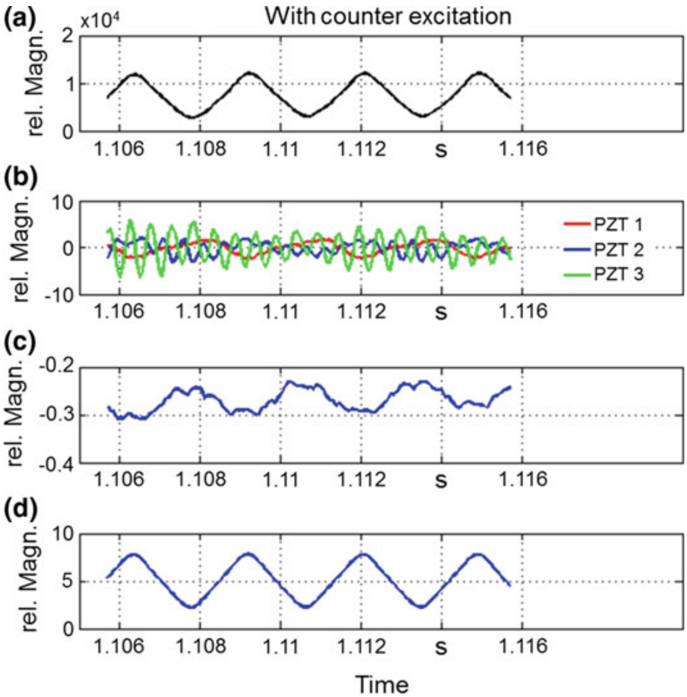

Fig. 1.20 Sensor signals during milling with counter excitation: **a** force at piezo actuator, **b** signals of integrated piezo sensors, **c** signal of laser sensor, **d** piezo actuator monitoring signal [6]

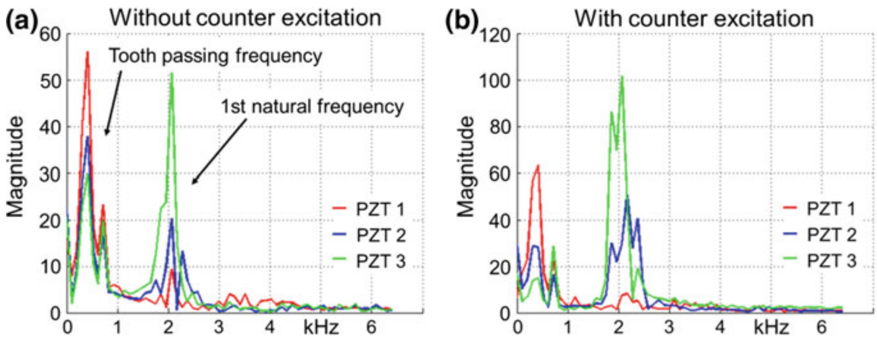

Fig. 1.21 Frequency spectra of integrated piezo sensor signals for milling without (**a**) and with (**b**) counter excitation

1.8 Summary and Conclusion

This chapter introduces an approach and prototype of an intelligent fixture for the sensory detection and active reduction of inacceptable workpiece vibrations during milling of thin-walled impeller blades. The process dynamics and machining results regarding the geometry and surface quality of the workpiece can be predicted by process simulation techniques. This also allows the calculation and assessment of the influence of an active counter excitation on the process stability and surface location errors. In a first translatory test rig, the effect of the application of counter excitations was investigated and verified. Based on this, a rotational intelligent chuck was developed and realized as a prototype. This prototype involves a CFRP element with integrated piezo patch transducers for the sensory detection of workpiece vibrations. The clamped workpiece can be excited in a rotational degree of freedom by an integrated piezo actuator. Machining results and measurements show that a decrease of the waviness at the workpiece surface can be achieved by an active excitation of the workpiece and that the integrated sensors are capable to observe the workpiece vibrations during the process. However, a global surface location error occurs when the counter excitation is applied which has to be compensated by the milling path. The realized prototype has to be developed further with respect to an industrial product. Furthermore, in future basic research activities, the functionality and effects of the counter excitation approach have to be investigated in more detail. The described advanced simulation methods were validated as a suitable tool for the process simulation and optimization.

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Chapter 2
Case Study 1.2: Turning of Low Pressure Turbine Casing

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Abstract In the aeronautic industry the manufacturing of thin-walled components is common. Occurring problems are associated to the poor dynamic performance during the machining process, causing problems like chatter, poor surface quality, low precision or distortions. Furthermore, the use of advanced materials with low machinability amplifies the cited problems. In this case study of the INTEFIX project, the fixture development was oriented to the improvement of the dynamic behaviour of the workpiece using two approaches: (1) "Active modification of mechanical impedance" deals with the use of active vibration reducers that create a counteracting inertial force with a magnetic actuator controlled in a closed loop, minimizing the vibrations during the machining of the workpiece. (2) "Controlled deformation" deals with the use of actuators integrated in the fixture to apply controlled forces in defined areas of the workpiece that modify the clamping state of the workpiece and its dynamic behaviour, leading to a reduction of the vibrations during the machining process. Additionally, the application of CFRP materials to provide a higher damping to the fixture structure is tested. This chapter covers the

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development and integration of the active systems in the fixture prototype, and the results obtained in the experiments.

2.1 Introduction of the Case Study

The objective is the improvement of the turning performance of a turbine case made of low machinability Inconel 718 alloy with 1800 mm in diameter, 550 mm in height and common thickness of 2.5–6 mm, see Fig. 2.1. The steps of the manufacturing process in the analysed fixture involve several turning and grooving operations. The low stiffness and difficult fixturing process affect the manufacturing process, and the performance of the machining process is limited by the presence of vibrations and deformations that lead to limited cutting conditions and reduce the tool lifespan, affecting also the quality and the precision of the workpiece [1]. These problems result in additional reworks to correct the deviations or in the rejection of the component in the worst scenario. In order to minimize the effect of the problems associated to the turning process, the specific objectives are oriented to the following:

- Improvement of the process performance by reducing the vibrations associated to the process forces.
- Improvement of the workpiece behaviour through a modification of the clamping conditions.

The improvement of the workpiece behaviour during processing has been tackled using three approaches:

(1) *Active modification of mechanical impedance*: This solution deals with the use of active vibration reducers. The proposed system creates a counteracting inertial force with a magnetic actuator controlled in closed loop, minimizing the vibrations measured by the integrated accelerometer inside the system. The effect on the workpiece is a reduction of the dynamic amplification factor in a wide frequency bandwidth.

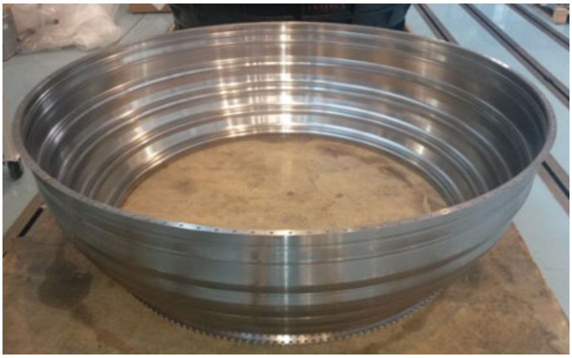

Fig. 2.1 Workpiece under assessment

(2) *Controlled deformation*: This solution deals with the use of four actuators integrated in the fixture to apply controlled forces in defined areas of the workpiece. The objective is the control of the deformation of the workpiece applying forces that increase the stiffness in the area near the cutting tool, avoiding shocks and vibrations. The local contact between the workpiece and fixture is improved and the apparent stiffness of the workpiece is increased. Thus, the workpiece is clamped by an active system under a controlled hyperstatic clamping situation.
(3) *Use of CFRP for locators*: This solution deals with the introduction of passive CFRP elements to substitute the metallic rings used as locators in the current fixture. The use of CFRP increases the damping (10 times higher than steel) of the fixture without reducing the stiffness. In this way, the effect of the shocks can be minimized.

2.2 Analysis of the Fixture and Workpiece

The clamping of the component is made in a fixture with an internal cone shape (see Fig. 2.2) for the machining of the internal face of the workpiece that is performed in a vertical lathe involving turning and grooving operations.

The fixture includes different clamping elements and supports which are shown in Fig. 2.3. These can be summarized in:

- Cast body (Cone shaped) reproducing the negative shape of the workpiece. The contact with the workpiece is limited to certain circumferential surfaces working as locators to provide support for the component. This cast body is the base to include the clamping elements and subsystems of the fixture.
- Circumferential locators: the contact is provided all around the circumference of the workpiece at selected heights. In the new fixture, one of the locators is manufactured in CFRP material in order to improve the damping of the fixture.

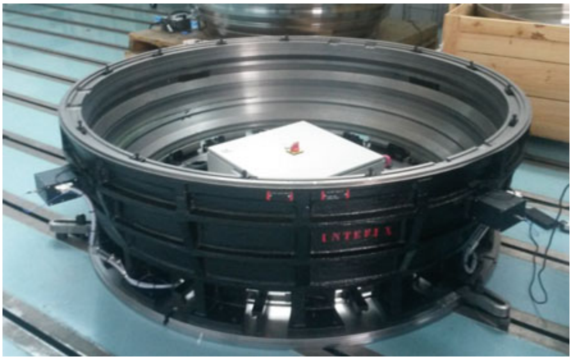

Fig. 2.2 Fixture developed in the INTEFIX project

- Axial clamp: mechanically clamps in the upper and lower flanges of the part to fix the workpiece axially, see Fig. 2.4.

Furthermore, the current fixtures used in production include flexible elements to improve the contact between the fixture and the workpiece. These elements also provide additional support and damping to the assembly.

The analysis done included the review of the current design, FEM analysis of the workpiece-fixture assembly and experimental modal analysis. The information obtained allowed the identification of the current fixture characteristics and working way; it can be summarized in the following points:

- Metallic circumferential locators provide radial stiffness in the tension mode, but in the compression mode only the own stiffness of the workpiece is noticed (see convention for modes in Fig. 2.5).
- The damping provided by the flexible elements is negligible.
- Clamping in the lower and upper flanges contribute to the global stiffness of the workpiece.

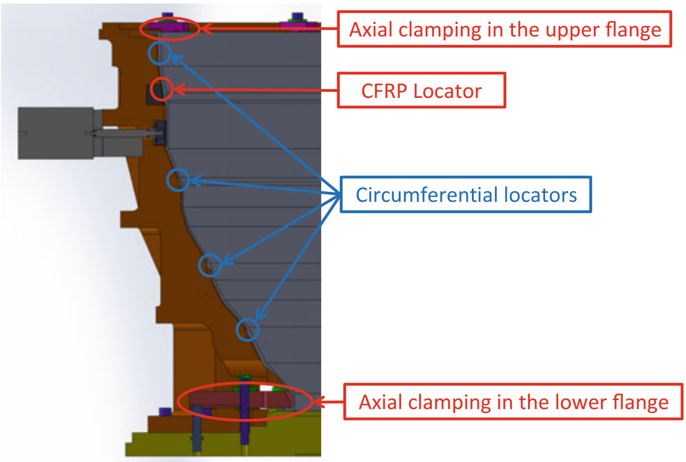

Fig. 2.3 Locators and axial clamping elements of the fixture

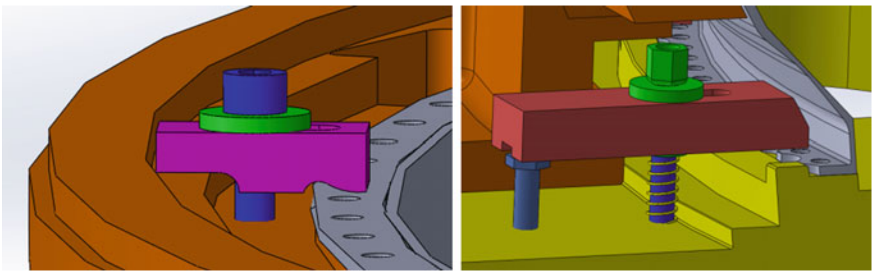

Fig. 2.4 Axial clamping elements (*Left* upper flange. *Right* lower flange)

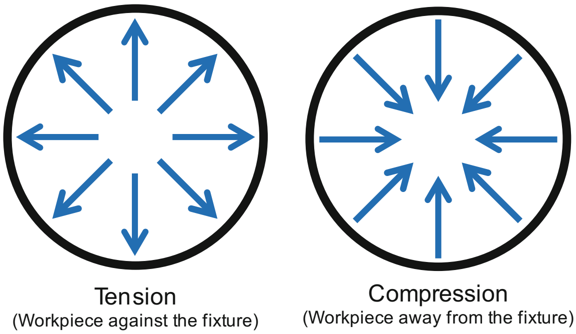

Fig. 2.5 Convention for the deformation of the workpiece

The analysis performed allowed the identification of key points to improve the workpiece-fixture assembly and to minimize the vibrations during the process. The main issue is associated to the contact between the workpiece and the fixture; due to the size and flexibility of the workpiece, and to the fact that the contact cannot be sustained all around the workpiece, the process forces drive to discontinuities in the contact between both elements. This is perceived as a lack of apparent stiffness of the workpiece that finally results in vibrations and deformations during the machining process.

The main conclusion about the current fixture behaviour is the lack of stiffness in the compression mode. This leads to potential vibrations due to (i) variable deformations in different areas of the workpiece associated to the cutting forces, and (ii) the bounce of the workpiece against the fixture resulting in shocks that dynamically excite the component during the machining process [2].

2.3 Fixture Development

In order to solve the main problems and limitations explained above, the design of the new fixture has been done integrating suitable elements and subsystems to achieve the performance of the three approaches explained at the beginning of this chapter:

(1) *Active modification of mechanical impedance*.
(2) *Controlled deformation*.
(3) *Use of CFRP for locators*.

The solution #1 deals with the use of active vibration reducers that create a counteracting inertial force to minimize vibrations. This is achieved using actuators controlled in a close loop with the feedback of sensor data to monitor the vibrations. From a mechanical point of view, the effect in the workpiece is a reduction of the dynamic amplification factor in a wide frequency bandwidth and an increment of the damping ratio. The schema of functioning of this kind of systems is presented in the Fig. 2.6, and this topic is covered in several scientific publications [2, 3].

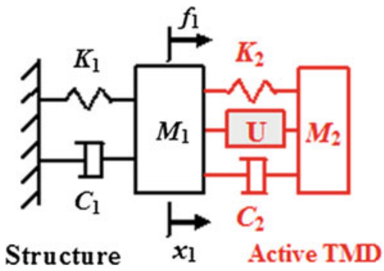

Fig. 2.6 Schema of an active vibration reducer

The solution #2 uses some actuators to apply controlled forces and displacements to the workpiece in selected zones to achieve a suitable deformation and clamping of the components. The objective is the control of the deformation and the improvement of the boundary conditions of the workpiece, increasing its stiffness in the cutting zone, as schematically shown in Fig. 2.7. This approach allows the improvement of the workpiece behaviour during cutting process avoiding shocks and vibrations.

The design of the fixture took into account the integration of the required elements (sensors and actuators) for the two approaches explained above, being the main element the actuation subsystem showed in Fig. 2.8.

This developed actuation subsystem can work in both modes (dynamically for "Active modification of mechanical impedance" and quasistatically for "Controlled deformation") with the same actuator using different sensors also integrated in the fixture. The subsystem is based on a MICA200 M [2–4] actuator located in the outside part of the fixture, including a connecting rod joined to an end effector in contact with the workpiece. This assembly needs to be preloaded to ensure the contact with the workpiece during machining using the "Active modification of mechanical impedance" mode.

The mechanical design of the fixture includes the designed actuation subsystem, the required sensors and the electric/control system as shown in Fig. 2.9. The actual fixture also includes conventional clamping elements in the upper and lower flanges

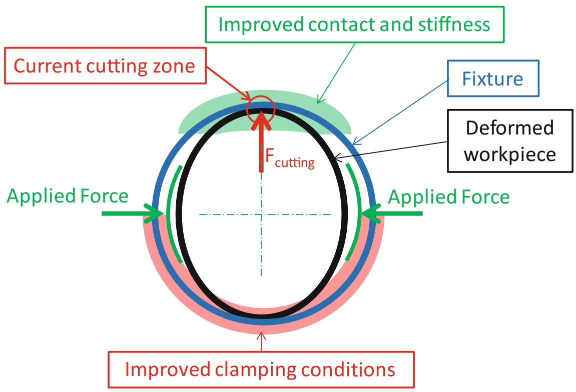

Fig. 2.7 Concept of the controlled deformation functioning

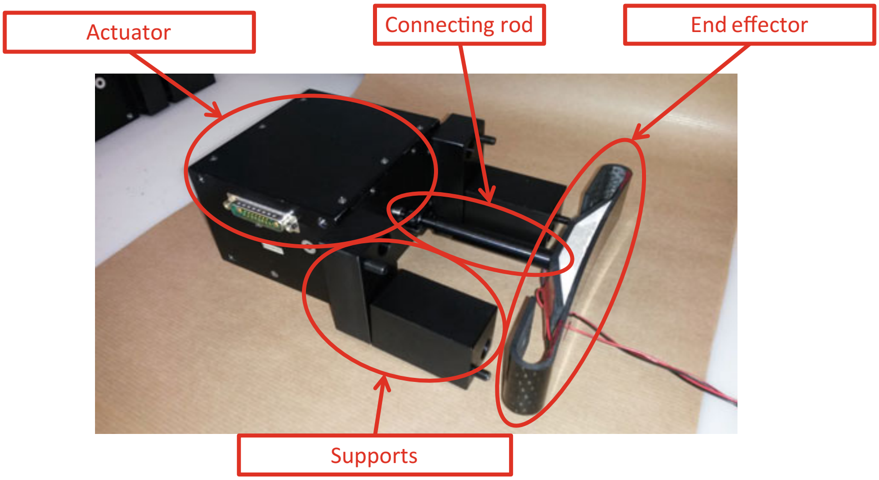

Fig. 2.8 Actuation subsystem used in the "Active modification of mechanical impedance" and "Controlled deformation" approaches

areas as used in the original fixture, and the CFRP locator designed as a third approach to improve the dynamic behaviour during the machining process, see Fig. 2.3.

Figure 2.10 shows the fixture assembly including the four actuation subsystems and a detail of this integration. Also, the CFRP locator ring installed in the fixture and the electric cabinet in the centre of the fixture is visible.

The sensors used in the fixture include one accelerometer in each actuation subsystem and an inductive sensor to establish a rotating reference during the turning process. Additionally, for testing purpose, eddy current displacement sensors and FBG strain sensors have been used to monitor the deformation of the workpiece.

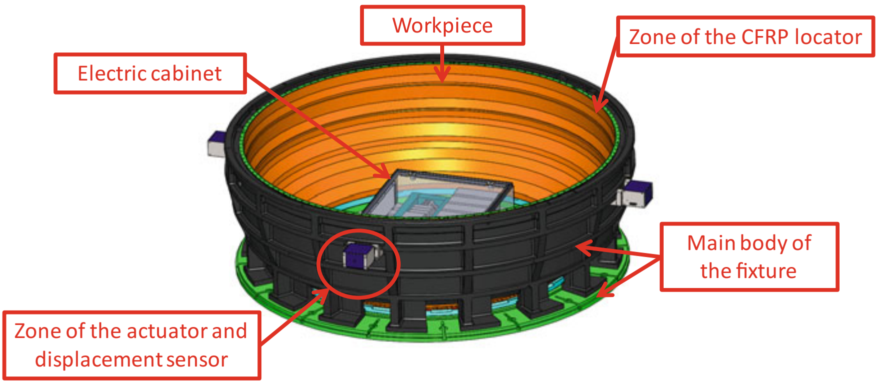

Fig. 2.9 Identification of the elements included in the fixture

Fig. 2.10 Fixture assembly and detail of the actuation subsystem assembly (*Left* External view; *Right* Internal view)

The electric cabinet is mounted in the central area of the fixture with wired connection to all the sensors and actuators used in the final assembly. The main elements are the controller, the drives of the actuators, the conditioners for the different sensors and the battery to power the whole system. Figure 2.11 shows the location of the different elements included in the cabinet. The battery works at 100 V and it is located below the controller and the electric and safety elements.

The control system can manage the system working in both modes ("Active modification of mechanical impedance" and "Controlled deformation") as a standalone controller able to manage the I/O signals without communication with the CNC of the machine tool.

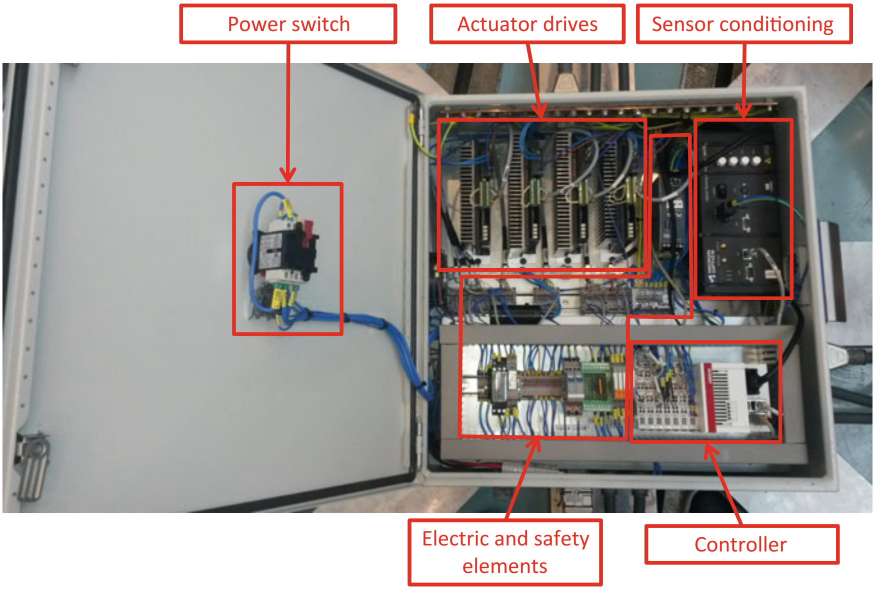

Fig. 2.11 Electric cabinet and components included

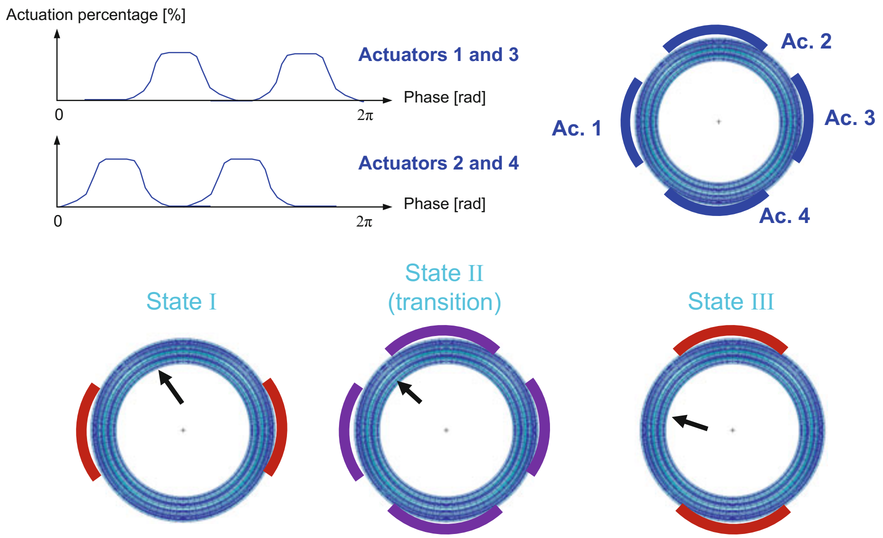

Fig. 2.12 Schema of the control algorithm for the "Controlled deformation" solution (*arrow* indicates the cutting tool position)

The control algorithm for the "Controlled deformation" solution is based on the synchronization of the four actuation subsystems to achieve a suitable result attending to the current cutting tool position. This means that the actuation must be constantly modifying the force exerted by each actuator during a revolution of the workpiece with a common angular reference. The sequence followed by the four actuation subsystems is graphically described in the Fig. 2.12; the control law follows a logistic function with two cycles per revolution of the workpiece.

2.4 Verification and Validation Tests

The tests were performed to evaluate the effects of the fixture working under the modes defined previously: "Active modification of mechanical impedance" and "Controlled deformation". Figure 2.13 shows the referencing of the four active actuation subsystems located in the fixture.

2.4.1 Verification tests

The verification tests were carried out in the laboratory including: (i) static tests to monitor the internal sensors of the system and the workpiece deformation; and (ii) dynamic tests using modal analysis to evaluate the changes in the workpiece

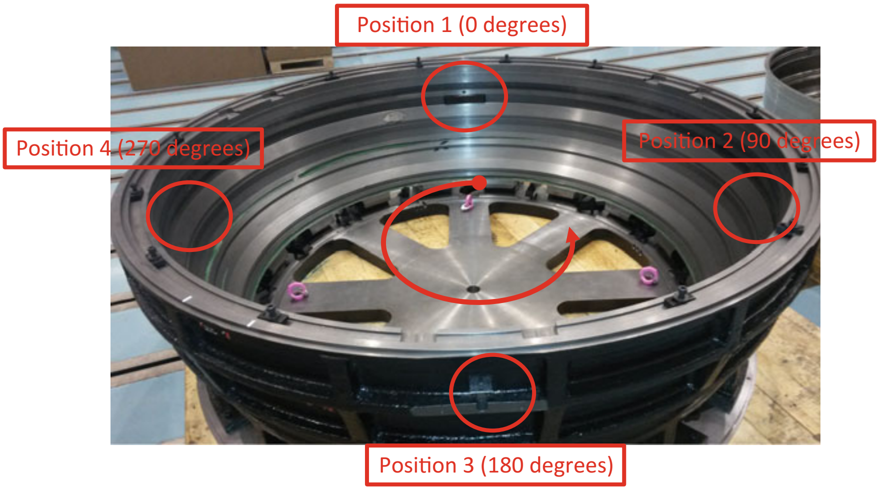

Fig. 2.13 Angular referencing

behaviour due to the actuation. These tests were done without the rotation movement in the workpiece and with the fixture clamped to the ground.

The static tests were used to verify the deformation capabilities of the actuation subsystems in different positions of the fixture, supplying the higher power allowed by the actuator to obtain a theoretical deformation force of 200 N in each actuation point.

The performance of the different actuators was highly variable with values of the measured deformation which differ significantly in the four positions as can be seen in Table 2.1. This variability was attributed to the following issues:

- The MICA 200 M actuators are systems sensible to their internal assembly, so the behaviour can vary according to internal parameters associated to the assembly process.
- The whole actuation subsystem (actuator + supports + connecting rod + end-effector) is subjected to an assembly process for the integration in the fixture that modifies the interaction with the workpiece (contact angle, initial gap…) due to differences in the adjustment and alignment of the elements.

The dynamic tests were used to verify the change of the dynamic behaviour of the workpiece when the actuators are exerting a clamping force according to the

Table 2.1 Variability of the behaviour using the four actuation subsystems

Actuator Id.	Workpiece deformation measured (µm)
Actuator @ 0°	7
Actuator @ 90°	11
Actuator @ 180°	3
Actuator @ 270°	5

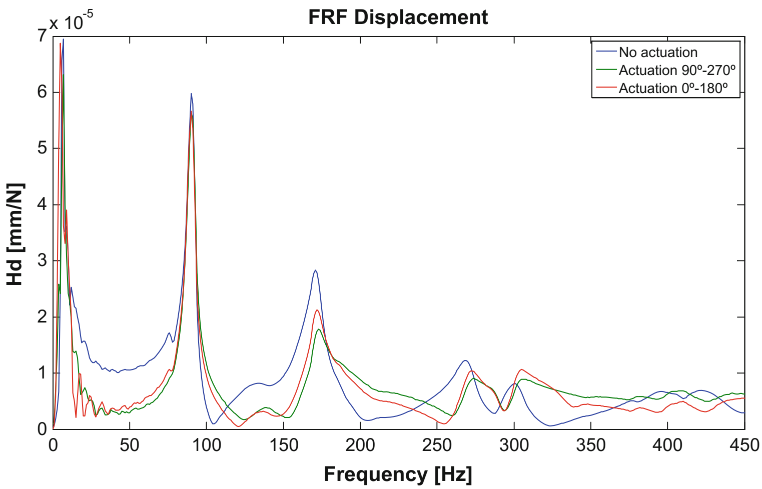

Fig. 2.14 Improved dynamic behaviour: FRF with excitation and measurement in position 1 (0º)

"Controlled deformation" functioning mode. The tests consisted in a series of modal analysis to obtain the FRF under different configurations, as an assessment of the improved clamping condition of the workpiece and the expected improvement to avoid shocks and vibrations during machining process.

The basic information obtained from the modal tests are the FRF for a position with the actuators off, the FRF for a position with the contiguous actuators on (+90° and −90°), and the FRF for a position with that actuator and the opposite on (+0° and +180°). Figure 2.14 shows an example of the measured FRFs in the three situations described above with excitation and measurement in the position 1 (0°), near the position of the actuator.

The measured FRF shows that the use of the actuation (positions 2 and 4; or positions 1 and 3) improves the behaviour of the workpiece with a general reduction of the dynamic amplification factor in the frequency domain, especially near some resonances. This indicated an improvement in the apparent stiffness, resulting in a workpiece with higher rigidity when the actuators are active. Moreover, the width of the resonance peaks indicates that the apparent damping is also increased, so the response of the workpiece against shocks and vibrations is improved. The blue curve is the base situation (without actuation) and the green curve is the situation that occurs during the "Controlled deformation" functioning mode when the cutting tool is passing through the position 1. The improvement in the dynamic behaviour is evident. The red curve is the situation that occurs at 90º of the position of the cutting tool; the amplification factor is also reduced indicating the improvement in the dynamic behaviour in that area.

2.4.2 Validation tests

The validation tests were carried out in the workshop using a GMTK ACCURACER vertical lathe to perform the machining operations. These machining tests have comprised the generation of different geometrical features like horizontal/radial slots, vertical/axial slots and cylindrical surfaces in the workpiece. Figure 2.15 shows an example of the machining tests.

The objective of the validation tests is the assessment of the results obtained during the machining process using the actuation subsystems compared to those obtained with a conventional machining process. The nominal cutting conditions established for the comparison are those currently used in the production of this kind of components.

The fixture was tested to verify the functioning in both modes "Active modification of mechanical impedance" and "Controlled deformation". During the tests in the "Controlled deformation" mode it was noticed that the rotation movement and the centrifugal forces do not affect negatively the functioning of the actuation subsystems, being the achieved deformation values in the workpiece similar to those obtained in a static situation. According to this behaviour, the machining of the slots using the actuation led to an improved run-out of the machined features. The results showed that the use of actuation produces a run-out value below 0.01 mm, while the conventional machining produces run-out values up to 0.02 mm in some areas. This is considered a consequence of the better clamping achieved in the workpiece observed during the verification tests. On the other hand, the main drawback noticed is the generation of a taper surface during cylindrical turning operations; with a taper ratio of 0.02–0.03 mm in 10 mm. The reason for this behaviour could be the misalignment of the actuation system or the asymmetric deformation of the workpiece when the actuators are pushing it. This is an aspect to consider during the design of this kind of solution for a deformable workpiece.

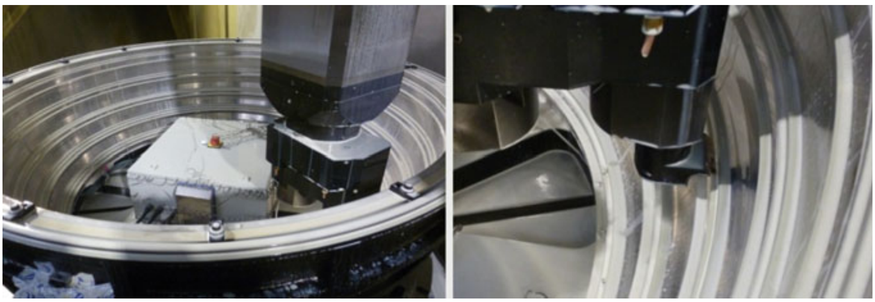

Fig. 2.15 Photographs of the machining of a horizontal/radial slot

2.5 Summary and Conclusion

The development of this case study has been oriented to the reduction of the effects of the vibrations and the low stiffness of the workpiece during the turning of the component. The work has included the development of an active fixture able to adapt the behaviour of the workpiece according to the conditions imposed by the machining process. The developed intelligent fixture allows the improvement of the workpiece behaviour and the precision of the machining process; and considering the lower vibration level, the cutting conditions could also be increased to obtain a more productive machining process.

The main contributions of this case study are the two approaches used "Active modification of mechanical impedance" and "Controlled deformation". The first one is related to the use of active vibration dampers to reduce the vibration of the workpiece during the machining process; while the second one deals with the active modification of the clamping situation of a workpiece in order to adapt the dynamic behaviour according to the cutting tool position during the machining process.

This kind of solutions is mainly oriented to large components with different dynamic behaviour depending on the zone of the workpiece or components that change their shape during the machining process requiring the modification of the fixture configuration to adapt the clamping of the workpiece during the process.

The tests performed allowed obtaining the main conclusions about the capabilities of the use of active clamping elements to apply forces to the workpiece during processing: producing a controlled deformation and working as a vibration absorber. Attending to the technical characteristics and the performance of the subsystems developed and assembled in the fixture, the main conclusions are:

- The actuators produce a deformation as expected during the design phase. This deformation is mainly a local effect, and the actuation must be carefully controlled to avoid undesired effects.
- The designed systems can work in rotating systems without significant drawbacks or malfunctioning.

Attending to the requirements of the case study and the industrial application analysed in the case study, the main conclusions of the work can be summarized as:

- Both solutions ("Active modification of mechanical impedance" and "Controlled deformation") can provide better results attending to run-out, surface roughness and vibration behaviour; being this manly related to the improvement of the clamping conditions and the dynamic behaviour of the clamped workpiece.
- The actuation allows the improvement of the clamping of the workpiece, increasing the apparent stiffness and providing additional damping to the whole system.
- The use of actuators (local deformation) affects negatively some geometrical aspects of the finished workpiece. This is related to the asymmetrical deformation achieved in the workpiece.

The developed solution is specific for the workpiece analysed in this case study, but the same methodology can be used for the development of fixtures for work-pieces with low stiffness and big size that is a common situation in the aeronautic industry in the manufacturing of both, structural and engine components. This kind of solutions is specially indicated for those components that are difficult to clamp avoiding the deformations during the machining process.

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Chapter 3
Case Study 1.3: Auto-adaptive Vibrations and Instabilities Suppression in General Milling Operations

Lorenzo Sallese, Jason Tsahalis, Niccolò Grossi, Antonio Scippa, Gianni Campatelli and Harry Tsahalis

Abstract In general rough-milling operations, unstable tool vibrations due to the interaction between process forces and tool flexibility could arise. The onset of these unstable vibrations, usually referred to as chatter, poses limitations in terms of the achievable material removal rates, hence directly impacting on the productivity. Moreover, chatter vibrations generally lead to an increase in tool wear, imposing premature tool changes and careful monitoring of the process, potentially impeding unmanned operations. Within the INTEFIX project, an active fixture prototype was developed to detect and mitigate the level of chatter vibrations in general rough-milling operations with the purpose of improving the achievable material removal rates. This contribution covers the main aspects of the global development of this prototype, from the mechanical design to the adaptive control logic used in order to drastically reduce the inputs and expertise required for its operability.

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3.1 Introduction of the Case Study

This case study deals with the mitigation of unstable chatter vibrations arisen in milling operations, particularly in the roughing phase, in which the material removal rate is taken to the extreme in order to maximize productivity. The component to be manufactured often presents geometrical features that impose the use of slender tools, making the process more prone to the onset of these unwanted vibrations. Such a case is representative of most component of the aerospace and die/mold sectors where, in addition, the amount of removed material gets particularly high. In this scenario chatter vibrations get carefully regarded mainly because of their severe impact on tool wear [1] that imposes more frequent tool changes and complicates the operations in unmanned conditions.

Chatter vibrations in machining processes are a renowned issue both in the scientific and industrial world [2]. Several techniques have already been developed to prevent this phenomenon by selectin optimal cutting parameters to keep the process in stable conditions, exploiting numerical models [3] or dedicated experimental procedures [4]. Nevertheless, most of these approaches are limited by the required expertise and by the fact that the predicted optimal conditions are representative only of a specific tool-material combination. As a consequence, their applicability in a general industrial environment is limited.

Recently, the use of active materials has strongly contributed to the development of alternative active techniques based on the integration of mechatronic systems in the machine-tool structure, capable of interfering with the process in real-time in order to stabilize it. Among these, active fixtures seem to represent the most industrial appealing solutions. Their direct retrofittability would indeed demand for lower expertise and reduced set-up time [5].

The present case study had the goal of developing an active fixture capable of reducing the severity of the unstable vibrations level in the rough-milling cycle of a mold component. The activities performed within the case study allowed the definition of a suitable mechanical design for a two degrees of freedom active fixture. A careful selection of the hardware implemented in the fixture allowed to increase the actuation bandwidth and to improve the robustness in industrial applications. A crucial task within this case study was the development of a dedicated black-box control logic capable of avoiding preliminary system identification and modeling as generally required for the control development and implementation in this kind of devices [6]. All the tasks contributed to the increase of the retrofittability features of this kind of devices and ensured a level of performance close to the industrial standards and requirements.

The chapter covers the main aspects of all the tasks of this case study, discussing the main challenges and the general approach used for the global development. Finally, the results obtained on an industrial test-case are presented in order to show the achievable improvements in terms of chatter mitigation.

3.2 Active Fixture Development

The development of an active fixture goes through the integration of different subsystems with peculiar issues to be tackled, as for most mechatronic devices. The next sections cover the most relevant aspects of the prototype development, discussing the main issues that needed to be addressed in order to achieve the desired global behaviour.

3.2.1 Fixture Architecture and Mechanical Design

In analogy to similar micro-positioning applications, a literature overview shows two main fixture architectures for a two Degrees of Freedom (DoFs) device capable of counteracting tool vibrations in the plane normal to the tool axis. The simplest solution could be represented by a compliant mechanism with parallel kinematics, schematized in Fig. 3.1a, which would allow for symmetric fixture response while reducing the overall masses and dimensions [5].

The main drawback of this kind of architecture is represented by the relevant cross-talk effect that could arise between the actuated axes and that could be overcome only by employing additional sensors, actuators and control strategies. This would sensibly complicate the overall development and impose a larger budget effort. For these reasons, a different architecture was selected for the active fixture prototype, opting for a structure based on serial kinematics, schematized in Fig. 3.1b, that would theoretically allow for a decoupled motion of the stages [7]. Nevertheless, the nested structure would imply different geometries and masses for the inner and outer stages that would hence show different dynamics and should be carefully considered during the fixture design phase.

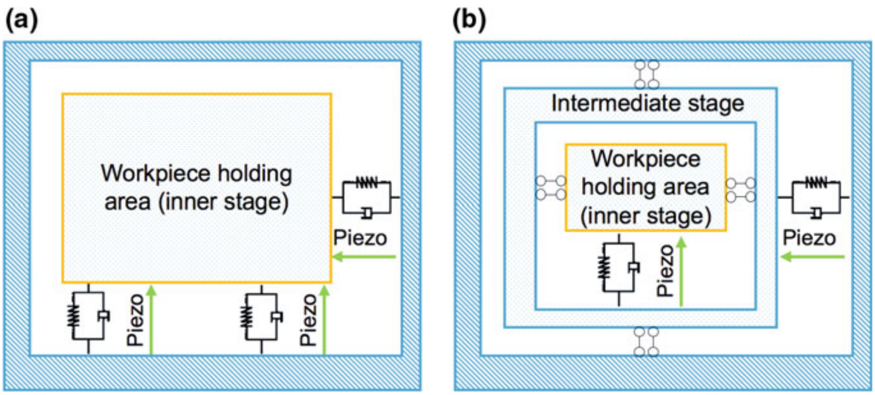

Fig. 3.1 Schematization of **a** parallel-kinematics architecture. **b** serial-kinematics architecture

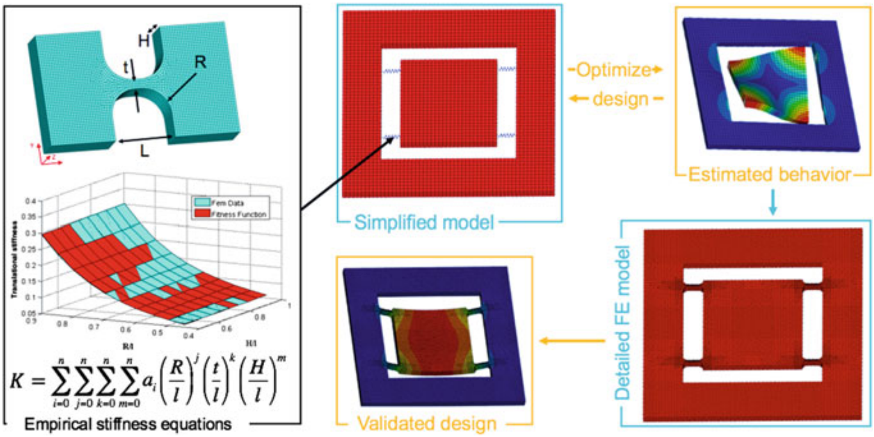

Fig. 3.2 Conceptualization of the general approach used to simplify the mechanical design of the active fixture

Regardless the fixture architecture selected, the design of the fixture frame plays a crucial role in assessing the achievable active fixture performance. It should indeed be capable of simultaneously ensuring the needed stiffness, imposed by precision requirements, while allowing enough flexibility for the actuators to produce adequate workpiece displacements [8]. These conflicting requirements are usually met by integrating monolithic flexure hinges in the frame in order to adequately decouple axes motion and achieve the desired compliance level. Literature works dedicated to micro/nano-positioning applications provide different empirical equations for the draft dimensioning of these mechanical components in order to achieve the desired motion [9]. Nonetheless, a different perspective should be used to design the flexure hinges for this kind of dynamic applications. In this case, the focus should be put on the stiffness characteristics as a function of hinge geometries in order to investigate the fixture dynamics in the early design stage. The empirical equations relating hinge stiffness with its geometries could be proficiently exploited with a simplified lumped model for the flexure hinges in order to shorten the preliminary design phase, focusing on the optimization of the number, geometries and positioning of the flexure hinges within the fixture frames. Detailed numerical models could then be used to validate the preliminary design in accordance to the application requirements. This global approach is summarized with the schema reported in Fig. 3.2.

Moreover, a detailed numerical model would allow for a better insight on other relevant aspects of the mechanical design, such as providing an estimate for the stress distributions within the fixture, needed to investigate the fatigue limits in highly dynamic application, such as the proposed one.

The manufactured prototype, designed with the described procedure, is shown in Fig. 3.3. The main aspects of the prototype assembly will be discussed in the following section.

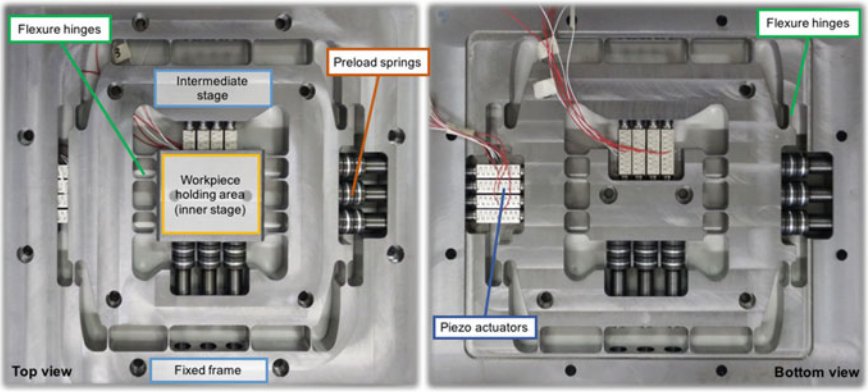

Fig. 3.3 Active fixture prototype (external dimensions 343 × 289 × 20 mm)

A valuable support in manufacturing and assembling the prototype was provided by the project partner Tecma s.r.l., an Italian SME specialized in precision machining and manufacturing.

3.2.2 Actuators Selection and Implementation

As shown in Fig. 3.3, the developed prototype integrates four piezoelectric stacks actuator for each dynamic axis. The selection of suitable actuation devices represented the main issue for the development of a device with adequate bandwidth and reliability.

In recent years, several alternative actuation techniques became available and their level of performance is continuously growing. Nevertheless, piezoelectric technology still represents the most appealing solution, mainly due to the achievable power density and bandwidth [10]. The integration of this kind of actuation devices in the machine tool components with the purpose of interacting with the machining process, is a renowned topic [11], but the features of the piezo-ceramic used could drastically reflect on the achievable bandwidth and performance. Self-heating issues represent one of the main limiting factors in long-term dynamic operation of piezoelectric actuators. In that sense hard-doped piezo ceramic represents the best trade-off between the achievable level of force/displacement generation and the influence of self-heating [12].

All these considerations where taken into account in selecting the suitable actuators to be implemented in the active fixture prototype. It should indeed be considered that this device must be capable of generating counteracting vibrations at the chatter frequency that can easily exceed the kHz range, and possibly for a long operative time. Considering the commercially available alternative, Noliac actuators based on NCE46 hard-doped ceramics have been selected. The main features of the selected actuators are reported in Table 3.1.

Table 3.1 Features of the selected SCMAP-NCE46-10-10-2-200-H36-C01 Noliac actuators (one single actuator)

Dimensions W × H × L (tips excluded)	10 × 10 × 36 mm
Estimated blocking force	3200 N
Capacitance value (typical)	5300 nF
Maximum displacement (typical)	32.3 μm
Maximum operative voltage	200 V

Particular attention has been put in adequately housing the piezo actuators within the fixture. These components are indeed capable of withstanding mostly compressive stresses, hence adequate counter measurements should be taken to prevent them against bending and tensile stresses. In order to accomplish an adequate housing of the actuators, hemi-spherical end-tips have been glued to the actuators extremities and dedicated engraved hemi-spherical supports have been machined in the fixture frame and in the actuators set screws, as shown in Fig. 3.4.

Even though such a unilateral constraint would intrinsically prevent any tensile stress on the actuators, adequate preload has been applied to prevent the onset of play within the joints, potentially leading to shocks on the actuators tips in demanding dynamics applications. The preload is applied by means of three stacks of Belleville springs acting against the stages, oppositely to the actuators, as shown in Fig. 3.3. The required preload force has been estimated thanks to numerical simulations of the FEM model of the fixture under operational conditions.

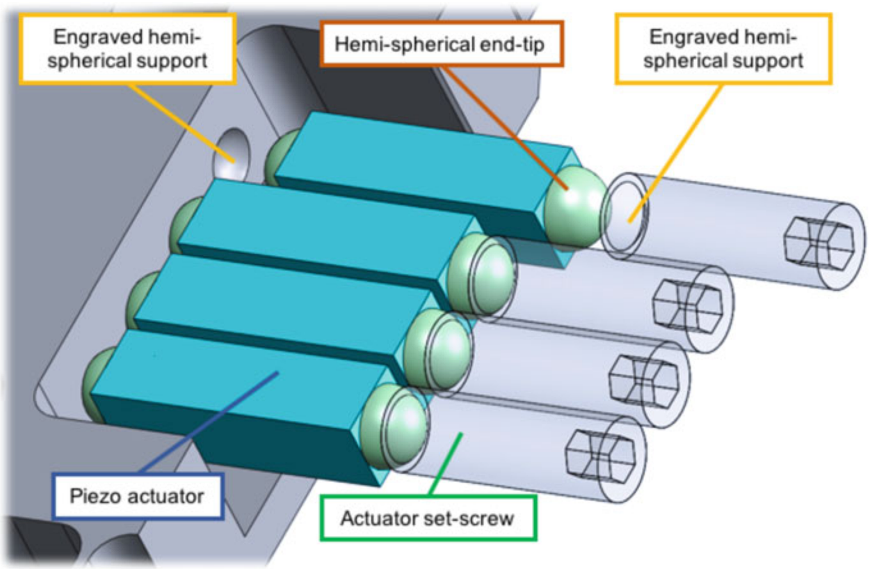

Fig. 3.4 Detail of the piezo-actuators tips and housing within the fixture frame

3.3 Control Logic Development/Implementation

As an alternative to renowned control logic techniques used for active damping in milling applications [6], the proposed approach does not require a prior investigation and modelling of the system to be implemented. An intelligent control based on a set of integrated modules is used to identify the chatter frequency to be mitigated and the optimal control signals needed for the purpose (i.e., the actuation parameters that would allow a condition of disruptive interference of the chatter vibrations). In the frame of intelligent control techniques, Artificial Neural Networks (ANNs) are employed as function approximators. The methodology here proposed, developed in prior activities by the Gree project partner Paragon S.A., is a combination of ANNs and Genetic Algorithms (GAs), and falls into the category of indirect design approaches, more specifically under predictive control schemes.

Applying such a technique to milling process entailed the tackling of additional complexities. In milling, system dynamics is influenced by the chip removal process, changing cutting parameters affects vibration occurrence. Therefore, the implementation of the control was aided by a dedicated time-domain simulation model, developed by the University of Firenze and presented in detail in [13]. The dynamics of the milling process involving the active piezo driven workpiece holder was described by a four DOFs lumped parameters dynamics model (two orthogonal DOFs for both milling cutter and workpiece holder). By means of the time-domain simulator, the developed control was tuned in the software environment, as shown in Fig. 3.5. Optimized actuation obtained by the control logic is computed on the

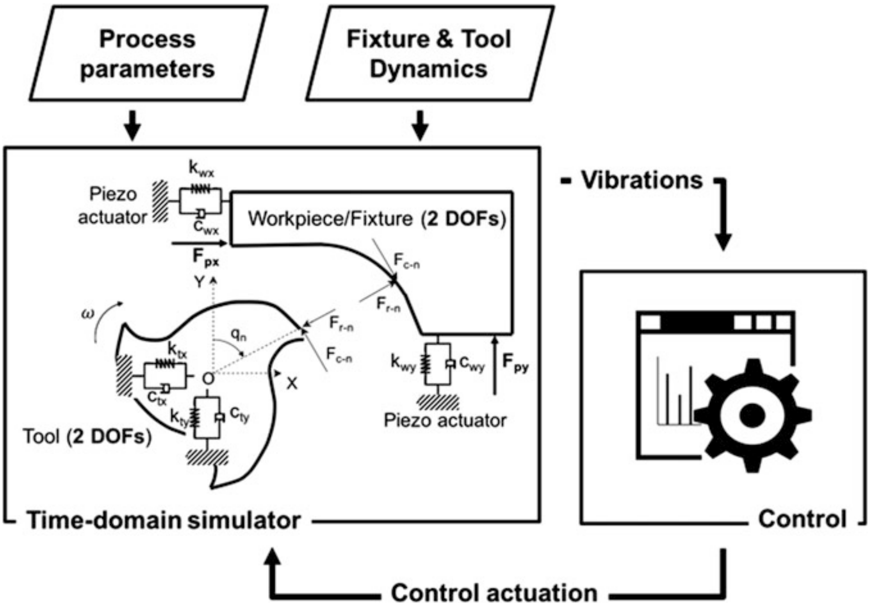

Fig. 3.5 Control testing through time-domain simulator of cutting process

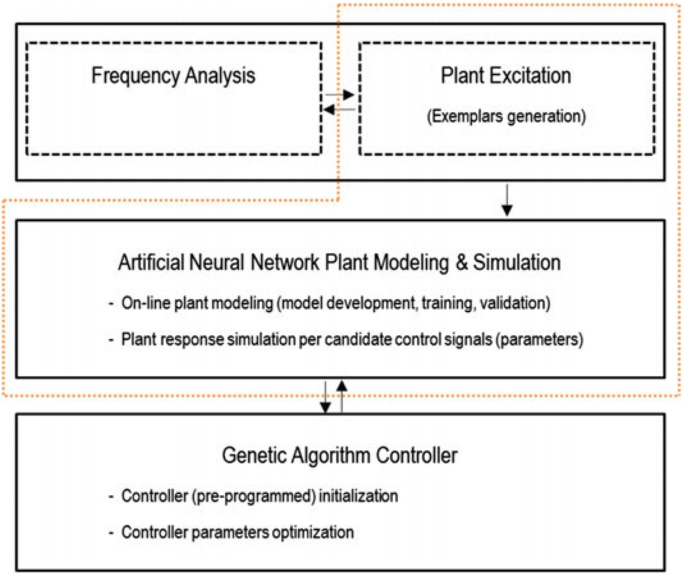

Fig. 3.6 Active Vibration Control (AVC) software modules and functions

basis of vibration signals simulated, and then included in the process model to assess its performances.

The control software application developed exists in several forms, the latest being a version developed using MATLAB®. This was done for several reasons, such as the wide-spread use of this particular development environment, simplification of the software application in so far as utilizing functions already available for DAQ and DSP purposes, and to allow for a greater application flexibility or extension via use with Simulink®. A diagram of the software modules–sequences is provided in Fig. 3.6.

3.3.1 Frequency Analysis and Excitation

Under the effect of external disturbances, in this application the forces generated by the machining process, the vibration of the structure (i.e., primary field) is measured at each sensor position (i.e., accelerometers in this application).

The data acquired from each sensor is analysed using the Fast Fourier Transform algorithm (FFT), and the dominant frequencies (i.e., chatter frequency and possibly its sidebands) and its corresponding characteristics per sensor/channel are identified. The sequence ends with the selection of the highest dominant frequencies identified. These are the vibration frequencies to be controlled/reduced.

Since the method aims at creating a system that reduces vibration through active means, the representative model of the system needs to include the effects of the vibration applied by the control. This allows to generate data related to the interaction between the over-imposed vibration and the external disturbances (i.e., the residual field).

Through specific procedures, with the primary vibration field present, each actuator is excited with control signals (i.e., secondary field) in a randomly defined sequence, not simultaneously; these correspond to all the identified dominant frequencies, but the signals are of random amplitude and phase. The accelerometers in each per actuator excitation sequence measure the resulting residual field at their location.

Specific data sets (i.e., exemplars) are created from the data generated from this sequence, which are in turn utilized for training and validation purposes during the development of the ANN-based behavioural model in the next step. This process runs until the necessary number of exemplars is created.

3.3.2 ANN Model and Simulation

In this sequence, the behavioural model is created, trained and validated (on-line or off-line). As it is proprietary information of Paragon S.A., it won't be described in detail due to confidentiality.

During the development of the prototype, one type of ANN developed was a Feedforward Multilayer Perceptron (MLP) Neural Network, trained with a Back Propagation (BP) approach.

- Input layer parameters: Control signals amplitude and phase (in relation to the dominant frequencies and actuators).
- Output layer parameters: Residual field amplitude measured at each sensor location. The number of nodes in the output layer of the ANN is equal to the number of sensors used.
- The ANN generated is trained (update of network architecture and weights) and validated using the exemplar patterns that were generated in the previous sequence.

Giving the control signal inputs to each actuator, the completed ANN model is able, to simulate the resulting residual field.

3.3.3 GA Controller

In this final sequence, the control algorithm is initiated. As a global optimization technique, GA is utilized to determine the optimal control signals to the actuators, i.e., in terms of amplitude and phase.

The optimization loop aims to determine the optimal parameters to achieve the best possible reduction of amplitudes across the dominant frequencies, and candidate control parameters solution are tested using the ANN model (Fig. 3.7).

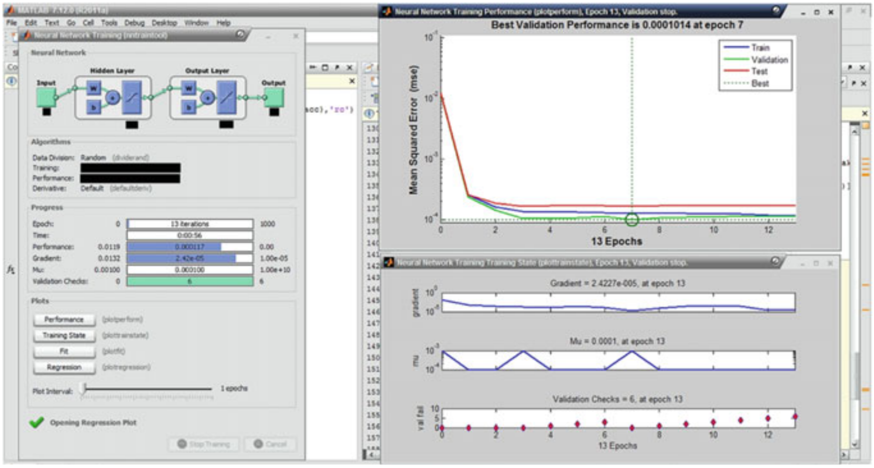

Fig. 3.7 ANN model training phase

The optimization loop will be executed until the GA converges. Afterwards the software application ends with the operation of the controller that proceeds to generate the optimized control signals to drive the actuators and the FAS monitors the AVC performance (Fig. 3.8).

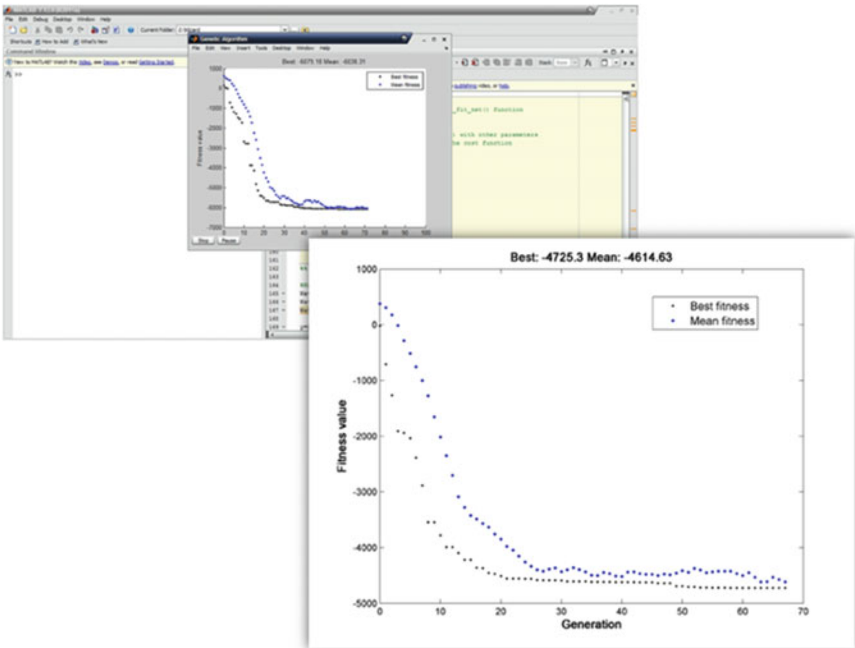

Fig. 3.8 Controller generation execution and GA (optimization) convergence

Unfortunately, no further details can be published at this time about details such as the gene coding or the fitness function, as they are proprietary information of the developer that was brought as technical background to this research activity.

3.3.4 Synthesis

Once best actuations are extracted by the proposed control strategy for linear cutting on main directions (i.e., X and Y), a synthesis strategy was developed. The concept was to track the motion of the cutting tool and synthesize the suitable counter-vibration signal from percentages of its X and Y components, using a basic PID control scheme and trigonometric summation of the axes vectors.

3.4 Validation Results

The functionalities of the developed active fixture were tested with known actuations signals to analyse the fixture components behaviour, in a sort of a Hardware in the Loop (HIL) testing. Then, the control performances were assessed in chatter mitigation for simplified milling case studies in a laboratory at the University of Firenze. Finally, the active fixture was applied to industrial environment thanks to the collaboration with the project partner Girardini s.r.l., an Italian company specialized in cold-press steel and related die/mold manufacturing [14]. The developed active fixture was used to improve the production of a die for stamping components for the appliances market. The results will be focused on this final validation.

3.4.1 Equipment and Test-Case

Tests were carried out on a DMG DMC 635 V eco 3-axis milling machine. Three triaxial accelerometers were used as sensors for the derivation of the optimal control signals. Two of these were secured to the bottom of the fixture in order to measure the vibrations of each dynamic stage, while the third one was placed at the base of the spindle housing in order to get a better estimation of the tool-tip vibrations. An additional optical tachometer was used to get the phase reference for the control to compute the optimal counteracting vibrations. The test setup is shown in Fig. 3.9. The workpiece was a 60 × 132 × 25 mm stock made of AISI P20 s steel, used for manufacturing the final test-case, a rescaled archetype of a die for a kitchen hood ventilation component (Fig. 3.10b), as presented in Fig. 3.10a. A 16 mm indexable mill with two cutting flutes was used for the tests.

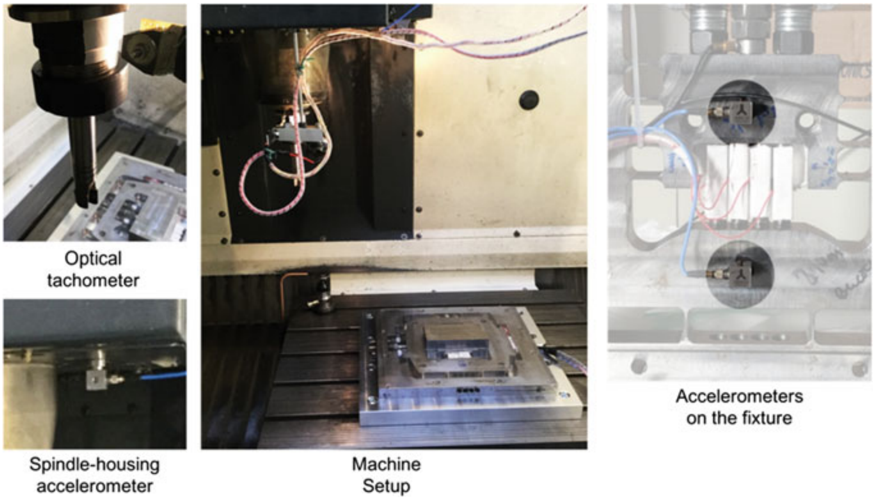

Fig. 3.9 Experimental test setup

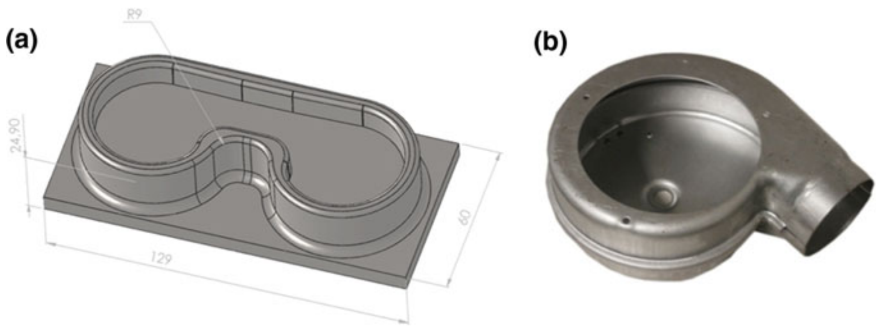

Fig. 3.10 Final die test-case (**a**), dedicated to the stamping of kitchen hood ventilation component (**b**)

3.4.2 Tests Description and Performance Assessment

Cutting tests were focused on full-immersion milling (i.e., slotting), since it is the most prone operation to severe chatter condition and particularly suitable for the investigation of roughing operations. According to the control logic strategy, linear cutting on the two main directions (X and Y machine axis) were performed first. For these tests, the dedicated learning phases (i.e., random excitation to acquire response of the fixture) were carried out. ANNs were generated for both tests and the optimized control actuations were computed. Then, the chatter mitigation effect was assessed on these simple linear operations. Thanks to the synthesis strategy previously presented, a general tool-path, part of the final test case cycle and

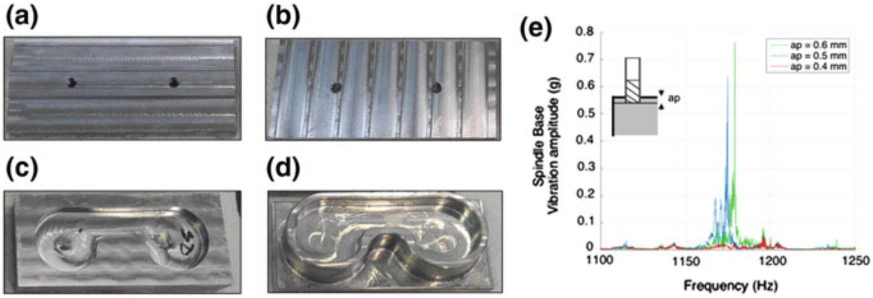

Fig. 3.11 Tests specimen: X linear slotting (**a**), Y linear slotting (**b**), General tool-path (**c**), Test case (**d**), and chatter vibration at different depth of cut (**e**)

composed by linear and circular paths, side and slot milling, is performed with and without control on. Finally, the test case was machined to assess the productivity improvement. The machined specimen for the 4 types of operations is presented in Fig. 3.11a–d.

Since the goal of the fixture is to mitigate chatter by counter-acting the phenomenon with actuation at its characteristic frequency, the assessment of the achieved performance was based on the vibration level associated to the chatter frequency. The results will be discussed in accordance with the acceleration signal measured at the base of the spindle housing, given that this sensor provides the better estimation of tool-tip vibrations. The tri-axial accelerometers placed below the inner and outer stages of the active fixture are an important part of the controller, as they are necessary for the ANN model generation process, particularly for measuring the response from the random signals generation. Preliminary cutting tests in slotting without control showed chatter occurring at 0.5 mm depth of cut (a_p) and about 1200 Hz, for the rotational speed used in the tests (i.e., 3600 rpm).

Indeed, as shown in Fig. 3.11e, the amplitude associated to the chatter vibration spectral contribution becomes dominant on the spectrum at 0.5 mm depth of cut and increases at 0.6 mm, as expected [15]. The goal of the active fixture in this application was hence to achieve a lower level of vibrations with the device turned on at 0.6 mm depth of cut, compared to the reference 0.5 mm depth of cut without control. Hereinafter, performance assessment will be shown as a comparison between frequency spectra of the spindle base accelerometer between 0.6 mm depth of cut with control and 0.5 mm depth of cut without control.

3.4.3 Results

The active fixture chatter mitigation effect on linear slotting operation is presented in Fig. 3.12, focusing on X-axis acceleration of the spindle base.

The results show the significant reductions achieved on both linear cutting tests. For the linear on X direction, chatter level at 0.5 mm depth of cut (blue) is reduced

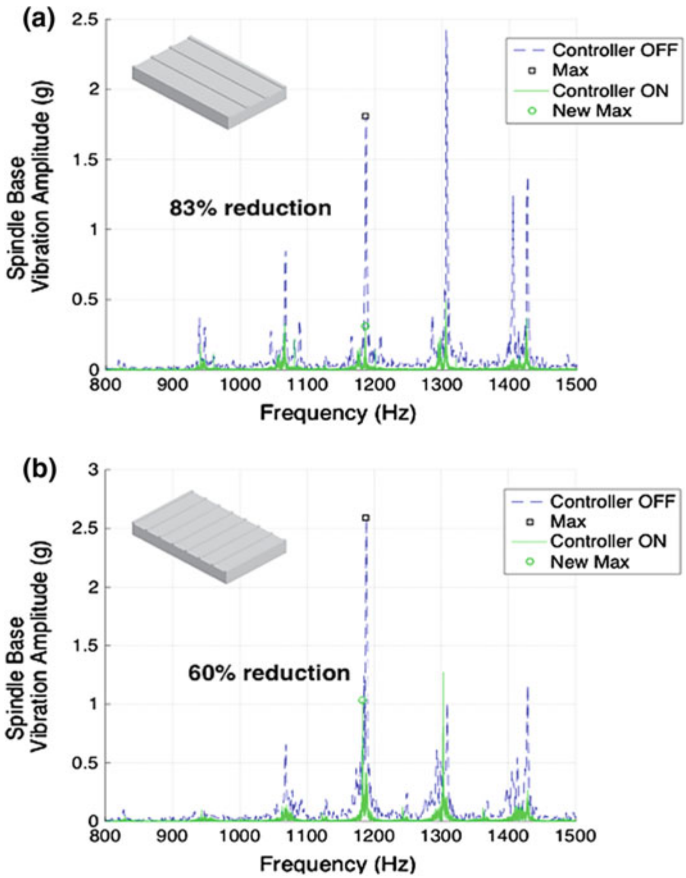

Fig. 3.12 Spindle base acceleration (X-axis) spectra at a_p = 0.5 mm (*blue*) without control and at depth of a_p = 0.6 mm (*green*) with control for linear slotting on X-axis (**a**) and Y-axis (**b**)

of about 80% with the controller on, together with an increasing of depth of cut. Similarly, for the linear Y cut, a reduction of 60% is reached.

As previously mentioned, starting from the optimized actuations computed for linear cutting, a synthesized actuation is implemented to general toolpaths. Results for the defined general toolpath and the test-case are presented in Fig. 3.13.

For both cases, the synthesis strategy demonstrated to be able to return appreciable reduction on chatter vibration level (more than 70%). In all the four cases, the controller and the active fixture are effective in enabling the machining at a_p = 0.6 mm with reduced chatter vibrations, allowing for higher material removal rates and presumably reduced tool wear. The final test-case cycle was machined at 0.5 mm depth of cut without control in 55 min and 30 s, while at 0.6 mm depth of cut with control in 46 min and 55 s. As a result, the active fixture allowed a 15% faster machining cycle with lower level of vibrations.

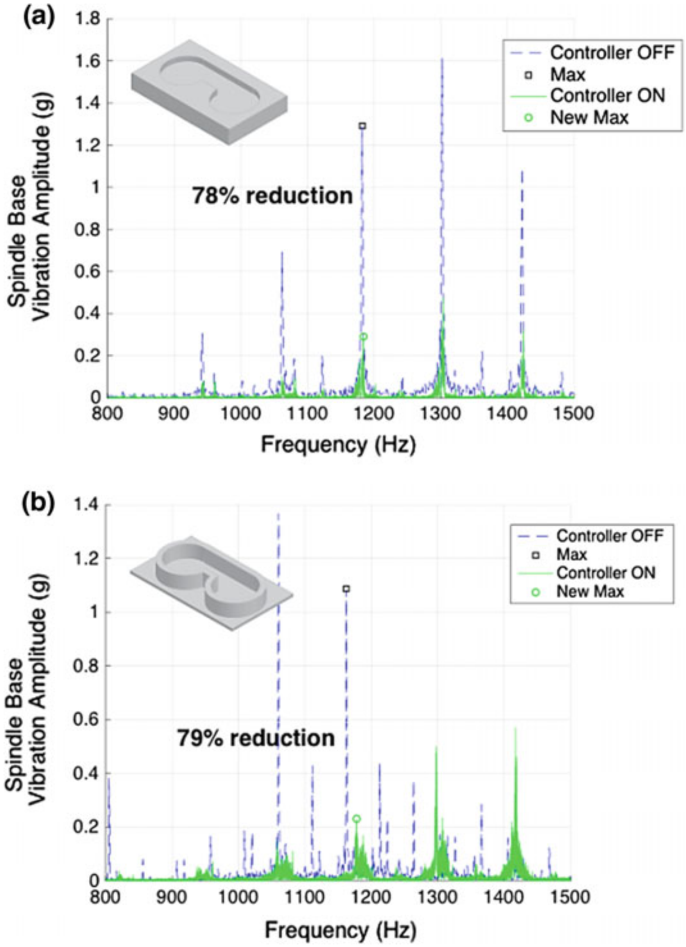

Fig. 3.13 Spindle base acceleration (X-axis) spectra at a_p = 0.5 mm (*blue*) without control and at depth of a_p = 0.6 mm (*green*) with control for general tool-path (**a**) and final test-case (**b**)

3.5 Summary and Conclusion

This case study deals with the development of an active fixture aimed at mitigating chatter vibrations in general rough milling operations. The mechanical design of the fixture was carried out in accordance with previous literature works, but particular focus was put in improving the achievable performance by a careful mechanical design and improved actuation devices. The use of hard-doped piezoelectric actuators allowed indeed to sufficiently extend the bandwidth of the developed device, with respect to the previous works presented in literature.

The novel controller strategy implemented in the active fixture prototype demonstrated to be suitable for chatter reduction in the validation tests. The achieved reduction allows to use higher depths of cut with a lower vibration level, potentially increasing productivity. Valuable practical information has been gathered through this first practical implementation. The control algorithm performed as expected on the selected hardware platform. The actual operation was simple and straightforward, allowing for a quick process of initial controller tuning using a small part of a single workpiece and from then on no other user intervention is required. The developed active fixture withstood temperature as high as 90 °C, with hot chip and occasional fluid sprays, while exposed to cutting forces as high as 1kN and actuation frequencies exceeding the kilohertz range, without returning any issue. This proves the practical and robust design, including the selection of hard-doped piezo-actuators. The performance of the developed prototype is in line with the previous results from literature, for general application with low-frequency chatter vibrations. On the other hand, the results on the industrial test-case proved the active fixture capabilities in mitigating chatter vibrations even at higher frequencies, extending its practical applicability. Limitations in terms of inertial forces, when higher mass workpieces are used or with higher actuation frequencies, represent a challenging issue to further improve the performance in general applications. The future developments will hence be focused on improving the prototype accordingly, by potentially exploiting changes in the fixture design, actuator selection and eventually developing alternative control logics, based on low frequency actuations that seem a promising approach [16–18].

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Part II
Deformation

Chapter 4
Case Study 2.1: Detection and Compensation of Workpiece Distortions During Machining of Slender and Thin-Walled Aerospace Parts

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Abstract In machining of thin-walled large parts in aerospace industry, workpiece distortions occur during and after the processes due to residual stresses which are introduced or set free by the material removal process. These distortions lead to an inacceptable shape and geometric errors of the produced components and, thus, to deficient products. Considering that milling operations at large aerospace structural parts take several hours and that often expensive workpiece materials (such as titanium alloys) are used, these critical deformations cause high costs in the manufacturing companies. In some cases, post-treatments such as shot peening is applied in order to reduce the influence of residual stresses. This also means a significant increase of production costs of the parts. With the aim to overcome these challenges of part deformations, in this case study an intelligent fixture was developed which detects the tendency of workpiece distortions within sequenced processing steps and which allows an active adjustment of the clamping conditions in order to compensate for the influences of residual stresses on the final shape of the part.

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4.1 Introduction of the Case Study

In machining of large aerospace parts, e.g. made of aluminium or titanium alloys, workpiece distortions occur due to the influence of residual stresses which are introduced or set free by the material removal processes [1–3]. In most cases, these part deformations become visible not before the final workpiece is dismounted from its clamping. The workpiece distortions can lead to inacceptable shapes of the parts and geometric errors which exceed predefined tolerances. Due to the machining time (which often amounts to several hours) and serious effort as well as the value of raw materials, high costs arise when defective parts are produced. Post treatment of distorted workpieces, such as shot peening for reducing the influence of residual stresses, also causes significant costs and reduces the effectiveness of the manufacturing chain.

In this case study, milling of an exemplary aluminium part from the aerospace industry is regarded. The dimensions of this part amount to $L = 1970$ mm, $B = 100$ mm and $H = 48$ mm (Fig. 4.1).

In the conventional milling operations, workpiece distortions in form of a bended shape occur which can be characterised by a deviation value of up to 10 mm. These distortions are distributed unevenly about the length of the part. The amount and occurrence of the distortions depends on the individual piece and the initial state of the raw material. Consequently, a prediction of the distortions and an associated compensational layout of the machining processes is hardly possible. Up to now, the workpieces are manufactured in multiple successive both-sided milling steps which are interrupted by a manual turning and re-clamping of the workpiece. The pure milling time amounts to approx. 3 h; whereas the manual work can take up to 1 h.

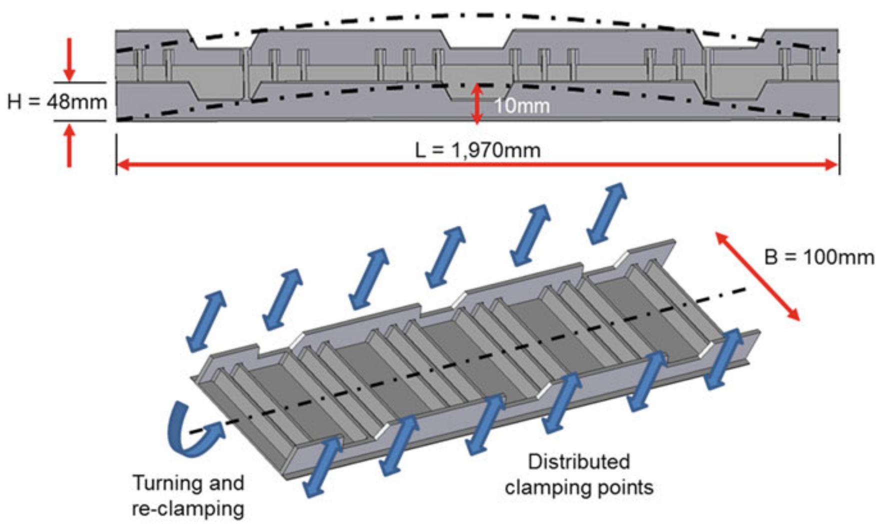


Fig. 4.1 Exemplary aerospace workpiece in case study 2.1

4.2 Principle Approach

The principle approach in this case study is based on the development and application of an innovative fixture frame, in which the workpiece is clamped in an upright position (Fig. 4.2). The fixture frame provides accessibility of the workpiece from both, the front and the rear side, in order to supersede the manual turning of the part. Within the fixture frame, distributed hydraulic floating clamps are located in which the workpiece can be held during the machining processes. The floating clamps allow an adjustment of the real position of each clamping point in the range of a few millimetres and, by this, and adaptation of the clamping conditions to the deformed shape of the workpiece.

In order to reduce the remaining residual stresses and resulting distortions of the final part, the following strategy can be implemented by the use of the new fixture frame:

- Clamp the raw material block in a neutral position utilizing the reference locators and floating clamps which adapt their position to the initial shape of the unmachined workpiece.
- Carry out first milling operations (with closed clamps and locked floating mechanism).
- Detect the tendency of workpiece distortions by fixture integrated force sensors.
- Adjust the positions of the floating clamps so that the workpiece is stress-relieved within the fixture; for this, an unlocking and actuation of the floating mechanism shall be provided.
- Carry on with subsequent milling steps.
- Repeat the detection of the tendency of workpiece distortions, the re-adjustment of the floating clamps and the accomplishment of subsequent milling steps until the final geometry of the workpiece is achieved.

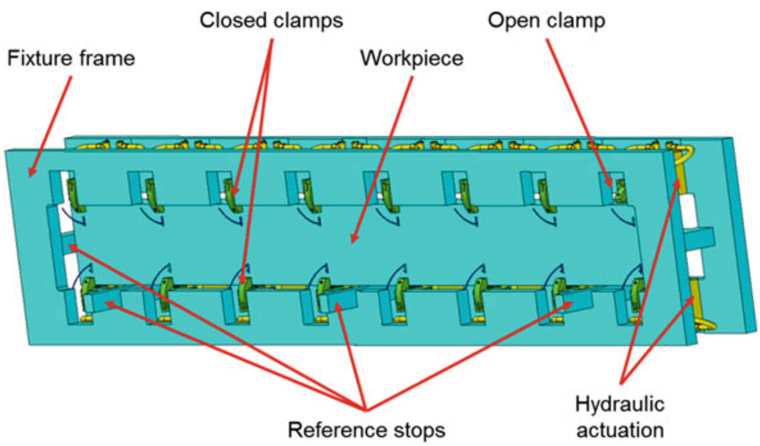


Fig. 4.2 Concept of the fixture frame with distributed floating clamps

Sensory components have to be integrated which are sensitive with respect to the tendency of the workpiece to distort. This means that workpiece forces due to residual stresses can be measured whereas the sensors have to be decoupled from the clamping forces which act between the workpiece and the clamping claws in order to hold the workpiece. Consequently, the sensors have to be integrated in the floating mechanism.

Regarding the adaptation of the positions of the distributed clamping points to intermediate deformed workpiece shapes, two strategies are possible:

- The adaptation can be conducted passively. For this, the floating mechanisms of the clamps have to be unlocked so that the distorting workpiece forces can move the clamps to the unstressed positions in which the floating mechanisms are locked again.
- The adaptation is implemented actively by means of appropriate integrated actuators which move the released floating mechanisms of the clamps until the integrated sensors detect an unstressed workpiece clamping condition. The floating mechanisms are locked again if the desired clamping condition is achieved.

The drawback of the passive approach is that friction forces inside the floating clamping device interact with the distorting workpiece forces and that consequently the workpiece forces could be too low to move the floating mechanisms to a properly adapted position.

As a result, in this case study, the approach of a fixture frame with actively movable floating clamps is followed. Two different floating clamping elements and related fixture frame designs were analysed by means of test rigs in basic investigations and experiments before the final prototype of the intelligent fixture was realized (see Sects. 4.3 and 4.6).

Since the workpiece is released inside the fixture frame at intermediate steps in order to allow interim distortions and to re-clamp the part in an unstressed condition, an adaptation of the pre-defined NC code might become necessary due to the modified clamping and deformed state of the workpiece geometry. This adaptation requires the measuring of the actual workpiece geometry within the machine tool and an adjustment of the set points which define the contour of the NC path (see Sect. 4.5).

4.3 Fixture Frame Test Rigs

In order to verify and analyse the capability of the fixture frame approach, downscaled test rigs were built which allow fundamental milling tests at sections of the exemplary demonstrator workpiece (Fig. 4.3). A crucial question is, whether the upright fixture concept enables stable machining operations with reasonable material removal rates under economically advantageous conditions. Furthermore, the use of Finite Element Analysis (FEA) models for the layout and optimisation of the fixture structure was investigated.

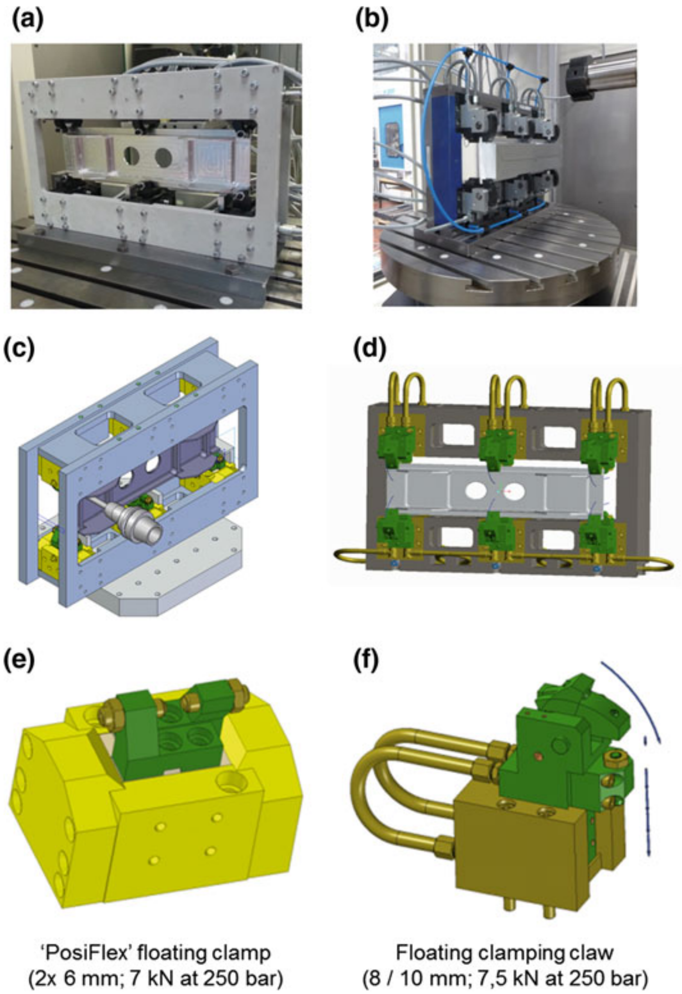
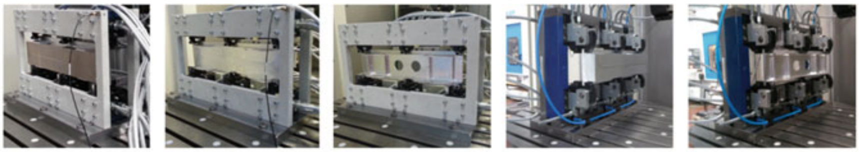


Fig. 4.3 Test rigs of fixture frames with floating clamps: **a** first test rig with 'PosiFlex' floating clamps, **b** second test rig with floating clamping claws, **c** design of first test rig, **d** design of second test rig, **e** 'PosiFlex' clamping element, **f** floating clamping claw

The first test rig consists of two steel frame components which are connected by the 'PosiFlex' clamping elements and additional structural components (Fig. 4.3a, c, e). The 'PosiFlex' clamping elements provide a floating degree of freedom (DoF) in a range of up to 6 mm. Since the base frame of the clamping element can be directly used for mounting the fixture frame components together, a compact design of the overall fixture is possible. The floating clamping claw used in the second test rig (Fig. 4.3b, d, f) provides a floating DoF of up to 10 mm. Compared to the first test rig, the frame structure of the second test fixture is built up of several steel elements. In a first attempt, the floating clamping claws are mounted to back



(a)

Mode ↓	Clamping pressure [bar] →	Natural frequency [Hz] Workpiece state								
		Raw part			Intermediate step			Final part		
		150	200	250	150	200	250	150	200	250
1		127	125	126	127	130	129	126	129	126
2		291	285	290	234	234	233	224	224	224
3		630	635	630	652	659	649	636	636	642
4		780	785	781	754	757	754	751	751	752
5		1027	1022	1020	988	988	987	983	987	996
6		1367	1345	1347	1298	1302	1274	1042	1010	1050
7		1521	1521	1511	1531	1523	1507	1517	1483	1513
8		1621	1605	1604	1604	1608	1609	1606	1598	1609

(b)

Mode	Natural frequency [Hz] Workpiece state					
	Raw part	Intermediate step 1	Intermediate step 2	Intermediate step 3	Final part	Without workpiece
1	138	145	141	148	146	130
2	296	298	294	300	300	263
3	619	600	603	615	619	345
4	777	760	745	714	715	500
5	973	966	971	984	984	587
6	1288	1278	1277	1304	1350	899
7	1514	1557	1553	1549	1448	1413
8	1859	1786	1783	1826	1827	1833

Fig. 4.4 Results of modal testing of the first test rig (**a**) and the second test rig (**b**)

plates by means of the four mounting screws as visible in Fig. 4.3f. The realized test rigs were tested by modal analyses (Fig. 4.4).

In the analysis of the first test rig (Fig. 4.4a), a clamped raw material block, a clamped workpiece at an intermediate machining step and a clamped final part were considered in order to identify the influence of the stiffness of the workpiece on the total dynamic behaviour of the fixture-workpiece system. Due to the substantial material removal, the stiffness of the workpiece is decreased significantly with the progress of the machining process from the raw part to the final workpiece. Furthermore, with the first test rig, the influence of the hydraulic clamping pressure was investigated. For the second test rig, the dynamic behaviour was analysed at three intermediate steps and also without a clamped workpiece (Fig. 4.4b). The variation of the clamping pressure in the useful range does not show any noteworthy effect.

For the first test rig, the most significant influence of the material removal progress can be observed for the second, fourth, fifth and sixth mode. For the second test fixture, the most significant influence appears for the fourth mode. Some results regarding the dynamic modal shape of the test fixtures obtained by FEA are depicted in Fig. 4.5.

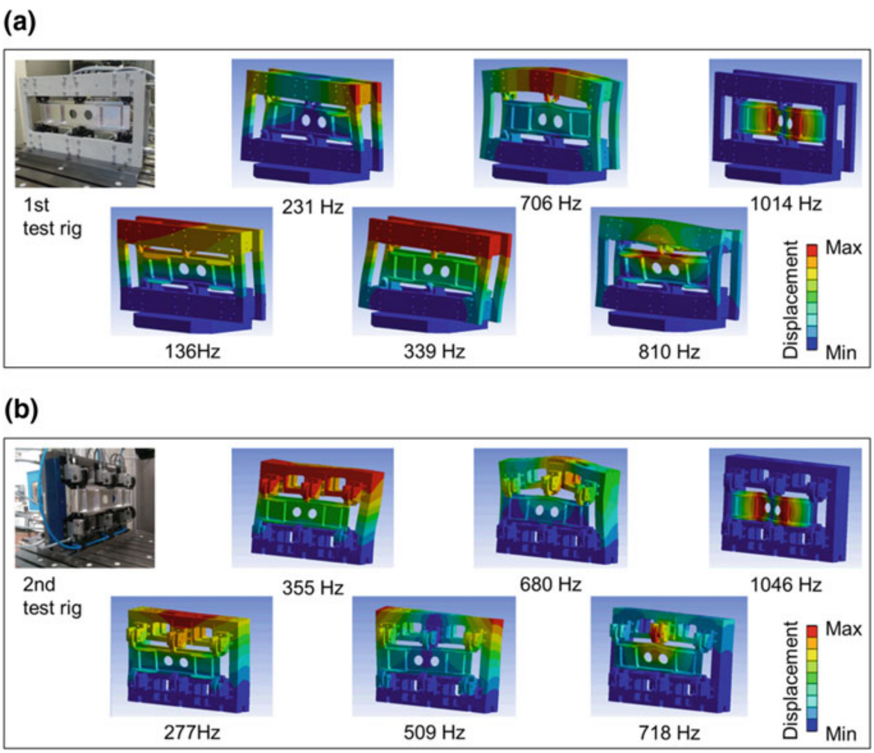
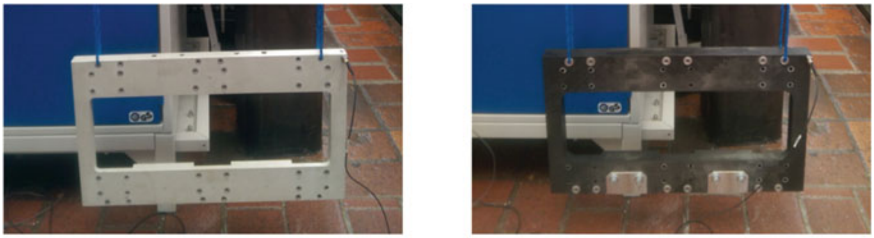


Fig. 4.5 FEA results regarding the dynamic behaviour of the first (**a**) and second (**b**) test fixture

Due to simplifications in the FE models (especially regarding the behaviour of mechanical interfaces) the calculated natural frequencies do not conform to the experimentally measured values. However, the main dynamic characteristics and trends become visible. It can be observed that for some modes a significant interaction between the dynamics of the fixture and the workpiece takes place. For these modes, the influence of the material removal progress is important.

In order to analyse the potentials of the use of CFRP (carbon fibre reinforced polymers) elements for the fixture frame structure with respect to the exploitation of the higher material damping [4], a variant of the first test rig with CFRP frame components was built (Figs. 4.6 and 4.7).

Although the pure CFRP frame component possesses a higher dynamic stiffness and damping compared to the steel component, the measured natural frequencies of the assembled test fixture with CFRP elements are lower and the vibration amplitudes are higher than those of the test fixture with steel frame. This results from the inappropriate mounting of the CFRP elements at the fixture base plate. It can be concluded that the use of CFRP components has a high potential regarding the improvement of the dynamic fixture behaviour if the structural integration and the layout of mechanical joints is implemented adequately.



	Steel frame		CFRP frame	
Mode	**Natural frequency [Hz]**	**Damping ratio [%]**	**Natural frequency [Hz]**	**Damping ratio [%]**
1	211	0.08	295	0.52
2	269	0.06	482	0.22
3	396	0.09	587	0.36
4	564	0.04	714	0.42
5	656	0.05	851	0.17
6	712	0.03	976	0.32
7	770	0.03	1216	0.38
8	977	0.02	1364	0.37
9	1068	0.03	1533	0.47

Fig. 4.6 Experimental modal analysis results for steel and CFRP frame components for the first test fixture

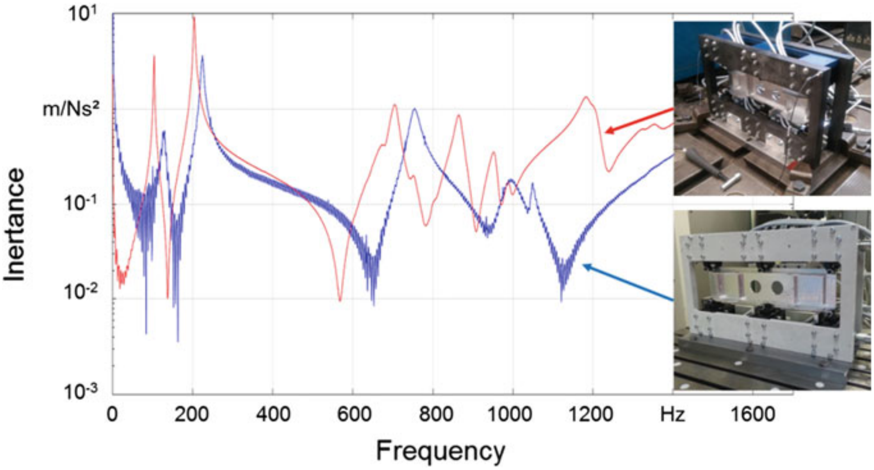


Fig. 4.7 Frequency response functions for test fixtures with steel and CFRP frame components

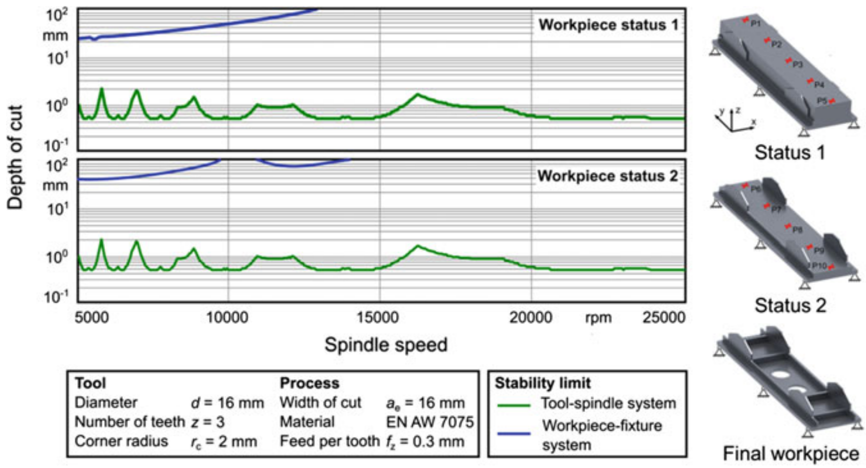


Fig. 4.8 Simulated stability diagrams for different workpiece states [6]

For both, the first test fixture with steel frame components and the second test fixture, milling tests and process simulations were carried out in order to verify the fixture concept and to analyse process stability limits [5, 6]. Regarding the stability with respect to inacceptable vibrations of the fixture and workpiece as well as the occurrence of regenerative chatter, different workpiece states (raw material block, intermediate state and final part) were considered. In Fig. 4.8 stability diagrams which were obtained by means of the process simulation system of the ISF (see also Chap. 1) are presented for two different workpiece states.

As can be seen, for the chosen milling scenario, the process stability is predominantly limited by the dynamics of the used tool but not by the dynamic compliance of the fixture or the workpiece. Different stability limits can be observed for different workpiece states (indicated by the blue curves in the upper parts of the diagrams) in Fig. 4.8. Consequently, the changing dynamic characteristics of the workpiece due to the material removal progress have to be considered in the layout of the fixture system. Furthermore, the layout of the milling operations has to consider the changing properties of the coupled workpiece-fixture system.

4.4 Sensor and Actuator Integration Concept

An essential functionality of the intelligent fixture is the sensory detection of workpiece distorting forces and the active adaptation of the clamping point locations to an unstressed intermediate shape of the clamped workpiece. As already mentioned in Sect. 4.2, the sensor integration has to be decoupled from the clamping flux of force inside the floating clamping elements (Fig. 4.9).

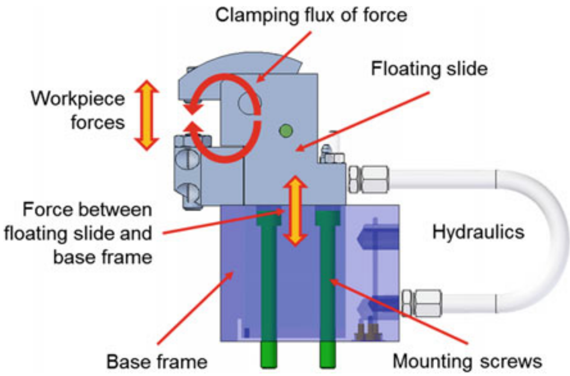


Fig. 4.9 Forces at floating clamping claw

Since the workpiece distorting forces act on the floating slide which is guided and locked within the base frame of the clamping element, a promising approach is to measure the forces between the floating slide and the base frame. At that point the workpiece forces are superposed by friction forces which occur in the guiding of the floating slide and retroactive effects from the hydraulic locking mechanism. Furthermore, the active adaptation of the clamping point positions can be realized by an actuation of the floating slides of the clamping elements. For implementing this actuation, the floating slide of a clamping element can be connected to a hydraulic double-acting piston by an actuation link (Fig. 4.10). The force between the floating slide and the base frame can then be measured by means of strain gauges which are mounted at the actuation link. This arrangement in principle allows both, position and force control of the clamping point position as well as hybrid control approaches. The functionality of this sensor integration and actuation concept was analysed by use of a bending beam test rig (Fig. 4.10). The bending forces of the cantilever beam represent the workpiece distorting forces in the fixture. The displacements of the beam due to movements of the clamp are measured by an eddy current sensor. In addition to the strain gauges at the actuation link, a reference force sensor was mounted at the connection between the hydraulic piston and the actuation link. Characteristic curves for a movement of the floating slide from one bound to the other are shown in Fig. 4.11 (in the test setup the middle position of the floating slide does not necessarily coincide with the unstressed neutral shape of the beam). Starting from a position in which the cantilever is bent, in a first phase the bending forces support the movement of the floating slide; during the further movement of the floating DoF, the cantilever is bent in the opposite direction. The force values obtained by the strain gauges correspond well with the signals of the reference sensor.

Since the functionality of the sensor and actuator integration could be verified by means of the bending beam test rig, the integration concept was implemented in the fixture design. Figure 4.12 shows the ‘active floating clamps’ integrated in the second test fixture.

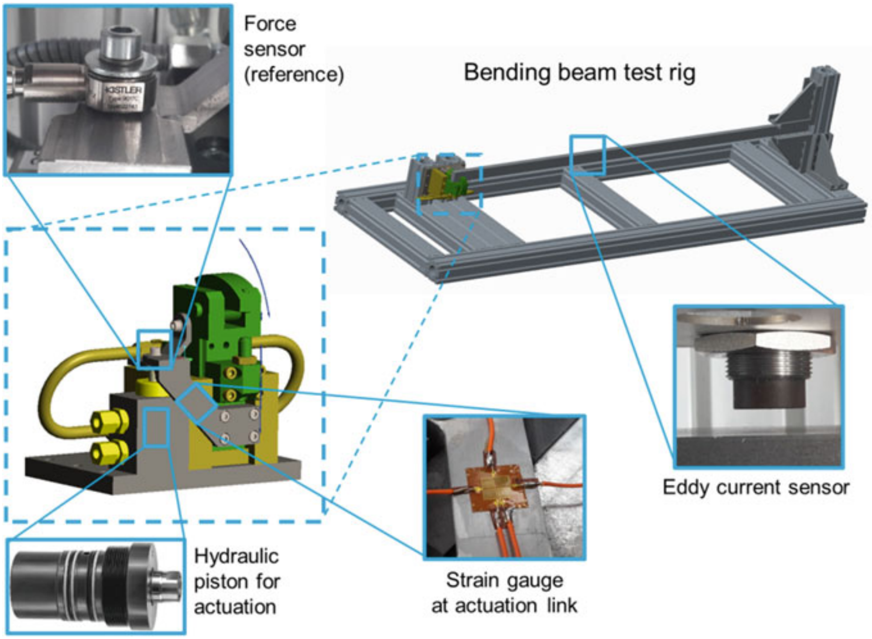


Fig. 4.10 Bending beam test rig with actuated and sensor integrated floating clamping claw [6]

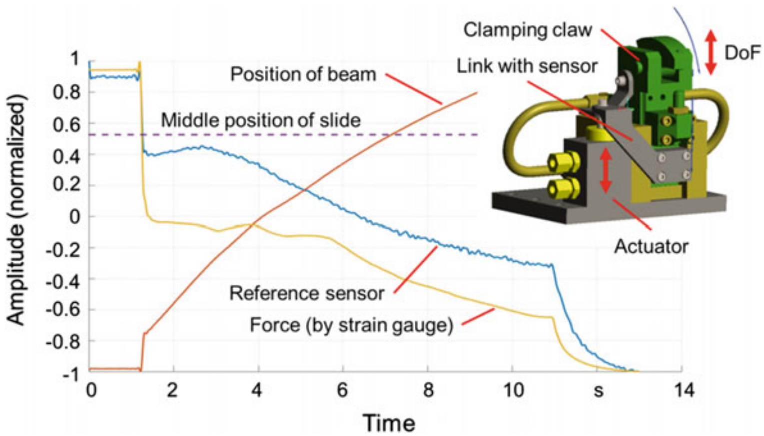


Fig. 4.11 Bending beam test rig with actuated and sensor integrated floating clamping claw [6]

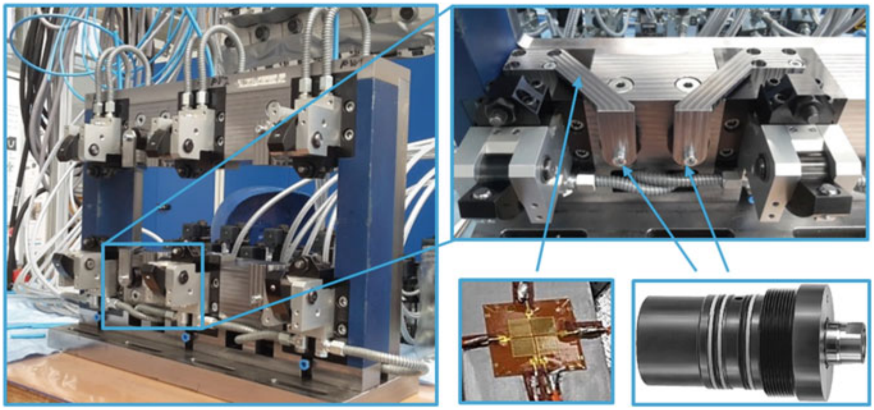


Fig. 4.12 Integrated clamp actuation concept [7]

4.5 Adaption of NC-Milling Paths

BCT's OpenCHECK[1] is able to measure workpieces directly inside the manufacturing machine. The currently produced geometry can be checked against the nominal geometry represented in form of a CAD file. The main advantage of the machine integrated measuring technology is the capability to measure intermediate stages of the parts during the manufacturing process (Fig. 4.13a). Unclamping the parts, any transport to a dedicated coordinate measuring machine and the time consuming recovery of the workpiece setup for continued machining can be avoided. Supported by the simple software handling (Fig. 4.13b), measuring programs can be realized economically.

The system for measuring the workpieces consists of a NC machine, a touch trigger probe with a stylus (Fig. 4.13a) and the software BCT OpenCHECK running on a separate PC, but connected to the NC controller of the machine. The nominal geometry of the workpiece is imported in form of the CAD description, being the basis for defining the measuring process. The user can determine measuring points by a simple mouse click. Points on freeform surfaces can be measured in the same way as, e.g., cylinders or cones. Additional features allow the definition of specific measuring patterns like lines or grids. In this work, the machine integrated measuring software is used to measure the post machining deformations of the demonstrator parts. Based upon the detected deviations compared to the original 3D model of the part, a decision is made whether the adaption of the subsequent NC paths is required or not (Fig. 4.14).

The demonstrator workpiece is milled in several iterations in order to minimize internal residual stresses. At the end of each iteration step, the workpiece is released

[1]http://www.bct-online.de/.

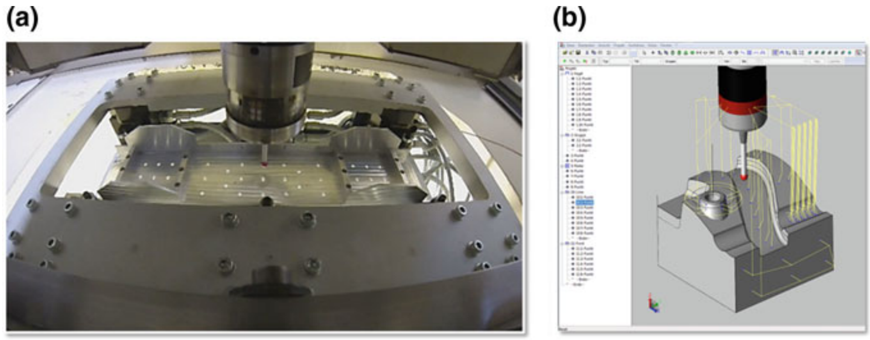


Fig. 4.13 Digitizing the clamped workpiece (**a**) and User-Interface of BCT openCHECK (**b**) showing the measurement paths for a demonstrator part

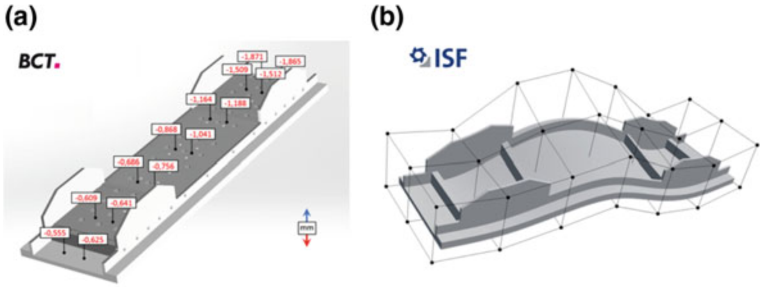


Fig. 4.14 Definition of measuring points in OpenCHECK (**a**) and representation of workpiece deformations (**b**)

Fig. 4.15 Principle of an adaption of the NC path for milling

inside the fixture by an adaptation of the floating clamping positions in order to re-clamp it in an unstressed shape. To be able to use the predefined NC paths, it is necessary that the current workpiece geometry is close to the CAD description that was used to generate these NC paths. If this is not the case, the NC paths have to be adapted onto the current part geometry (Fig. 4.15).

The basic principle of the adaptation approach is to adjust a predefined NC program to the individual shape of the workpiece. Defining a NC operation based on a CAD model means to define a huge number of path interpolation points having a specific distance to the workpiece surface. The task of the adaptation is to transfer this specific distance to the newly generated workpiece surface. The principle of this transfer is shown in Fig. 4.15 for a 2D example. The tool centre point (TCP) is moved having a specific distance to the surface. If the surface changes, the adaptation takes care that this specific distance is used as well.

4.6 Prototype of the Intelligent Fixture

Based on the described findings, the design of the real size intelligent fixture prototype was elaborated (Fig. 4.16). In machining tests using the new fixture, the overall processing time could be reduced to approx. 2½ h (compared to the initial 3 h for machining and 1 h for manual re-clamping). With the new fixture, manual re-clamping can be avoided. In the tests, the workpiece distortions of the final part could be reduced to approx. 1 mm (compared to an initial value of 10 mm as depicted in Fig. 4.1).

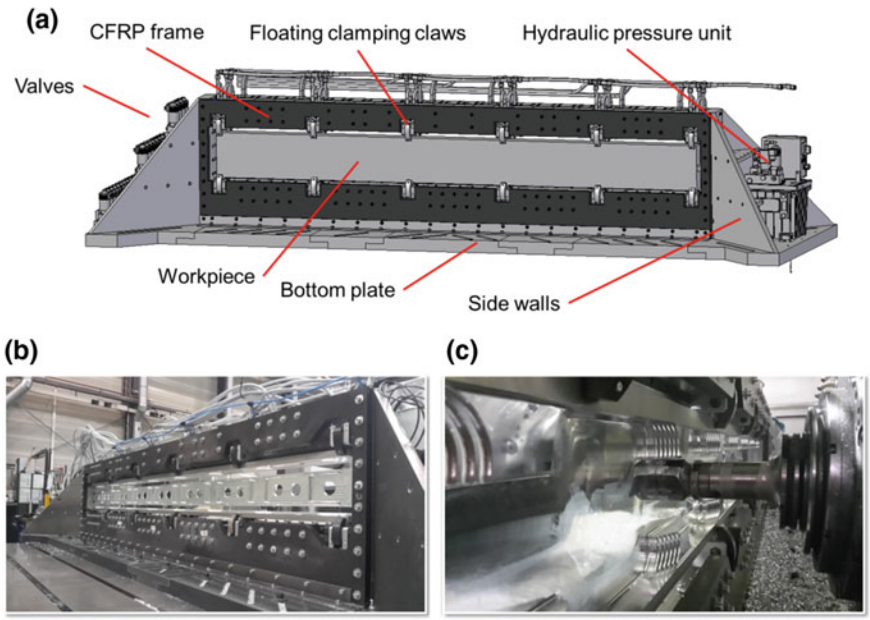


Fig. 4.16 Design (**a**), implementation (**b**) and testing (**c**) of the intelligent fixture prototype [6, 8, 16]

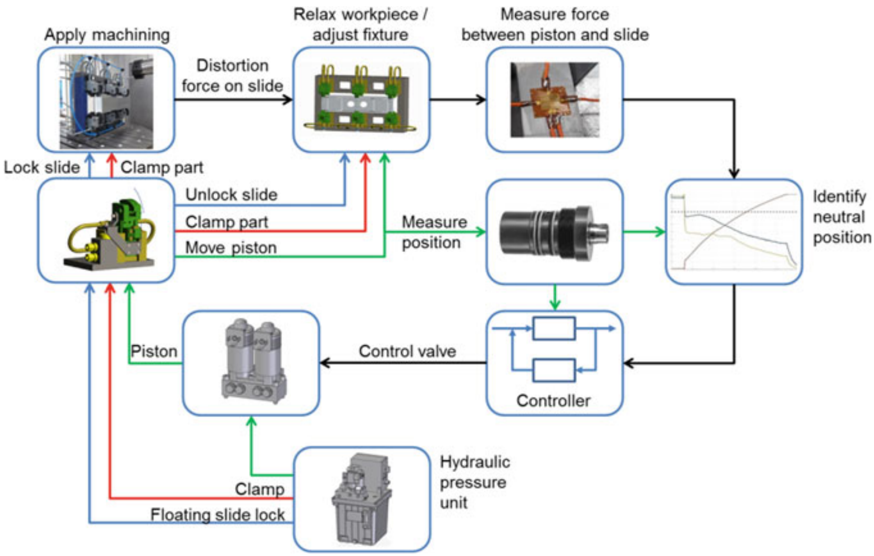


Fig. 4.17 Working principle of the intelligent fixture [6]

A CFRP frame is combined with a steel structure in order to improve the dynamic stiffness and damping of the overall fixture. The active floating clamps are pressurized in groups in order to reduce the complexity of the hydraulic system. All hydraulic system components are directly attached to the fixture so that it can be applied in a 'plug-and-produce' manner. The working principle of the fixture and its application is described in Fig. 4.17.

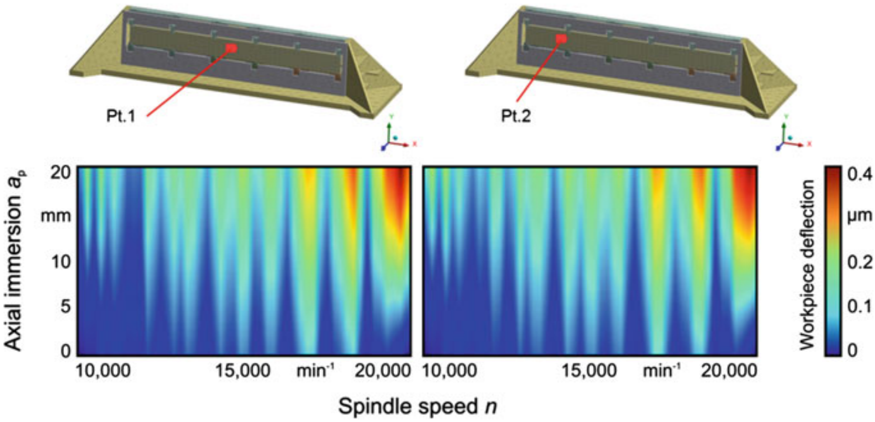


Fig. 4.18 Position dependent stability maps [6]

An essential aspect of the fixture development is the integration of the process simulation techniques [6, 8] (see also Sect. 4.8). Since the final thin-walled workpiece is machined out of a rigid material block, the compliance of the part changes significantly during the process. Moreover, due to the size of the workpiece and the fixture, the dynamic response of the clamped workpiece, which interacts with the milling cutter and spindle, depends on the engagement position of the tool at the workpiece (Fig. 4.18). These effects have to be considered in the fixture design and layout in order to ensure stable cutting conditions in the application of the fixture.

4.7 Process-Simulation Integrated Machining Operations

The milling-process simulation that is described in Chap. 1 (Sect. 1.2) more precisely and which is developed by the Institute of Machining Technology (ISF), was used during the design phase of the fixture layout described in Sects. 4.3 and 4.6. Figure 4.19 shows a scheme of the proposed method, which is applied to the demonstrator workpiece that was introduced in Sect. 4.1.

A standard process layout for milling workpieces for aerospace structures is pocket milling in layers. After machining a certain number of layers, the fixture re-clamps the workpiece to relax possible internal stresses. In order to measure actual distortions, a measurement with the touch probe of the machine, as it is described in Sect. 4.5, is conducted. In the following, the occurrence of chatter during the machining of the next layers is determined by utilizing the process simulation. For this, two different methods were used: Either a deformation of the workpiece model with the free-form deformation technique (FFD) [9] is conducted with a subsequent simulation of occurring chatter vibrations or stability limits are looked up in pre-calculated stability charts.

For this, the milling process is classified into similar tool engagements [10]. For the process which is depicted in Fig. 4.20, this leads to six different clusters. For

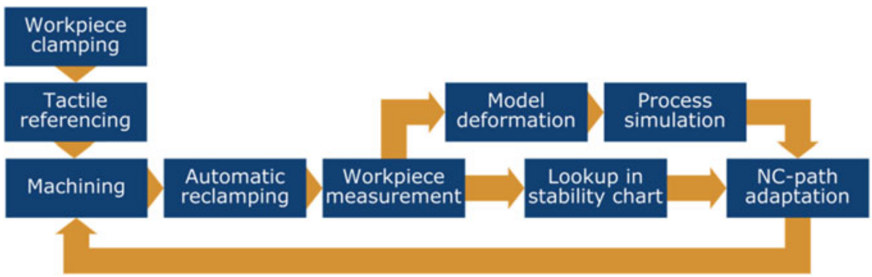


Fig. 4.19 Scheme of the proposed workflow for machining distorted workpieces

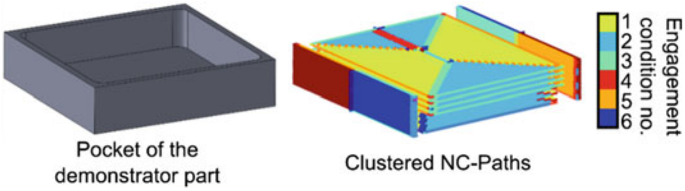


Fig. 4.20 Clustering of the NC path of one pocket of the demonstrator part for fast stability prediction

every cluster, stability charts have been calculated in advance for a several number of possible distortions. In this manner a very fast decision about potential chatter problems for a measured distortion can be taken. After this step, the NC path can be adapted if necessary with the techniques described in Sect. 4.5.

4.8 Process Simulation of the Final Prototype

The fixture-design process was supported by simulation results, as during the planning stage of design processes real experiments or measurements cannot be carried out. Additionally, layout changes are most expensive at the end of the design process. Thus, simulated process forces or deflections are an appreciated instrument for dimensioning elements of the fixture based on the resistance to deflections and vibrations during machining.

The input parameter values for the simulation system in this early stage of the layout bases on experiences or have to be simulated as well. Force parameter values, e.g., can be transferred from force measurements with the same material and tool as in the planned process. Modal parameter values of the fixture-workpiece system have to be obtained with FE simulations. For this purpose, a close cooperation of the design engineers and the simulation experts is necessary. Figure 4.21 shows the schema of a process simulation of occurring forces and deflections, which were used for the fixture design that is described in Sects. 4.3 and 4.6.

In pocket-milling processes, thin walls and thin floors tend to vibrate. The simulation of vibrations and resulting surfaces in milling processes of thin walled parts was subject of several scientific research works [11–13]. However, investigations on milling thin floors of workpieces with varying dynamic parameter values cannot be found in the literature. The modelling of processes with those parts implies two difficulties:

- The dynamic properties of the bottom is changing during machining due to the material removal process and the subsequent mass reduction.
- The dynamic properties are different for each tool position, which is a result of the mode shapes of the structure.

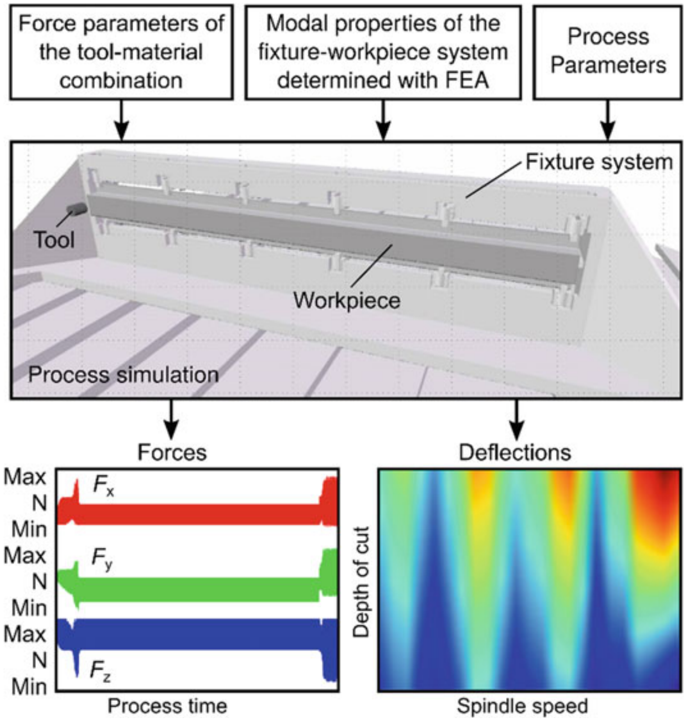


Fig. 4.21 Schema of the process simulation of the demonstrator part including the dynamic behaviour of the tool and the workpiece-fixture system

Figure 4.22 shows the first three mode shapes of one pocket of the demonstrator part, which were simulated with FEM. Analysing a part of the demonstrator workpiece showed that the first mode of the pocket is critical and leads to vibrations if suitable process parameter values were not selected [5].

The used simulation system was therefore enhanced to simulate this kind of vibrations. Similar to the concept for simulating vibrations of impeller blades (Chap. 1), the time and position dependent modal properties of the workpiece can be modelled by a set of oscillator models. For this purpose, the frequency response

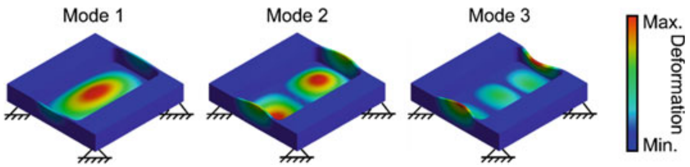


Fig. 4.22 FE simulated mode shapes of one pocket of the demonstrator part

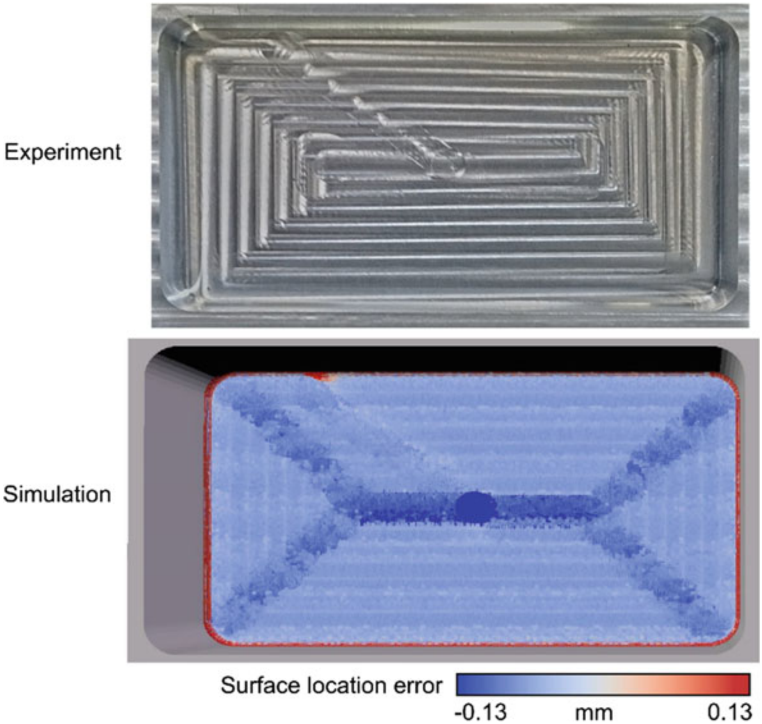


Fig. 4.23 Photography of the machined workpiece and simulated surface location error of the demonstrator pocket [15]

functions at several points of the workpiece have to be measured, e.g., with the impact hammer test or simulated with FEM. The modal properties at arbitrary points can then be interpolated by a barycentric approach, which is also described in Chap. 1 (Sect. 1.2) [14]. A detailed description of the simulation approach is published in [15]. The comparison of the simulated and experimental results is shown in Fig. 4.23. Surface artefacts that arise from the vibration of the pocket bottom can be seen in both cases in the same regions of the workpiece.

4.9 Summary and Conclusion

This chapter introduces the development of an intelligent fixture for the reduction of workpiece distortions in machining of large thin-walled structural parts in the aerospace industry. The solution adopted is to relax the workpiece inside the fixture at intermediate processing steps in order to release the influences of residual stresses and to re-clamp the part in an unstressed shape. The integration of sensors for detecting workpiece distorting forces and of actuators for the active adjustment of the clamping conditions is described. By means of a NC-path adaptation software, a significantly altered geometry of the interim state of the workpiece can be considered in the layout of subsequent machining operations. Both, the fixture development and the process layout are considerably enhanced and improved by the exploitation of sophisticated process simulation techniques. The investigations show that the changing characteristics of the workpiece due to the material removal process and the workpiece-fixture interactions have to be taken into account for fixture and process optimisation.

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Chapter 5
Case Study 2.2: Clamping of Thin-Walled Curved Workpieces

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Abstract Thin-walled curved workpieces are typical for structural parts of airplanes. The issue in the workpiece clamping and subsequent machining is the changeable workpiece stiffness during material removal. The fixture forces and the cutting forces deform the workpiece with dependence on the part decreasing static stiffness that causes large local surface location errors of the part. As a result, the workpiece wall thickness is out of tolerance and consequently the part's weight is also out of tolerance. The proposed solution is based on new fixtures with integrated support and clamping function. The workpiece is clamped using a vacuum. A suitable thickness measurement sensor was integrated into the machine tool. The new fixture elements are autonomous and plug-and-produce ready, with integrated safety by monitoring the minimal workpiece clamping force. The fixture control enables fully automated operation using the specific control software. The machining process was optimized in terms of tool path strategy and cutting conditions to avoid chatter during machining and shorten the production time. The proposed manufacturing process leads to a shortening of the production time with the requested surface quality. The presented manufacturing procedure is beneficial from the productivity and cost point of view. A group of fixtures, including the necessary harness and control, offers a universal possibility for replacing a set of six specific fixtures designed as a mould with part negative shape.

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5.1 Introduction of the Case Study

This case study is focused on clamping and machining of thin-walled curved workpieces. Such type of workpieces is often used for airplane structures. The aluminium parts are typically machined from a block of material. In this case, typical machining operations are high material volume removal during roughing and finishing of straight or curved thin walls. If the thin-walled parts are made of composite, the typical operations are finishing using edge trimming and rivet hole boring. The issue in the workpiece clamping in both mentioned cases is the curved shape and the compliance of the final part. The fixture system should clamp the part tight but must not deform it. The fixture should also stiffen the part for improving machining productivity.

Machining of the thin-walled aluminium part from a block of material is described in this case study. The main requirement is machining of the part with a specified part weight tolerance. The main challenge is changeable workpiece stiffness during material removal. The fixture forces and the cutting forces deform the workpiece with dependence on the part decreasing static stiffness that causes large local surface location errors of the part. As a result, the workpiece wall thickness is out of tolerance and consequently the weight of the part is also out of tolerance. This causes weight changes of the airplane structure which are critical for the final airplane parameters.

This case study has two related topics. Firstly, the wall thickness deviation is related to the low static stiffness of the workpiece. Dedicated "mould-type" fixtures with the negative shape of the part for full-surface clamping using the vacuum are often used in industry [1]. The main disadvantages of this solution are the high price, dedicated use and still non-defined part position due to compliance of the vacuum field seals that does not ensure for 100% production of the requested wall thickness. Secondly, the machining productivity is limited by the low dynamic stiffness of the part. The chatter theory is known from 1960s [2, 3]. However, the workpiece stiffness is changing during machining, which makes the process control challenging. There are various approaches dealing with simulation of the stable

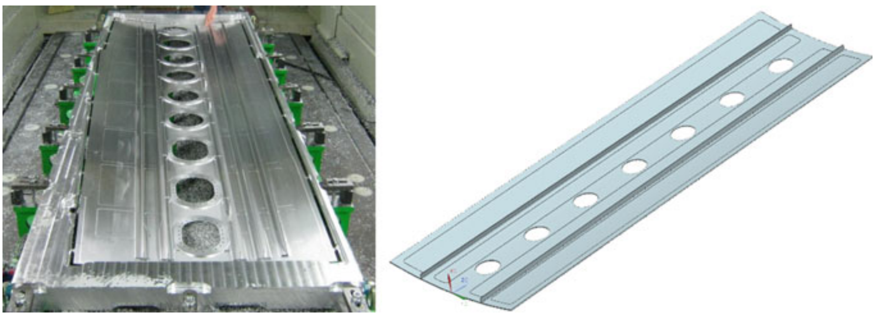


Fig. 5.1 The reference part for the case study (aluminium alloy 7075; outer dimensions: 1100 × 3000 mm; standard wall thickness: 2 mm; the margins have a thickness of 3 mm)

Table 5.1 Key performance indicators of the case study

Parameter	Request	Previous technology
Workpiece wall thickness tolerance	±0.05 mm	±0.1 mm
Machining time of the inner side	to minimize	100 h
Workpiece weight tolerance	max. +1 kg	up to +2 kg
Surface roughness	Ra 0.8	Ra 0.8

machining limits and also surface roughness characteristic during thin-walled part machining [4–6].

The part used in this case study is a component of the wing of a "commuter" category airplane. The part main dimensions are presented in Fig. 5.1. The case study key performance indicators (KPIs) are presented in Table 5.1. The design request and previous production technology results are compared. As can be seen, the improvement of the wall thickness is the main goal of the case study.

The principle approach is based on the new fixture design supporting the workpiece in selected points, optimized machining strategy and adaptive machining technology involving the inspection of the current state of the workpiece geometry. The fixture and the thickness measurement sensor are connected with the machine tool control system. Specifically developed software is used for the control of the fixture clamping status and measurement procedures (path planning, measured data acquisition) using a touch probe and a thickness sensor. The machining technology was optimized to avoid chatter vibration and to minimize the cutting force that deforms the workpiece.

5.2 Demonstration Workpiece

For machining demonstration, a section of the whole real part was used for less expensive and less time-consuming proof-of-the-concept testing. Instead of downscaling the whole workpiece geometry, a section with outer dimensions of 1100 × 600 mm was used (Fig. 5.2).

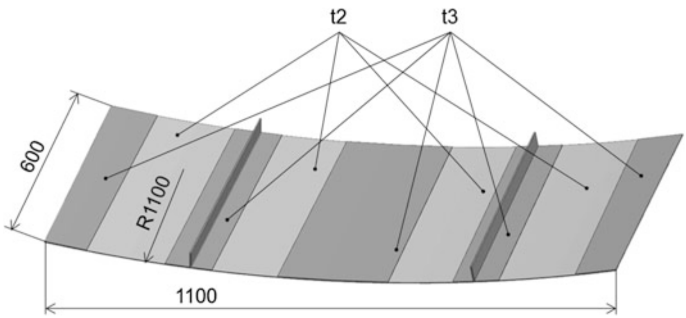


Fig. 5.2 CAD model of demonstration workpiece—a section of the airplane wing part

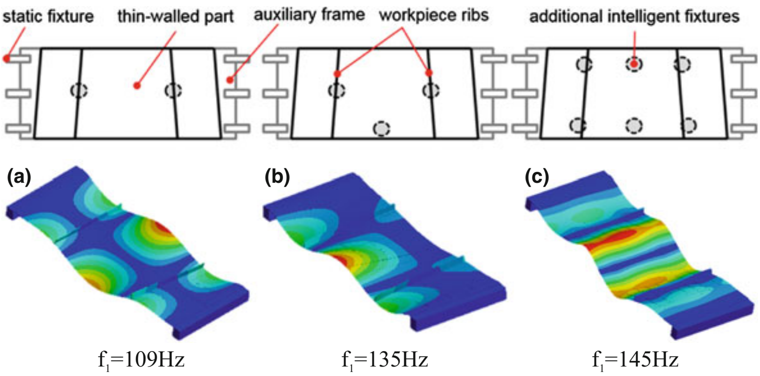


Fig. 5.3 Three clamping configurations: (a) with two additional fixtures; (b) with three additional fixtures; (c) with six additional fixtures. Workpiece first eigenvalues and related eigenmodes after clamping are shown

As FEM simulation in the free-free state confirmed, the modal behaviour of the demonstration workpiece is similar to the full-sized part. Thus, the short demonstration part can be used for testing of the whole technology. The results can be easily applied to the real part machining because the local dynamic behaviour of the workpiece with respect to the machining operation is similar.

The real full-sized part is clamped around the whole workpiece by an auxiliary frame. The thin wall is supported by a group of clamping and supporting points. The demonstration part behaviour (section of the full-sized part) was tested in four clamping situations: without additional fixture points and with three different fixture configurations. The auxiliary frame is applied only on two sides in case of the demonstration part (Fig. 5.3, top).

When analysing the workpiece first eigenmodes for the different clamping scenarios (Fig. 5.3), a high compliance of the workpiece central region in the case of two additional fixture points can be observed. Stiffening of the longer free edge with the third fixture brings partial improvement of the dynamic behaviour. The application of six fixtures gives small improvement of the static and dynamic workpiece properties. As can be seen, additional supporting points partially improve the workpiece stiffness and mainly influence the character of the eigenmodes. A significant part stiffening (e.g. increasing the frequency of the first eigenmode about factor 2 and more) is not possible if a limited number of supporting points is used. The large unsupported thin-walled area remains the main issue for machining.

The analysis of the static compliance of the finished and semi-finished workpiece with six supports was performed using FEA. The workpiece load by an axial cutting force was simulated by a force of 20 N. This force value was identified experimentally as usual finishing cutting force in normal direction to the machined surface. The static compliance graph and the total workpiece deformation is depicted in Fig. 5.4. As can be seen, the influence of the supporting points to the static stiffness is limited. A significant improvement is visible in the region of both

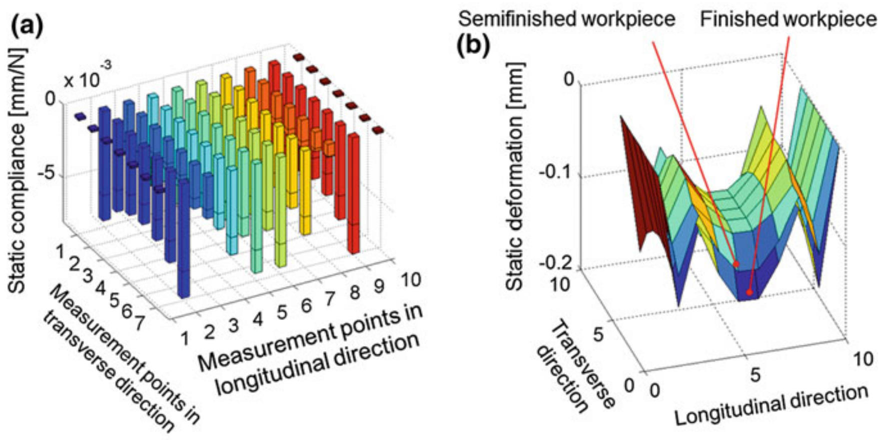


Fig. 5.4 FEA results of workpiece structural behaviour: (a) static compliance of finished and semi-finished workpiece; (b) comparison of workpiece static deformation due to axial cutting force

ribs only. The maximum value of the workpiece deformation is about 0.2 mm during machining. This deformation has to be compensated using a corrected tool path in order to stay within the requested part tolerance. The presented stiffness map is used for this operation, see Sect. 5.8.

5.3 Introduction of the Fixture Unit

The main functionality of the fixture unit is to set the specific height, lock this position and to clamp the workpiece. The main components of the developed fixture unit are shown in Fig. 5.5. The unit has a compact design. The piston rod is

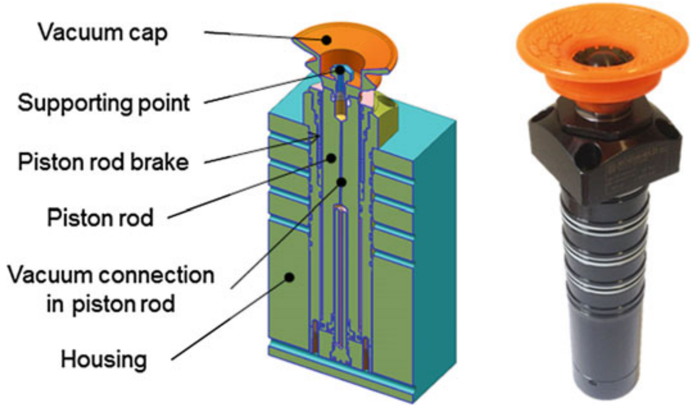


Fig. 5.5 The main components of the fixture unit

Table 5.2 Technical parameters of the fixture unit

Dimensional parameters: Minimum fixture height: 300 mm Piston rod stroke: 100 mm Piston rod diameter: 32 mm Vacuum cup diameter (changeable), starting from: 25 mm	
Hydraulic circuit parameters: Working pressure: 1.5–6.0 MPa Oil flow: 2.1 l/min Hose size: DN8 Positioning force range: 120–470 N	*Vacuum circuit parameters* Working pressure: 98 kPa Hose size: DN5 *Communication* EtherCAT connector

operated by hydraulic pressure. There is a hydraulic brake integrated in the unit body. The vacuum is led through the center of the unit. The fixture unit is mounted in the housing. The hydraulic hoses are mounted on the housing. The communication electronics and the hydraulic servo-valves are mounted next to the hydraulic cylinder. The housing is custom-made and robust for ensuring stiff support of the part. The technical parameters of the fixture are summarized in Table 5.2.

In general, two types of raw parts are typically used: rigid and flexible. An aluminium block is an example of a rigid raw part. Pre-formed metal or composite sheet is an example of a flexible raw part. The unit can work in two operational

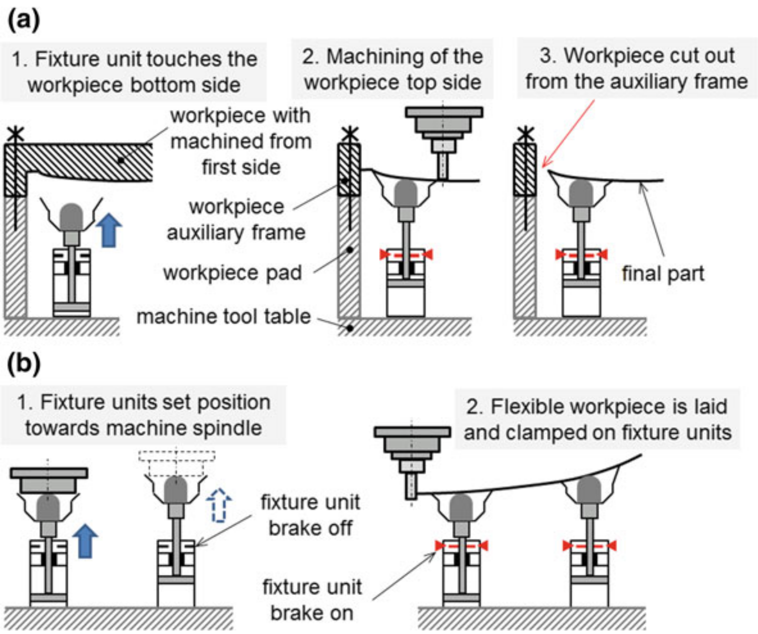


Fig. 5.6 Strategies for position setting of the support point and workpiece clamping: (a) clamping of the rigid raw part; (b) clamping of the flexible raw part

modes to be able to clamp both mentioned raw part types. The main difference is in position setting of the support point.

In case of the rigid raw part, the workpiece is clamped with standard fixtures using the auxiliary frame (Fig. 5.6a) that is an integral part of the workpiece. The positions of all fixture units are set according to the workpiece shape machined in a previous step. The fixture movement force should be very small for ensuring just a gentle touch with the raw part without its deformation. Then, the fixture position is locked by the fixture brake. The workpiece is clamped to the fixture using the vacuum cup. The top side of the part can be machined. As a last operation, the final workpiece is cut out from the auxiliary frame.

If the flexible raw part is used, the fixture can set the support points to the workpiece negative shape. Since the raw part has low stiffness, it cannot be used for setting the positions of every particular fixture unit. The fixture unit positions should be set by touching the supporting points towards the specific Z position defined by the spindle position (Fig. 5.6b). This constitutes an easy solution that reduces the fixture unit cost and that ensures the accuracy of the whole fixture in relation to the machine tool accuracy.

The clamping of the thin-walled part using the vacuum cups can cause too big workpiece deformations if an improper combination of the vacuum cup diameter, the vacuum pressure and the fixture distance is used. An approximate analytic model of the workpiece deformation due to clamping using the vacuum cups was derived for fast decisions when designing the clamping of the workpieces with increased compliance. The solution provides a relationship between the workpiece deformation and the parameters of the clamping system, such as the size of the fixture, level of vacuum and distance between the fixture units.

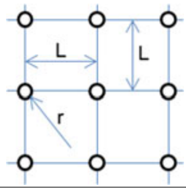
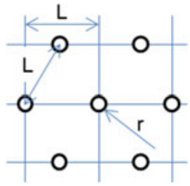
The equation was derived using the theory of thin plates. The main assumptions for the analytic model were the following: elastic behaviour of material, small rotations and deformations of the workpieces. The equation was derived for a plate of infinite width. The equation is valid only in the array between the fixture units, not outside of this array (between the fixture units and the edges of the workpiece). The deformation of the workpiece can be computed as:

$$u_{\max} = \frac{\alpha \cdot \beta}{64 \cdot D}\left[5 \cdot \rho \cdot g \cdot t \cdot \left(\frac{L}{2}\right)^4 + p \cdot \left(\frac{r}{\alpha}\right)^4 \cdot \left(5 + 4 \cdot \ln \frac{L/2}{r/\alpha}\right)\right] \tag{5.1}$$

where:

α, β [−]	are correction coefficients (see Table 5.3),
D [N/mm]	is bending stiffness of the workpiece,
g [m/s^2]	is gravitational acceleration,
r [mm]	is radius of the fixture's vacuum cup,
L [mm]	is distance between the fixture units,
p [MPa]	is vacuum pressure in the fixture unit,
t [mm]	is plate thickness,
ρ [tonnes/mm^3]	is density of workpiece material,

Table 5.3 Correction factors for two fixture patterns

	Square pattern: $\alpha = 1.101$ $\beta = 1.076$		Diamond pattern: $\alpha = 0.961$ $\beta = 0.792$

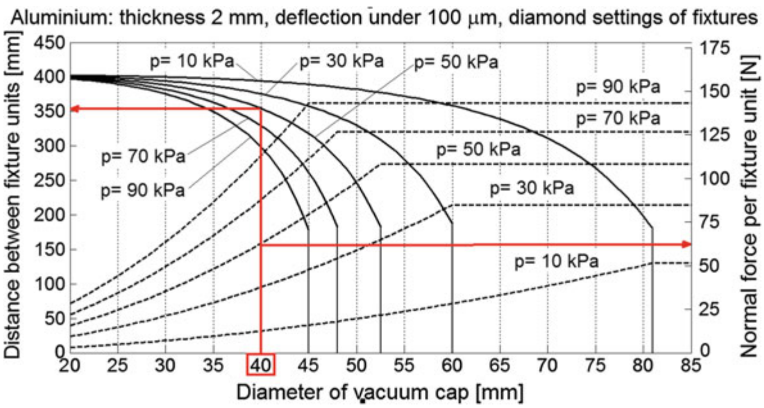


Fig. 5.7 Example of the alignment chart for an aluminium workpiece with thickness 2 mm, requested maximum deformation under 100 μm and diamond setting of fixture units

v [−] is Poisson constant of workpiece material,
E [N/mm^2] is Young's modulus of workpiece material.

The bending stiffness D of the workpiece can be computed using the thickness t and Young's modulus of the material as:

$$D = \frac{E}{1 - v^2} \cdot \frac{t^3}{12} \tag{5.2}$$

It can be seen from the comparison of the correction coefficients that the diamond configuration is more efficient than the square configuration, as its usage leads to a lower deflection while needing a lower number of fixture units in the same space. The diamond configuration results in a more uniform distribution of the deformation.

The analytic model was verified using finite element analysis. The variation of the result was in the range of ±3% in the case of the square pattern and ±8% in the case of the diamond pattern. This error is acceptable for an approximate determination of the fixture point positions and clamping system parameters.

Using Eq. (5.1), graphs for various combinations of the fixture system parameters can be computed. An example of this chart is depicted in Fig. 5.7. The diagram enables fast selection of the vacuum pressure for a specific vacuum cup diameter and a fixture unit distance. An additional information from the chart is the clamping force per fixture unit for the selected solution. Thereby, the fixture designer can quickly and easily select the clamping system configuration for a given workpiece material, workpiece wall thickness and requested precision.

The simplifications of the analytic solution do not enable to involve possible parameters of the real workpiece, such as its curvature or presence of the local reinforcements, for example ribs. The chart can still be used if the minimal wall thickness of the workpiece is chosen as the input parameter. In the case of the reinforced structures or of the curved structures, the usage of the charts, with design parameters from the flat workpieces of uniform thickness, will result in a tendency to predict lower distances than necessary, i.e. it will give safer results in terms of achieving the demanded precision. Therefore, the charts are suitable for practical application. On the other hand, the usage of charts might increase the number of fixture units in comparison to the number that would be necessary.

5.4 Thickness Sensor

Various methods for thickness measurement were analysed. Measurement methods based on ultrasound were identified as the most effective and accurate physical principle for thickness measurement of non-ferrous non-magnetic materials. There are several systems available on the market. Here, a system made by company Olympus was chosen. The Olympus 38DL Plus thickness gauge is shown with accessories in Fig. 5.8a. The accessories consist of a probe working on a frequency of 10 MHz and the RS232 cable for serial communication. The great advantage of the device is the real time communication using the RS232 interface. Other thickness gauges with RS232 interface exist; however none of them enables real time communication. The Olympus 38DL Plus allows a continuous output mode. The limitation of the serial communication is based on data transfer as a function of

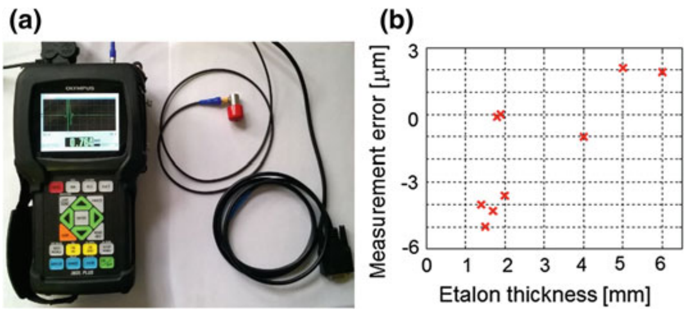


Fig. 5.8 The ultrasonic Olympus 38DL Plus thickness gauge: (a) device with accessories; (b) error of thickness measurement for different etalons

cable length. In the case of a sampling frequency $f_s = 20\,\text{Hz}$ the recommended cable length should be less than 60 m. The device can be operated using different power supplies, including both AC power and battery.

The ultrasonic thickness sensor was tested on the Johansson gauges [7]. The sampling frequency was set up to $f_s = 20\,\text{Hz}$ and 10 samples were captured. The largest gauge (t = 6 mm) was used for the ultrasonic velocity calibration, the smallest one (t = 1.4 mm) for the “zero point” calibration. The calibration has to be done for different materials and should be repeated in time in case of temperature change. The results of the measurements are shown in the graph in Fig. 5.8b. It can be concluded that the accuracy of the device in the experiment was ±5 μm which is suitable for the requested application.

5.5 Operator Software

A specific software called LECLIN (LEveling, CLamping, INspection) with modules for workpiece inspection using a touch probe and thickness measurement using the thickness sensor was developed for easy fixture system control by the machine operator.

Positions of the measuring points for the determination of the workpiece orientation within the working area of the machine tool are indicated graphically in the software. The system can automatically calculate a workpiece local coordinate system transformation after manual measurement of all necessary points. It is possible to perform automatic inspection measurement after workpiece alignment. The workpiece inspection is fully controlled in the designed software (trajectory planning, movement control, result display) which cooperates with a Heidenhain machine tool control system very closely and online (see next section). The measurement results are shown afterwards in the software main screen. The software is also used for the control of the movement of the fixture units and for vacuum clamping.

The software may be used for an inspection of the workpiece thickness using the ultrasonic probe. Although the thickness measurement represents a special type of inspection, the principle, trajectory planning and result visualization is the same as for measurements with the touch probe.

All mentioned software functions enable the machine tool operator to control the whole fixture and inspection process easily from one place.

5.6 Communication Concept and Complete Fixture System Description

The complete intelligent fixture system consists of a group of fixture units, a thickness sensor and a central unit (industrial PC—IPC), see Fig. 5.9. The IPC controls the movement of all connected fixture units and also includes the

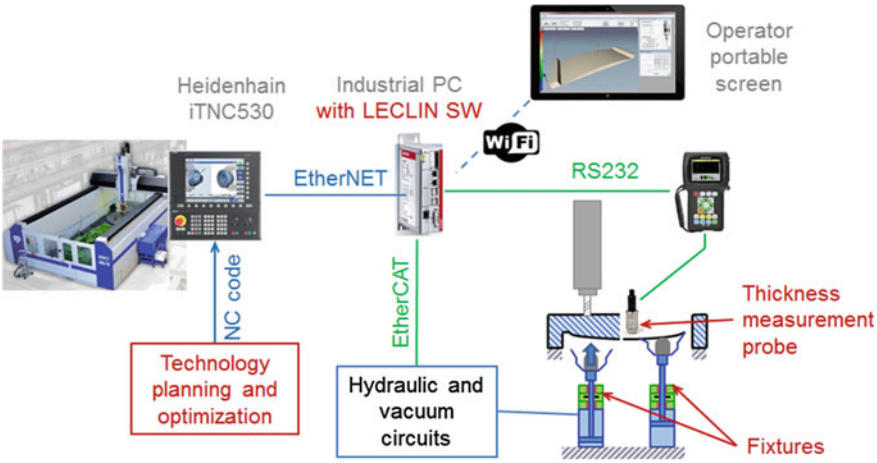


Fig. 5.9 Communication and connection scheme of the fixture system

human-machine-interface (software LECLIN) for checking, control and visualization of the fixture status. To fulfill these functions, the IPC is connected with the machine tool control system (Heidenhain iTNC530 in this case) and an operator portable screen through Ethernet. The IPC enables sharing information with the machine tool control regarding the system status, the actual position of the machine tool and the touch probe status. Concurrently, the IPC computes input values for the fixture system setting using information from the CAD representation of the workpiece. The IPC also processes measured thickness data together with the information from the machine tool control system. This solution enables the workpiece thickness inspection directly in the workspace of the machine tool. The vacuum and hydraulic actuators are centrally controlled by the IPC and its distributed input and outputs (IO) through EtherCAT. The thickness sensor is connected to the IPC and its distributed IO through serial communication.

5.7 Tool Selection and Cutting Condition Optimization

Machining stability is the key topic during the machining technology planning. In this work, there were two specific tasks: The first task was to find optimal chatter-free cutting conditions for all specific tools for high volume roughing. The second task was to find the optimal tool geometry for productive finishing operation, but minimized axial force.

An example of the chatter-free cutting conditions is given in Fig. 5.10. The stability of machining was checked with noise measurement using a microphone. The stable process conditions were evaluated by the noise spectrum analysis for

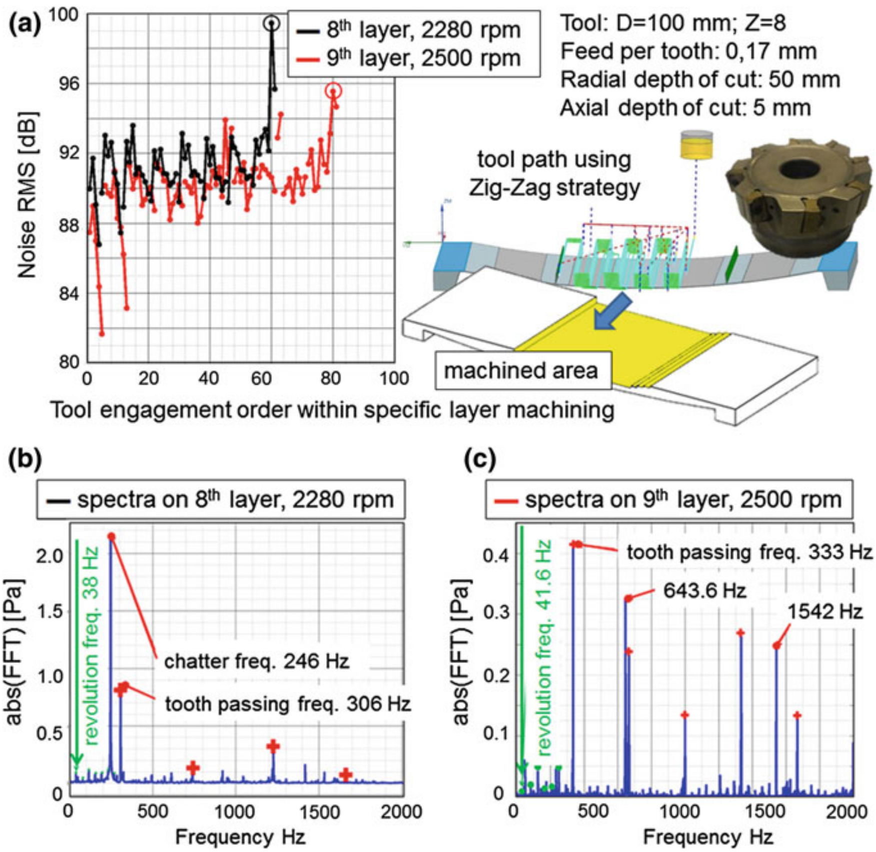


Fig. 5.10 Example of the tool revolution optimization procedure used during workpiece inner side roughing: (a) comparison of noise RMS values; (b) spectrum of the noisiest cut with 2280 rpm; (c) spectrum of the noisiest cut with 2500 rpm

operation with the highest noise RMS value (Fig. 5.10a). The workpiece roughing operation of the inner side was done layer by layer with a milling head using a zig-zag strategy. The layer thickness was 5 mm. A chatter frequency of 246 Hz was detected within machining of the 8th layer (Fig. 5.10b), thus the tool revolutions had to be changed.

Chatter arises due to dynamic forces. These forces are generated by cutting of a wavy workpiece surface with a vibrating tool. There must be a non-zero phase shift between the vibrating tool and the wavy surface [3]. The phase shift ψ can be computed for specific tool revolutions and a specific chatter frequency using Eq. (5.3). For zero dynamic force, the phase shift ψ must be equal to zero.

$$\frac{60 \cdot f_{chatter}(\mathrm{RPM}_{tool})}{RPM_{tool}} = \text{integer} + \frac{\psi}{2\pi} \tag{5.3}$$

The identified chatter frequency is uneven order of the revolution frequency:

$$\frac{60 \cdot 246}{2280} = 6.47 \tag{5.4}$$

In order to determine new tool revolution speeds, the value on the right side of the equation must be an integer:

$$\frac{60 \cdot 246}{6} = 2460\,\text{rpm}; \quad \frac{60 \cdot 246}{7} = 2108\,\text{rpm} \tag{5.5}$$

It is better to use higher tool revolutions for higher machining productivity. Since the chatter frequency of 246 Hz is higher than the frequency related to the relevant eigenmode identified by the measured FRF on the workpiece, the potentially higher chatter frequency could be expected with increased tool revolutions. In order to ensure zero dynamic force by the phase shift (5.3), the tool revolutions were set to 2500 rpm which is slightly higher than the computed revolutions of 2460 rpm (5.5).

The machining of the 9th layer with the new value of the tool revolution was stable compared to the previous case (Fig. 5.10c). The highest peak in the spectrum is the tooth passing frequency which indicates stable cutting. The described procedure was used for an optimization of all critical cutting conditions during preliminary machining tests. The optimized revolution values enabled stable cutting in all workpiece layers, therefore the axial depth of cut of 5 mm was not decreased in any layer.

Three cutting tool geometries were tested for finishing operations in order to find an appropriate compromise between productivity (larger tool tip radius = higher productivity at specific scallop size) and chatter limits (larger tool tip radius → higher axial cutting force → higher risk of chatter occurrence and higher static deformation of the workpiece). The following three tool geometries were used: monolithic cutter with a tip radius of 20 mm; toroidal cutter with round tips with a radius of 8 mm; cutter with changeable tips with a radius of 3 mm (Fig. 5.11b). The vibration signal was obtained using a microphone (Fig. 5.11a). The surface quality was also compared for all three tools (Fig. 5.11c). The tool with changeable tips with a corner radius of 3 mm was used for final machining of the demonstration part. The high tool revolution speed together with a small cutting contact zone of the 3 mm tool tip radius and tool tilt angle generated a low dynamic cutting force and subsequently also the stable cut.

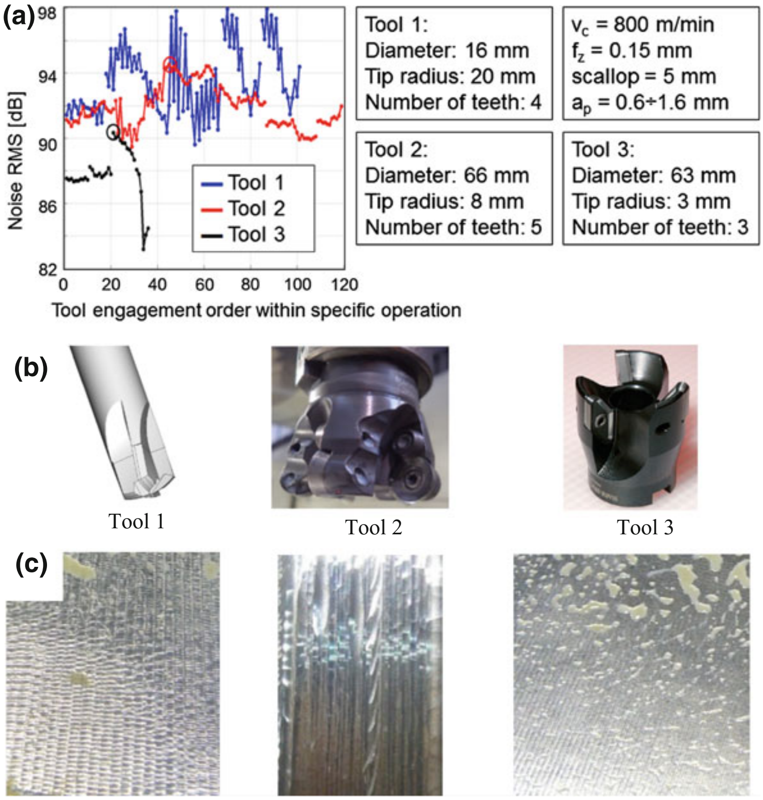


Fig. 5.11 The tested tools for finishing operation: (a) comparison of noise RMS values; (b) tool geometries; (c) final workpiece surfaces

5.8 Overall Machining Strategy

The final workpiece deformation of the thin-walled workpiece consists of partial deformations. Some of these workpiece deformations are predictable using mathematical models (e.g. static deformation due to cutting force load or clamping force load); some of these are unpredictable (e.g. deformations due to residual stress). Adaptive machining technology involving the inspection of the current state of the workpiece geometry seems to be suitable for effective finish machining. The machining approach was developed and verified for productive machining with high demands on final workpiece accuracy.

The main machining steps are summarized in the following. Please note that the procedure describes machining of the workpiece inner surface, i.e. top surface during the second machining step. The workpiece outer surface is the bottom surface during this phase of machining.

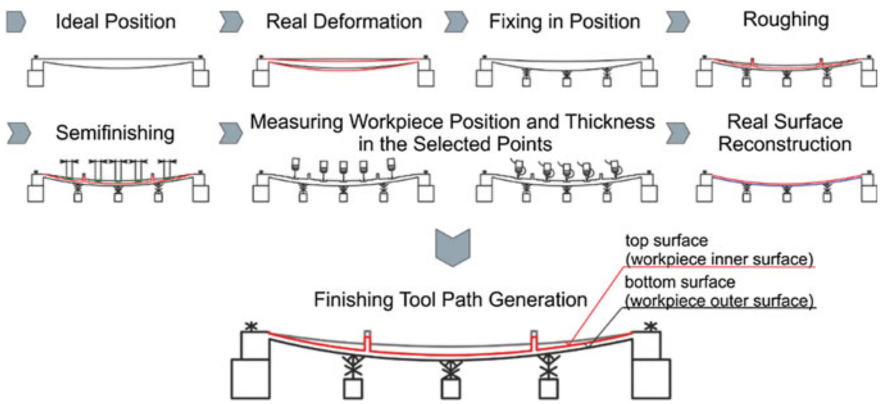


Fig. 5.12 Machining process overview

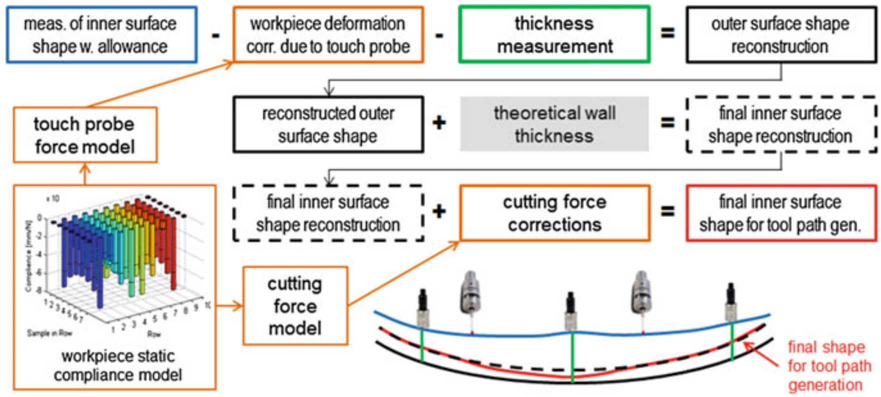


Fig. 5.13 Reconstruction of the substitutive surface for part finishing

The process starts with machining of the first (outer) side of the workpiece. It is conventional machining of a thick-walled stiff workpiece without any special issues. Then, the workpiece is turned around and clamped using the auxiliary frame and the additional fixture units with the vacuum cups (Fig. 5.12). A proposal of the number and position (pattern) of vacuum fixture units is elaborated for improving the workpiece stiffness. Suitable machining conditions are proposed and the tool path is generated for roughing and semi-finishing operation.

The adaptive machining technology is used for finishing of the part (Figs. 5.12 and 5.13). It involves an inspection of the current state of the workpiece geometry. The main goal is to gain information about the top and bottom surface shape and to create a substitutive surface for tool path generation for a correction of the wall thickness during the last machining operation.

The workpiece current state is inspected by a touch probe for real surface position identification in selected points (Fig. 5.14a). The workpiece deformation caused by the touch probe has to be compensated because of the high compliance of

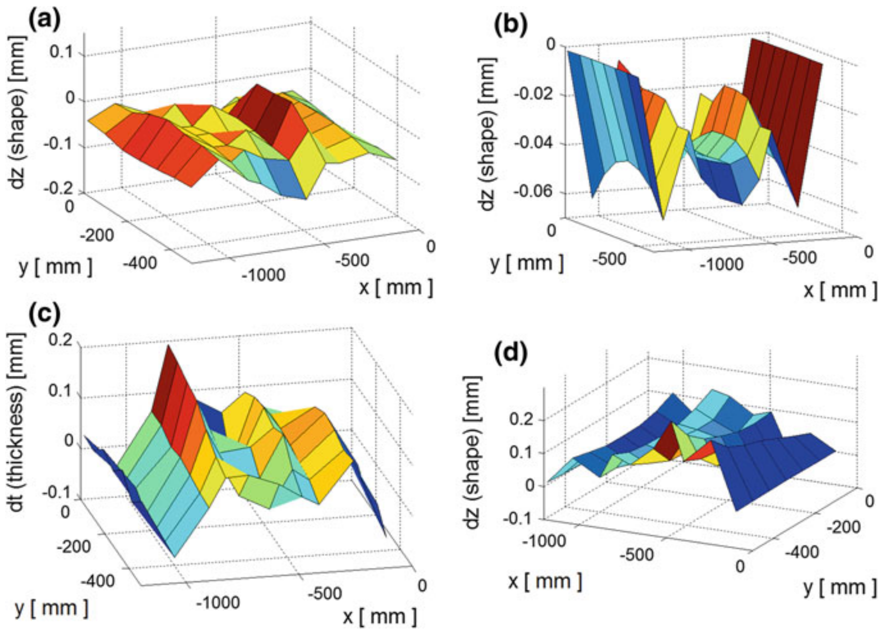


Fig. 5.14 Measured information about shape and thickness of the workpiece: (a) measured inner (*top*) surface shape; (b) workpiece deformation due to touch probe; (c) thickness deviation of finished workpiece with stiffness correction obtained from top surface deviation; (d) final inner surface shape for tool path generation using machining force and workpiece stiffness compensation

the workpiece and the high stiffness of the probe (Fig. 5.14b). The thickness of the workpiece is measured by an ultrasonic probe in the same selected points where the identification with the touch probe was done (Fig. 5.14c). The real bottom (outer) surface of the workpiece is reconstructed from the information about the top surface and the real wall thickness. The new theoretical top (inner) surface is generated using information about the real bottom surface and the theoretical thickness. This surface shape is corrected with respect to the cutting force model and the simulated workpiece compliance (Fig. 5.14d). The NC code for the finishing operation is generated using this corrected surface shape.

5.9 Case Study Results

The workpiece thickness was evaluated at 70 points. The chart of the thickness error is presented in Fig. 5.15. The wall thickness was below the lower tolerance in two cases and above the upper tolerance in 32 points. The maximum thickness error is ±0.1 mm. For comparison: if the machining process is done without the in-process workpiece inspection, the final thickness error reached a value of 0.9 mm.

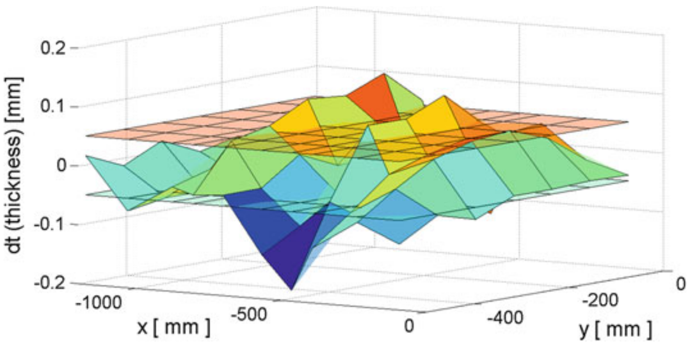


Fig. 5.15 Thickness measurement results

Table 5.4 Results compared with key performance indicators

Parameter	Requirements	Previous technology	Developed solution	Status
Workpiece wall thickness tolerance	±0.05 mm	±0.1 mm	±0.1 mm	Partially better
Workpiece weight tolerance	Max. +1 kg	+2 kg	+1 kg	Ok
Surface roughness	Ra 0.8	Ra 0.8	Ra 0.8	Ok
Machining time of the inner side	To minimize	100 h	85.1 h[a]	−15%
Price	To minimize	EUR 130,000[c]	EUR 95,000[b]	−27%

[a]Simulation result using the experimentally verified parameters
[b]Price of the full fixture set; the set includes six specific fixture devices for six main parts of the airplane wing
[c]Price of the universal fixture device based on the developed fixture units and control software

5.10 Case Study Summary

The main KPIs are compared in Table 5.4 with the results obtained on the demonstration part and applied to the full-sized part using a simulation. As can be seen, the proposed manufacturing procedure enables an improvement of the main manufacturing indicators compared to the results of the existing industrial solution.

The proposed manufacturing procedure is beneficial from the productivity point of view: The proposed manufacturing process leads to a shortening of the production time (of the inner surface) by about 15% with the requested quality of Ra = 0.8. The proposed manufacturing procedure is acceptable from the accuracy and weight point of view: The wall thickness is below the lower limit only in two points at the part margin. Since the value stayed within 2T (double tolerance) zone, the strength of the final part should not be affected. The wall thickness is above the upper limit at some points. Thus, the total weight should be evaluated in order to fulfill the requirements. The part weight is on the requested upper limit.

The proposed fixture system is cost-effective: The proposed universal solution has a lower price compared to the total price of the existing dedicated fixture set. A group of fixture units, including the necessary harness and control, offers a universal possibility how to replace a set of six specific fixtures designed as a mold with the negative shape of the part. Moreover, the new fixtures can be used for clamping during machining of both workpiece sides. The key financial benefit is the ability to replace more types of specialized clamping devices.

5.11 Conclusions

Production of thin-walled curved workpieces is difficult due to the low static and dynamic stiffness of the workpiece. The principle approach presented in this case study is based on a workpiece clamping using discrete fixture units, machining strategy optimization with respect to the part properties and adaptive machining technology involving the inspection of the current state of the workpiece geometry. As the results of the study showed, this solution is cost-effective and enables productive and accurate machining. The main advantage of the solution is the universal application of the developed fixture units and the automatic process control including part thickness measurement.

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Chapter 6
Case Study 2.3: Distortions in Aeronautical Structural Parts

Iñigo Llanos, Arkaitz Beristain, Jose Luis Lanzagorta and Hendric Matzat

Abstract The structural components employed for the aeronautical industry show highly restrictive requirements concerning their weight and strength capabilities. Following these requirements, they usually have a slender nature, showing a highly unsymmetrical ribbed geometry. This point coupled with the residual stresses present on the stocks from which these parts are machined, cause that the final machined parts show distortion problems that can make them unacceptable and, thus, generate the rejection of the manufactured component. Within the INTEFIX project, a solution has been developed comprising the use of fixtures coupled with calculation engines for tackling the manufacturing of this kind of parts. Taking into account the actual residual stress state for the stock, a software tool has been developed that is capable to automatically clamp the part in the optimal way and machine the part assuring the minimum distortion for the machined component. When developing this tool, the requirement for its usage by low skilled operators at workshop level has been taken into account, guaranteeing its usability in actual manufacturing environments.

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6.1 Introduction of the Case Study

Presently, aircraft manufacturing companies are heavily driven by weight saving and cost reduction initiatives. This way, most of the components for the aeronautics market need to fulfil the requirements for high mechanical load capacity with minimum weight. In this sense, and specifically related to structural components, the use of highly slender ribbed parts made out of newly developed aluminium alloys has been extensive in the last decade [1]. However, due to the nature of the used materials, together with the asymmetrical geometries related to these slender ribbed components, the appearance of geometrical distortions after the manufacturing of these components is a major issue [1]. Specifically in the case of the manufacturing of structural parts out of aluminium, the main reason for part distortion has been reported to be the initial residual stress state before the machining processes [2].

The Case Study 2.3 of the INTEFIX project focused on the development of intelligent fixtures and machining methodologies which are able to manufacture highly slender ribbed parts in such a way that the final part after the machining process achieves the required geometrical tolerances. The manufacturing of these parts usually shows a high material removal (up to 90–95%) by machining processes that, together with an unsymmetrical geometrical configuration of the part, can generate significant distortions of the part after the release of the clamps used during the machining process. This Case Study deals with the development of specific fixtures that can avoid the distortion problems reported by the industrial end-user, concerning aeronautical structural parts manufactured in aluminium alloy

Fig. 6.1 Part analysed within Case Study 2.3

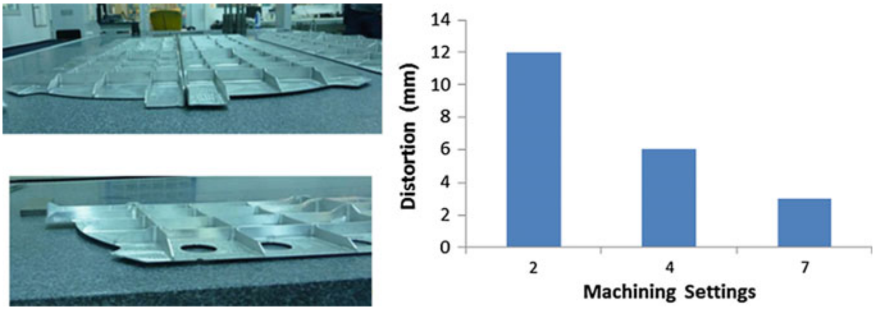

Fig. 6.2 Different part distortions (*left*), distortion depending on the machining setting (*right*)

7075-T7451 (Fig. 6.1). The problems that occurs in machining of these aeronautical parts can be summarized in the following points:

- The part distortion after the same machining process varies by up to 5 mm.
- The part distortions are non-repetitive from one part to another.
- The machining process is based on incremental material removal from both stock sides, comprising several machining settings.
- The clamping of the ribbed geometry is based on chemicals, generating long setting times.

In order to overcome these distortion problems, the classic solutions are based on the incremental removal of material from opposite sides of the machining stock, so the distortion could be balanced [3]. Concerning the effect of the number of machining settings on the part distortion, Fig. 6.2 (left) shows different parts after different machining settings. When two settings are applied, the part distortion reaches approximately 12 mm. When a process comprising 7 machining settings is employed, the resultant part distortion is reduced to a value close to 4 mm, see Fig. 6.2 (right). This way, the final part accuracy depends significantly on the number of settings and the knowledge of the machine operator to reduce the distortion by applying sequential machining settings.

In order to assure the part distortion to be below 1 mm when machining these parts, as well as to enable the reduction of the time required for their manufacturing, part clamping solutions coupled with knowledge-based engines for the calculation of the final part distortion are proposed here. On the one hand, an analytical model was developed for the calculation of both the residual stress state of the aluminium stocks and the final distortion of the parts after the machining process. On the other hand, two fixture solutions were developed. The first one allows for the modification of the initial state of the stock in case it is required for the minimization of the final distortion of the part. The second one allows for the clamping of the ribbed side usually present on aeronautical structural parts, avoiding the damage of the already machined features.

This solution was developed trying to maintain an easiness for its implementation on the actual manufacturing processes, being controlled by an agile and easy-to-use tool to be run by low-skilled machine operators at workshop level.

6.2 First Fixture Design

As commented previously, two fixtures were developed for the present solution. The first one would allow for the clamping of the raw aluminium stock while enabling the modification of the stress state of the stock. Next, the conceptual requirements defined for the first step fixture are exposed, as well as the approaches followed for the realization of these requirements.

6.2.1 Conceptual Requirements for Fixture 1

Four main conceptual requirements have been defined for the fixture to be employed on the first machining step. As a first point, the system should be capable to automatically define a machining process that would yield the minimum part distortion. In order to accomplish this point, a methodology capable to identify the actual residual stress state of the aluminium stocks to be employed for obtaining the final part should be developed. Also, a calculation engine for the final part distortion would be required in order to be able to analyse the effect of the machining process and the stock residual stress on the final part distortion and, thanks to it, generate an optimization procedure for defining the specific machining process that could yield the minimum part distortion. Taking into account the operative requirements, the system should show a seamless connection between the different modules and the fixture control in order to enable its automatic operation. As a final point, the fixture should be controlled by an agile and easy-to-use tool so a low skilled machine operator could use it at workshop level.

The second main requirement defined for the first fixture would be related to the part clamping. Taking into account the geometry of the test case to be used for the validation of the present development, the system should be able to clamp the part leaving full access to the upper surface by the machining tool, allowing the required machining while ensuring the part clamping. In order to assure this point, the stock should be clamped from the sides, while some supports should be used below it.

The third main point to be covered would be related to the capability to modify the stress state for the stock. The stock to be machined could have such a residual stress state that the minimum possible distortion obtained by the calculation engine would be higher than the required tolerance for the part to be machined. In order to overcome this point, the fixture shall have the capability to modify the residual stress state of the stock by the generation of a bending deformation on it. The new stress state generated on the stock would allow the minimization of the part distortion below the tolerances defined for it. In order to accomplish this point, the fixture should have a stock deformation system, with the capability to accurately identify the actual deformation induced on it.

The final point to be taken into account for the design of the fixture would be related to the forces to be generated during the clamping of the part. If excessive or uneven forces would be applied, mechanical distortions could appear on the part that had not been taken into account by the part distortion calculations. This way, the stock deformation system should have the capability to detect the contact with the stock, as well as the possibility to monitor the clamping forces during the whole clamping and machining processes.

6.2.2 Requirement Realization for Fixture 1

Once defined the conceptual requirements to be covered by the first step fixture, the present section exposes the software and hardware developments carried out for their fulfilment.

The first development is related to the methodology for the characterization of the actual residual stress of the stock. In this sense, a layer removal method was applied, following the approach proposed in [4]. In comparison to the classic layer removal method, this approach takes into account the contraction of the moment of inertia during the removal of consecutive layers. This way, it is possible to include the effect of the material removed on previous measurements/layers on the calculation of the stress state of a new layer.

This approach was coded into MATLAB in order to create a tool for the automatic calculation of the residual stresses on the machined stock. Tests were conducted for the evaluation of the results obtained from the exposed methodology, showing a good quantitative agreement with results reported in bibliography. Figure 6.3 (Left) shows an image for the residual stresses obtained for an

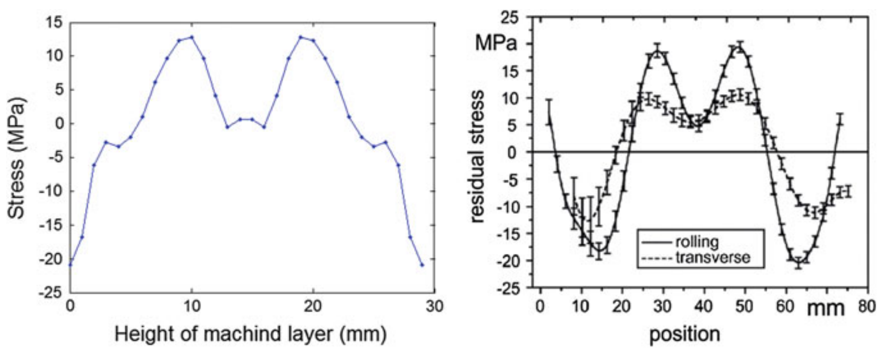

Fig. 6.3 Residual stress values obtained for Aluminium 7050-T7451 by the present methodology (*left*) and from bibliography (*right*)

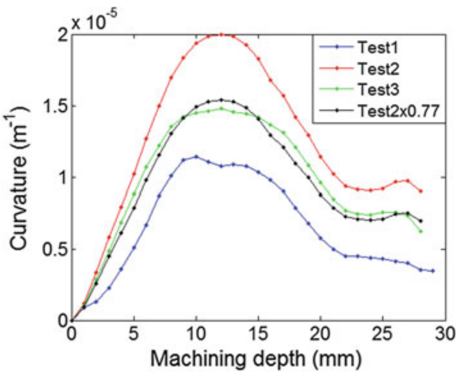

Fig. 6.4 Curvature values obtained after layer removal tests

aluminium stock with the present methodology, while Fig. 6.3 (Right) shows data obtained from bibliography [5].

When analysing residual stress values obtained for different stocks, it was observed that each of them would show different shapes for the residual stresses. However, in the case of the evolution of the curvatures generated on the part after each layer removal, it can be seen that they show consistent shapes for different tests (Fig. 6.4). In this sense, a scale factor could be defined between the different tests (Test3 $\approx$ Test2 $\cdot$ 0.77), enabling the possibility to use the data from one stock for the estimation of the curvature evolution for another stock and, thus, its residual stress state.

The second main development is related to the generation of a calculation engine for the final part distortion after the machining process has been carried out. Many developments can be found in bibliography related to this point, mainly based on the use of FEA models for the calculation of the distortions to be generated on the parts after the machining processes [2, 6–15]. However, besides the cost of the use of this kind of software, these tools would require a highly skilled operator for carrying out the calculations, while the recalculations to take into account the actual residual stress state from the stock would require considerable time.

Consequently, in order to enable the generation of an agile and easy-to-use tool, the use of analytical models was favoured instead of FEA models. The developed analytical model is based on several assumptions for covering the addressed industrial test-case:

- Stress state simplification, accounting only for longitudinal (X) direction
- Uniform longitudinal stress in X and Y directions
- Effect of transversal ribs disregarded from calculations
- Geometry simplification into an equivalent transversal section.

A graphical representation of these assumptions can be seen in Fig. 6.5. Since the first step fixture would show the capability to modify the initial stress state for the stock by applying some bending deformation on it, and the machined part would be straight, it must be taken into account that each section along the machined part will not have the same residual stress profile. In order to cover this

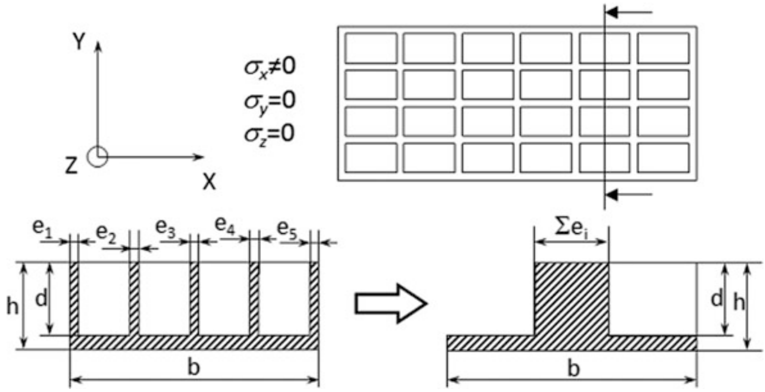

Fig. 6.5 Graphical representation of the hypotheses and the reduction of geometry to an equivalent section

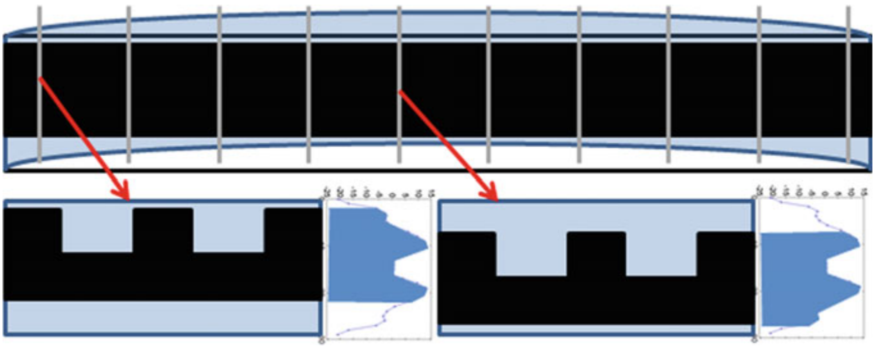

Fig. 6.6 Residual stress profiles for different sections after the part bending

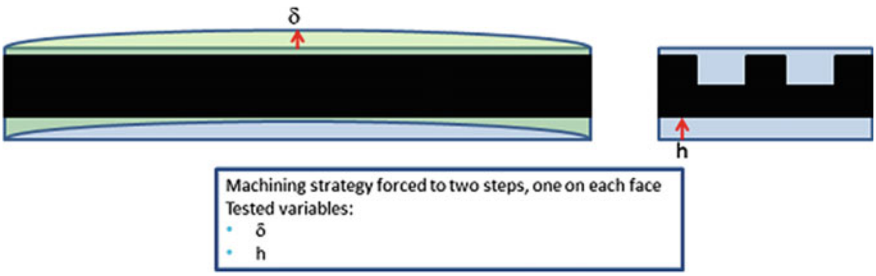

Fig. 6.7 Definition of the parameters for the optimization of the machining process

point, different sections must be defined along the machined part so the local curvature for each of them can be calculated.

Figure 6.6 exposes the effect for the appearance of different residual stress profiles on each longitudinal section after the part bending. Once these sections are defined, it is possible to calculate the final deflection generated on the machined part after its machining.

After the calculation engines for the estimation of the actual residual stress state of the stock and the final part distortion were realized, the development of an optimization loop for the generation of a 2 step machining strategy (one on each side of the part) that would yield the minimum part distortion was carried out. This strategy indicates the required deformation δ to be applied on the centre of the part by the first step fixture and the positioning of the part within the stock h (Fig. 6.7), allowing for the minimisation of the distortion of the part while optimising the machining time.

Following the development of the different software modules, the design of the hardware components for the first step fixture was carried out. In order to allow for the machining of the upper surface of the part, a fixture based on two supports including some lifting modules that would allow for the deformation of the aluminium stock in a controlled way was proposed. This design could easily be modified for accommodating different sized material stocks, enabling its application

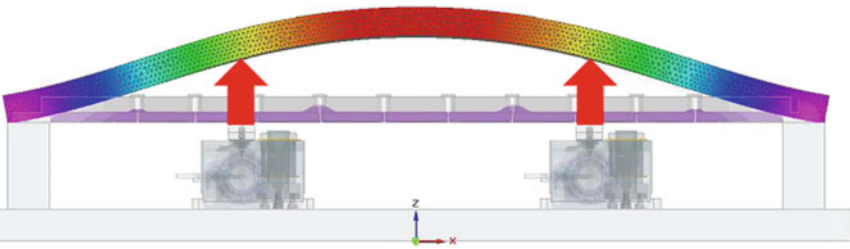

Fig. 6.8 Design of the first fixture for clamping and bending the test part

Fig. 6.9 Final assembly of the first step fixture

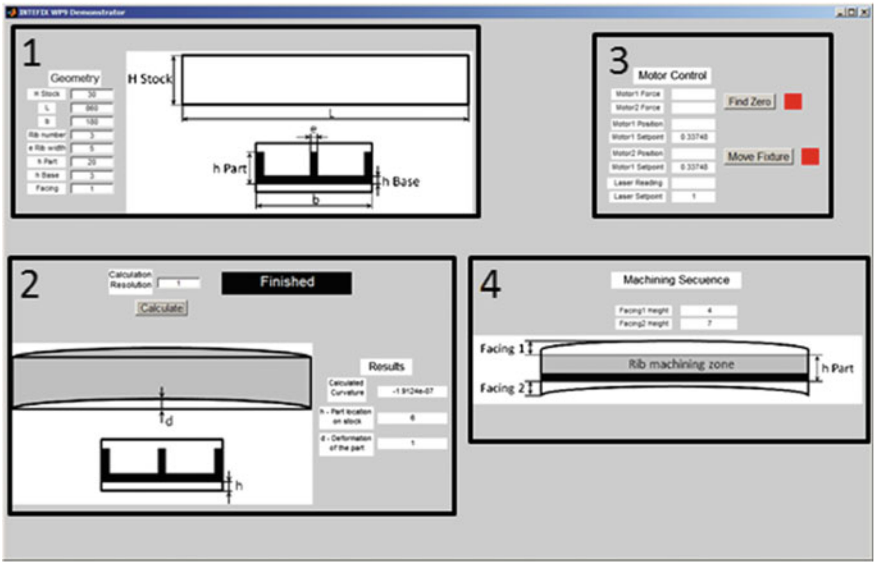

Fig. 6.10 GUI developed for the control of the system

for a broad range of part geometries. In order to clamp the test part proposed by the industrial end-user, the conceptual design for the fixture used in this case study can be seen in Fig. 6.8.

The lifting modules of the fixture are motorised for the automatic application of the deformation of the stock. A laser measurement system ensures the accurate deformation of the centre of the part. Some load cells are included in the lifting modules so that the contact between them and the part can be detected and it can be assured that both lifting modules apply the same load on the part. This point allows avoiding the generation of uneven clamping forces on the stock and the consequent appearance of mechanical distortions not accounted for by the part distortion calculation engine.

The final realization of the fixture with an aluminium stock located on it can be seen in Fig. 6.9. The control of the positioning of the lifting modules, the measurement of the forces applied on the load cells and the measurement of the laser system was carried out by a PLC connected to an industrial PC. The connection of this control with the residual stress calculation module, the final part distortion model and the machining process optimization engine was carried out by MATLAB. Finally, a simple GUI was developed for the control of the system by a low skilled operator (Fig. 6.10). This GUI is divided into 4 main features: (1) Definition of part geometry, (2) Calculation of the stock deformation and part positioning for minimal final distortion, (3) Minimization of uneven clamping forces and commanding the motors to the calculated position, (4) Representation of the calculated optimal machining sequence.

6.3 Second Fixture Design

The second step fixture would allow for the clamping of the part after the ribbed geometry has been machined. The conceptual requirements defined for this fixture are exposed in the following, together with the hardware realization.

6.3.1 Conceptual Requirements for Fixture 2

In the case of the second step fixture, the conceptual requirements are mainly related to the part clamping. Since this clamping should allow for the facing of the upper surface of the part, the clamping should be carried out by the sides of the workpiece and the already machined ribbed geometry. Concerning the clamping of the already machined ribbed geometry, the fixture should assure that no damage is generated on these features in order not to scrap the already machined part. Furthermore, the modules for holding the ribbed geometry should clamp the different ribs in a simultaneous way for avoiding the generation of uneven forces and to reduce the required clamping time.

6.3.2 Requirement Realization for Fixture 2

With respect to the definition of the conceptual requirements for the second step fixture, the hardware developments were carried out for their fulfilment that can be seen in this section.

In order to avoid the damage of the already machined geometry, the design of the clamping units for the ribs is based on two self-balancing heads which assure that no lateral forces are induced into the machined ribs. These clamping units are

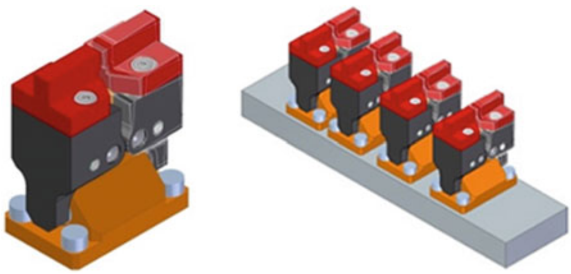

Fig. 6.11 Single clamping head and full clamping module for the second step fixture

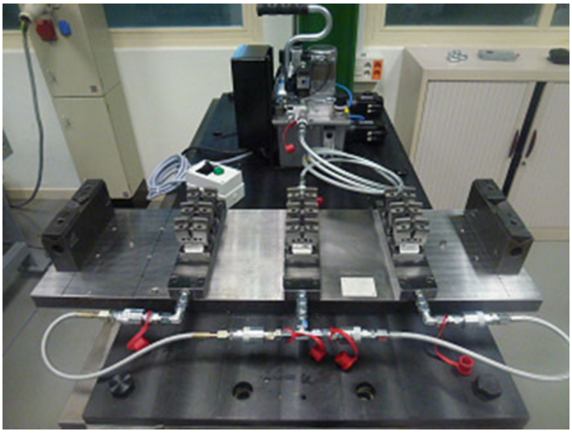

Fig. 6.12 Final assembly of the second step fixture

hydraulically operated and mounted on modules for feeding the different clamping heads with the hydraulic oil. The use of this hydraulic system ensures that the final clamping forces are applied simultaneously on the whole part, avoiding the generation of uneven forces on the part. Figure 6.11 shows images of the design of the clamping heads (left) and the mounting of these heads onto the hydraulic oil feeding system (right).

Once defined the way for clamping the already machined ribbed geometry, the location of the clamping modules was defined according to the actual geometry of the industrial test-case to be machined. The final assembly of the second step fixture is shown in Fig. 6.12, where, besides the location of the rib clamping modules and the lateral supports for the part, the connection between the clamping modules to the hydraulic oil feeding system can be seen.

6.4 Results

In this section, the results obtained concerning the stock residual stress characterization methodology and the part distortion calculation engine are shown. Afterwards, the results obtained when applying the developed methodology to an actual industrial test case are presented.

6.4.1 Evaluation of the Stock Residual Stress Characterization and Part Distortion Modules

The behaviour of the distortion model was evaluated by the manufacturing of some simplified parts. Two parts with same geometry but obtained from different zones of

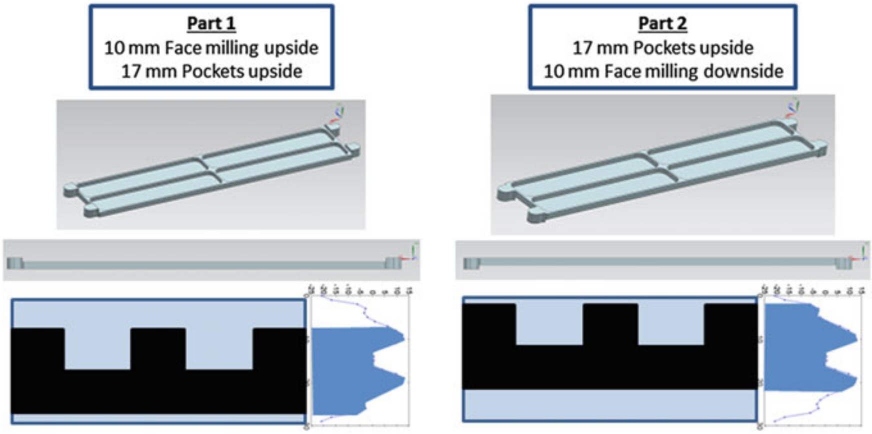

Fig. 6.13 Preliminary validation parts

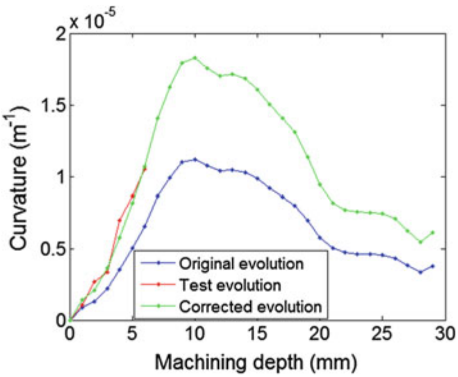

Fig. 6.14 Comparison of the curvature values from previous tests and present stock

the aluminium stock were machined. As a result, the stress fields of the final parts coming from the residual stresses from the stock are different (Fig. 6.13) and, thus, generate different part curvature.

First, the initial methodology for the estimation of the residual stress fields of the stocks was applied for the manufacturing of the parts. In this way, 7 mm pockets were machined into the parts using 7 steps with 1 mm depth of cut. After the machining of each one of these steps, the curvature attained by the part was measured. By the comparison of this curvature data to the data obtained from previous characterisation tests, the residual stress field present on the whole

Table 6.1 Curvature results obtained from both experimental and numerical tests

	Part 1	Part 2
Simulation average	2.23e−5	−1.93e−5
Experimental	2.31e−5	−1.82e−5
Error (%)	3%	6%

aluminium stock was estimated. Figure 6.14 shows the comparison of the curvature values from a previous test to the data obtained from the aluminium stock for Part 1.

Based on the comparison of the curvature values, the residual stress field present on the actual aluminium stock was estimated. Subsequently, the final curvature values obtained from the simulation of the machining of each part were averaged and a final curvature value was obtained for each of the analysed geometries.

For the evaluation of the results obtained from the simulations, the actual machining of the simulated geometries was carried out. The final curvature results obtained from the experimental and numerical tests are shown in Table 6.1 for both Part 1 and Part 2. As it can be seen, the results obtained from the simulations carried out with the developed model show a good agreement (less than 10% error) with the experimental results.

In this way, the capability of the developed solution for the estimation of the initial residual stress field of the aluminium stocks, as well as the calculation of the final distortion of a part after a given machining process were validated.

6.4.2 Application of the Developed Methodology to the Test Part

The developed methodology within case study 2.3 was applied to the manufacturing of the actual part from the industrial end-user. The application of this methodology involves the use of the different developments: the first step fixture with capabilities for the accurate deformation of the part stocks, the part distortion model coupled to the control of the first step fixture and the second step fixture for clamping the ribbed parts via the ribs. The different operations to be followed for the application of the developed methodology to the machining of a given slender ribbed part can be seen in Table 6.2.

First, a characterization of the material state must be carried out in order to calculate the part distortion based on the actual mechanical state from its stock. Then, the procedure for the optimisation of the machining sequence can be applied

Table 6.2 Sequence for the present methodology

Sequence	Operation
1.	Characterization of residual stress state
2.	Calculation of machining positioning for distortion minimization
3.	Machining of ribbed geometry (Side A)
4.	Facing of lower geometry (Side B) and cutting of the part

Fig. 6.15 Image of the part after the finishing of the ribbed face

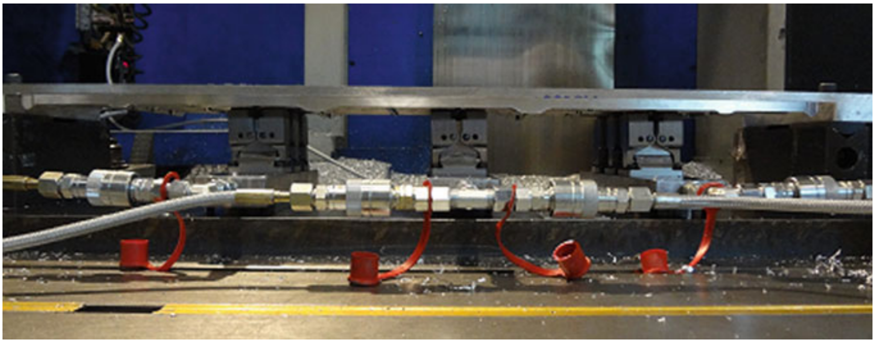

Fig. 6.16 Image of the part clamped on the second face fixture

based on the geometry of the part to be machined and the estimated residual stress field at the stock.

The first step was the identification of the residual stress state from the aluminium stock. For that, a sequential elimination of material was carried out using the roughing CNC program for the required part geometry: 5 mm of material was removed in 5 layers of 1 mm. Following the elimination of each of these layers, the part was unclamped and the curvature achieved was measured.

After the evolution of the curvature with the removed material was obtained, by comparison to results from previous characterisation tests, the estimation of the actual residual stress state of the aluminium stock was undertaken. Following the identification of a residual stress state, the calculation procedure indicates the most adequate part deformation (δ) and positioning of the stock (h) for the minimization of the final part distortion (Fig. 6.7). The direct connection between the distortion

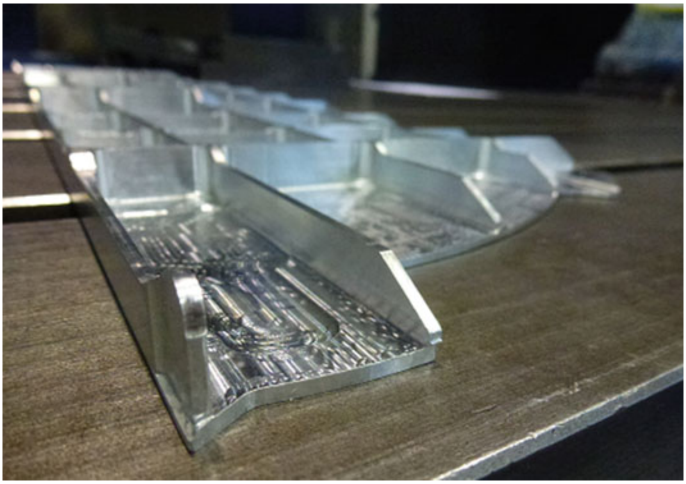

Fig. 6.17 Detail of the finished part end with no appreciable distortion

model and the fixture control allows for the automatic part detection and deformation to the required values. Once the part was set-up, and the zero-offset was modified accordingly to match the part positioning of the stock (h) indicated by the model, the machining of the whole side A of the part was conducted. Figure 6.15 shows an image of the part after the finishing of the ribbed geometry.

Subsequently to the machining of the first side of the part, the workpiece was unclamped, flipped up-down and fastened on the second step fixture (Fig. 6.16). Once the part was clamped, the required facing operations were carried out in order to obtain the desired thickness of the part. After these facing steps, the part was cut off its laterals to its final geometry.

Following the machining and cleaning of the part, it was measured for the evaluation of the obtained distortion results. A maximum flatness error of 0.3 mm was achieved. Figure 6.17 shows an image of the finished part, where no considerable distortion can be observed at the part end.

6.5 Summary and Conclusion

The manufacturing of the industrial test-pieces following both the methodology developed within case study 2.3 and the manufacturing process from the industrial end-user, allowed for the evaluation of the capabilities of the developed solution.

The application of the present developments in comparison to the previous process has

- improved the part accuracy from 2 mm distortion to 0.3 mm distortion thanks to the application of the distortion minimization procedure and
- reduced machining time from 4 days to 2 days due to the avoidance of chemical clamps.

Furthermore, it must be taken into account that the machining programs used on both tests were the same. When applying the methodology developed here, there is no actual requirement to divide the machining of the ribbed side of the part because there is no need to flip it as in the conventional industrial process from the end-user. Thus, it is expected that the machining times could be further reduced by optimizing the machining of the ribbed side of the part.

The developed solution is potentially applicable to any part with a ribbed geometry manufactured in aluminium. By modifying the parameters related to the part geometry, both the stress state characterization procedure and the part distortion models could be satisfactorily applied to any part geometry. In this sense, any structural part with a ribbed geometry employed on the aeronautical industry could likely have the applicability for the solution presented here.

However, it must be taken into account that this methodology has been developed to reduce the distortion problems of a machined part in a given direction, neglecting the deformation effects in the other spatial directions. If a part would show significant distortion in two spatial directions, the developed solution would not be directly applicable; requiring the inclusion of the second spatial direction in the part distortion model, as well as on the part stress state characterization methodology.

In a similar way, if a part should be manufactured out of a material for which the residual stresses generated by the machining process itself would have a noteworthy effect on the part distortion (e.g. Titanium alloys), the developed solution could not be applied directly. The generation of a highly stressed zone below the machined surface should be accounted for in the distortion model, as well as in the stress state characterization methodology.

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Chapter 7
Case Study 2.4: Machining of Aircraft Turbine Support Structures

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Abstract The manufacturing chain of metallic components normally involves various processes like welding, machining or thermal treating. This combination leads to internal residual stresses that commonly result in deformations and distortions of the workpiece affecting the manufacturing precision and the quality of the component. This problem is especially relevant in large, slender and complex workpieces like those manufactured in the aeronautic industry. In this case study, the fixture development was oriented to the control and minimization of the deformation of a large component of an aircraft engine during the setup and clamping process to improve the precision during the machining process. The initial state of the component is an already deformed geometry as a consequence of previous welding processes; so, the objective is the development of an intelligent

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fixture able of clamping the deformed component without producing additional geometrical distortions. This chapter covers the development of a solution for the clamping of deformed components and the results obtained in the experiments.

7.1 Introduction of the Case Study

The objective of the case study is to control the deformation of a complex geometry welded structure during the setup and clamping process in order to achieve improved precision during the subsequent machining operations.

The workpiece is the Tail Bearing House (TBH) of a turbine, see Fig. 7.1. It is a structural component made of Inconel 718 with 1900 mm in diameter, 350 mm in height and common thickness of 6–10 mm. This structural component is made by welding different forged and casted components (2 rings, 12 vanes and multiple geometries to fix and join the component to other parts of the turbine) that are machined afterwards. The welding process results in deformations and distortions that must be taken into account during the setup in order to avoid additional errors during the machining process, that normally appear after releasing the component off the fixture.

The precision is one of the most important issues in the machining of aeronautics components, and it is affected by the geometrical distortions that occur during processing, being that deformation related to the existence of residual stresses (internal forces) and clamping boundary conditions (external forces). The deformation caused by a change in the residual stress state generated by previous manufacturing processes of the component is associated to the material removal during machining processes leading to a new internal equilibrium of the component. The deformation caused by external loads (clamping, cutting forces…) results in elastic deformation of the workpiece during processing that is recovered afterwards.

The fixture becomes a key component to avoid the geometrical error associated to deformation caused by external loads during machining processes. It is a

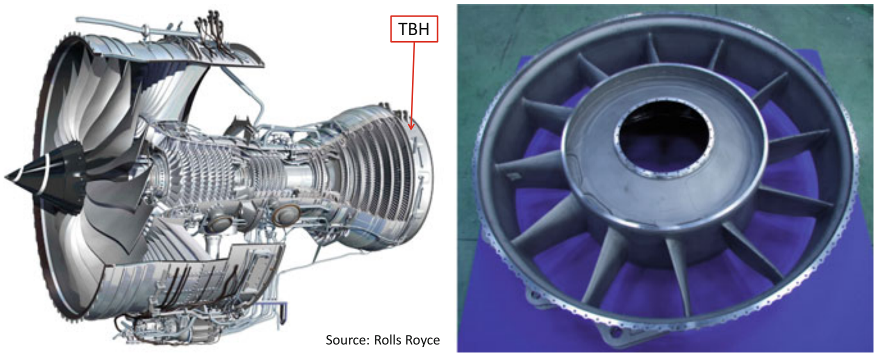

Fig. 7.1 (*Left*) Location of the TBH within the engine (courtesy: Rolls-Royce). (*Right*) Detail of the TBH

precision subsystem aiming to provide an accurate positioning of the workpiece in the work space and to rigidly hold and support the component in order to withstand the machining forces. In this way, the general strategy is to adapt the locators and clamps of the fixture to the deformed workpiece, minimizing the additional deformation produced by the external loads of the clamping process.

The machining process of this component is carried out in a 5-axis multifunctional CNC machining center involving several operations. The operation to control is the turning of the flanges of the TBH, in order to assure the suitable precision and to fulfil the requirements for the subsequent assembly process. In this case, the precision is limited by the deformations suffered by the workpiece during the clamping process, due to the already deformed geometry from previous processes and to the hyperstatic stress state generated in the fixture. So, these aspects must be minimized in order to improve the accuracy of the workpiece after the machining process.

The current fixture is a dedicated and manually actuated unit composed of various mechanical clamping elements and supports, see Fig. 7.2. The research activity has been focused on the improvement of the axial clamping step in the lower flange as shown in Fig. 7.3. This axial clamping step can produce deformations in the workpiece that have to be avoided in order to limit shape and tolerance errors in the final component after the turning of the upper flanges of the workpiece.

The axial clamping adjustment is done manually in two steps sequentially over the eleven distributed clamping elements. The process in each element involves the deformation of the workpiece 0.1 mm in the positive axial direction, and the subsequent correction of that deformation in the negative axial direction. This operation is currently done manually and carefully controlled to avoid excessive distortions, being time consuming and a potential source of problems, as it depends on the operator skills. The process is summarized in the Fig. 7.4.

The main problems appointed above and the current situation of the TBH prior to the machining can be summarized in the following points:

- Deformation of the workpiece due to previous manufacturing processes.
- Need to clamp the workpiece without introducing additional deformation.
- The clamping process involves a high set-up time and it depends on the operator skills.

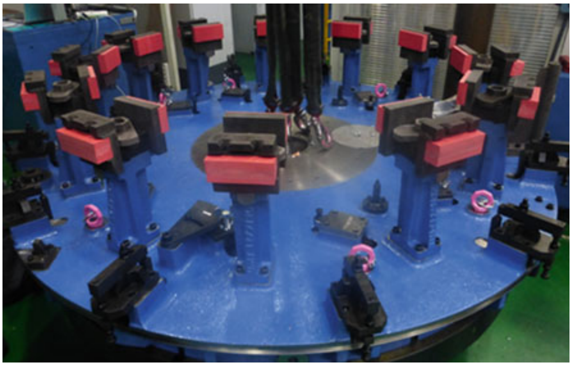

Fig. 7.2 General view of the fixture

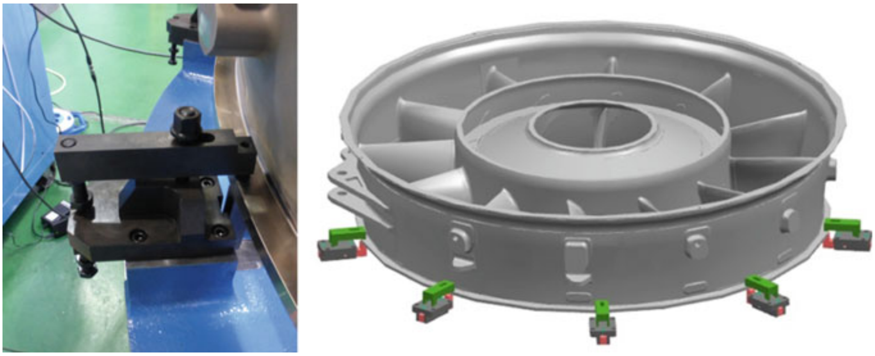

Fig. 7.3 Detail of an axial clamping element and clamping area of the workpiece

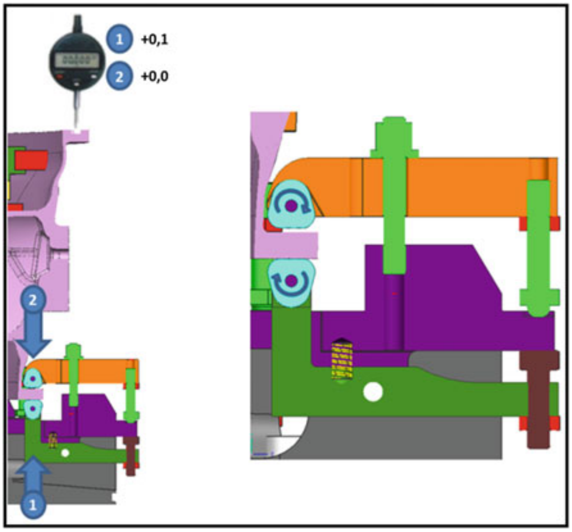

Fig. 7.4 Original axial clamping process to minimize the deformation

7.2 Fixture Development

In order to solve the main problems and limitations explained above, the development of an intelligent clamping unit with integrated sensors and actuators was carried out. The main functionalities of the unit are the correction and control of the deformations of the workpiece to improve the precision and performance of the machining process.

The designed intelligent clamping unit can counteract or produce a deformation in the workpiece through the modification and adaption of the position of the yaws and the clamping force, achieving also an automatic position correction based on the measurements of the position and force sensors. The main functionalities of the solution developed are:

- Floating clamping element hydraulically actuated to fix the workpiece without producing additional deformation or distortion of the workpiece, i.e. adapting the position of the yaws to the workpiece geometry and spatial position.
- Active stage to modify the position, introducing a deformation controlled in close loop to achieve a target reaction force or displacement. It can be also used to counteract (1) existing reaction forces and (2) known or measured displacements in the control point
- Fast hydraulic plug able to maintain the pressure in a closed circuit aided by an accumulator, in order to be able to mount the system in the rotating table of the lathe.

The selected solution aims at substituting the current manual clamping elements by a new concept of an intelligent clamping unit. The concept of this solution is summarized in Fig. 7.5.

In this sense, the new solution reduces the hyperstatic degree of the system and the additional deformation produced in the workpiece, as the axial clamping elements can be actuated at the same time (not sequentially), with controlled reaction force and displacement.

The clamping units fix the workpiece flange in a floating mode, also allowing the controlled positioning of the system to produce a controlled deformation or produce a reaction force. The proposed concept consists of different elements arranged in series to fulfill the requirements and expected functionality:

- Floating clamp: A floating stage able to clamp the workpiece without introducing additional deformation, i.e. the workpiece is clamped without fixing the position.
- Block system: A lock system to block the clamping unit in that position.

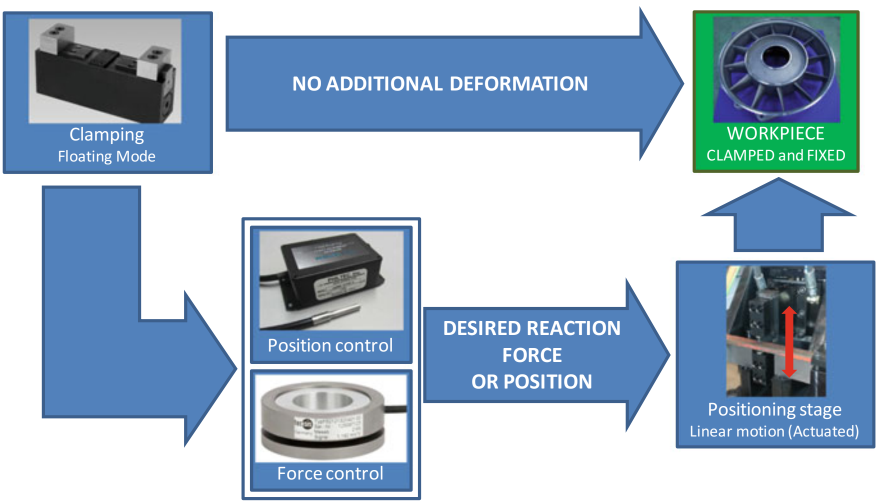

Fig. 7.5 Conceptual functions of the new clamping element

- Controlled movement: An electromechanically actuated stage to produce a controlled deformation in the workpiece.
- Closed loop: The sensors to measure the position or the reaction force exerted during the controlled deformation in order to adjust the clamping unit.

The design of the clamping unit was adapted to the current fixture (see Fig. 7.2), and some limitations constrained its design and manufacturing. The main limitation was related to the existence of a predefined interface structure for attaching the clamping unit in the fixture, see Fig. 7.6. The body of the clamping unit was adapted to this interface, affecting the configuration of the system and the final size of the assembly.

The fixture design was also affected by other aspects related to the workpiece behaviour, the clamping forces, the machining forces, and the characteristics of the sensors and actuators. The specifications established for the design after the analysis can be summarized in:

- Force of 4 kN for the floating clamping stage.
- Maximum force of 40 N for the floating resistance force.
- Force of 8 kN for the blocking/braking of the floating stage.
- Up to 2 kN of available force in the actuation stage.
- Blocking force of 8 kN in the actuation stage (to avoid movements once positioned).
- Positioning precision of 0.005 mm in the actuation stage.

The development of the clamping unit was carried out based on an existing commercial floating clamping element adding different subsystems. The different components of the clamping unit are:

- A floating clamping module (Roemheld I4.130) able to clamp the workpiece without introducing additional deformation.
- A motorized stage to provide a vertical movement to the system, including precision guides, a ball screw and a servomotor with brake. This produces the controlled deformation in the workpiece (position or force control in close loop).

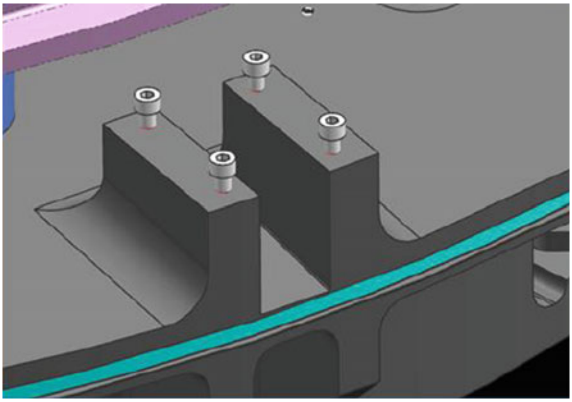

Fig. 7.6 Interface in the current fixture for the axial clamping elements

- A displacement sensor for monitoring of the position.
- A load cell for monitoring the reaction force.
- A drive for the motor with integrated controller to manage the clamping unit.
- Electric elements to connect all the elements.
- Hydraulic elements to actuate the floating clamping (pump, hoses, valves…).
- An adapted structure to fix the clamping unit in the current fixture structure.

The final design of the clamping unit includes the different elements indicated above integrated in a single subsystem with electrical and hydraulic connections, see Fig. 7.7. The schema of the integration of the main elements is shown in Fig. 7.8. As the clamping process is done statically and no changes occur during machining, the need for rotating systems for signal and power is not required in the lathe. The hydraulic pressure is only actuated during the workpiece loading and the pressure is maintained in a closed circuit aided by an accumulator.

The clamping unit was designed considering the working mode for the application of the case study, so the following aspects were taken into account:

- Once clamped the workpiece correctly, the electrical connections can be removed in order to perform the machining process at the rotating table of the lathe.
- Once clamped the workpiece correctly, the hydraulic connections can be removed. The integrated accumulator ensures to maintain the working pressure at the right level and the machining process at the rotating table of the lathe can be performed.

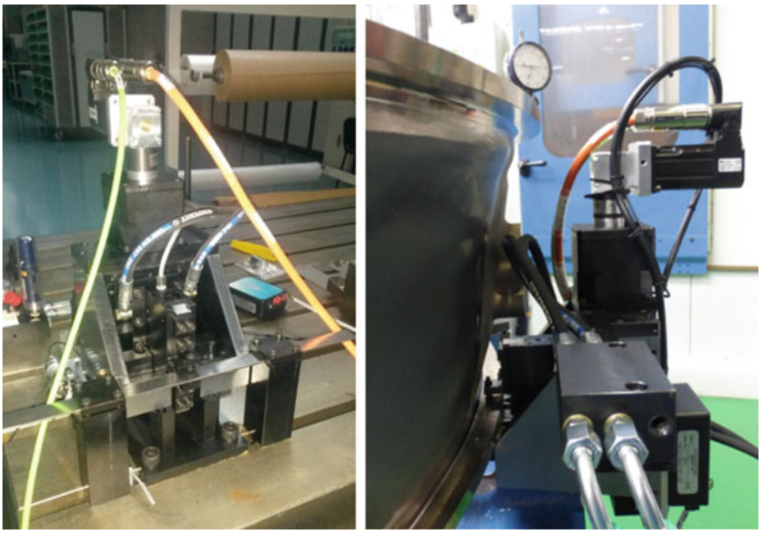

Fig. 7.7 Detail of the clamping unit assembled in the laboratory and mounted in the fixture

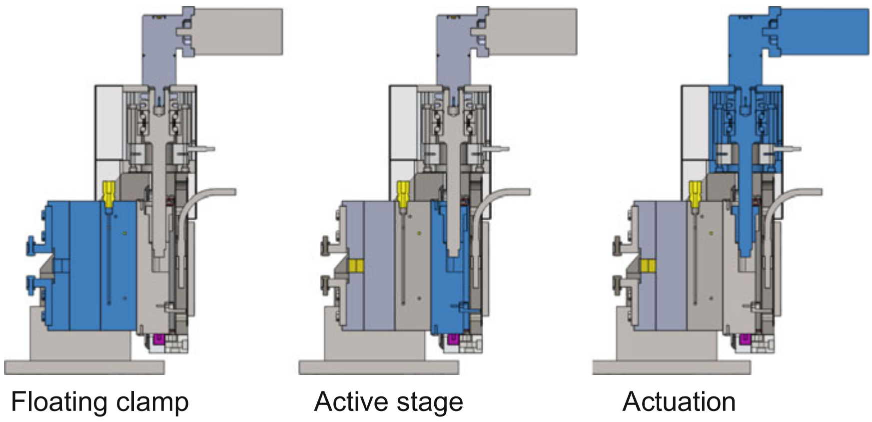

Fig. 7.8 Schema of the main elements (marked in *blue*)

The clamping system includes a wireless sensor allowing the pressure monitoring in the clamping unit. The objective is to control the pressure of the clamping unit during rotation in the lathe, allowing the rotation stop if a pressure drop is detected in the hydraulic circuit.

The electrical and hydraulic connections are detachable once the system is correctly set up. The next images show a detail of the clamping unit with the identification of the main elements. Attending to the working way of the clamping unit, the hydraulic system has two different parts:

- Clamping system: to be boarded in the fixture
- Pressure system: to be released after giving pressure to the system.

These two parts are connected with fast couplings that can be plugged under pressure, allowing the system to rotate with the lathe table without connection to the hydraulic pump. The control algorithms are deployed in a controller and there are two function ways:

- Position control: the target position is given by the user and the system moves to it. This target position can be obtained from theoretical calculations, external measurements or experience to correct own weight, known/measured deformation…
- Force control: when initially clamped the system measures null reaction force, as it is clamped in floating mode. Several disturbing external factors (deformations of the workpiece, external loads…) can produce the appearing of a reaction force. The system can automatically move the axis to a new position that compensates this reaction force, leaving the force again in zero; releasing the distortion associated.

7.3 Verification and Validation Tests

The tests carried out in this case study include the verification and validation tests of the floating clamping unit with reposition capabilities. The main functionalities of the system are the floating clamp (to fix the workpiece without introducing additional deformation), and the repositioning stage (to correct known deformations or existing reaction forces), so the tests have been designed to assess these functions.

On the one hand, the verification tests were carried out in a bench in the laboratory to obtain information about the performance of the system analyzing the results, the real capabilities of the system concerning the clamping without deformation, the precision of the repositioning stage and the precision in the measurement of the reaction forces.

On the other hand, the validation tests were performed in the real fixture available in the workshop, in order to obtain data about the real performance to avoid distortions in the workpiece during clamping.

7.3.1 Verification tests

The test bench to verify the functioning of the system includes the system itself and a beam mounted in 2 supports as the workpiece, see Fig. 7.9.

The simplified scheme of the test bench can be seen in Fig. 7.10, where the sign convention of force and displacement is shown. The characteristic dimensions of the beam are the length (L), width (W) and height (H).

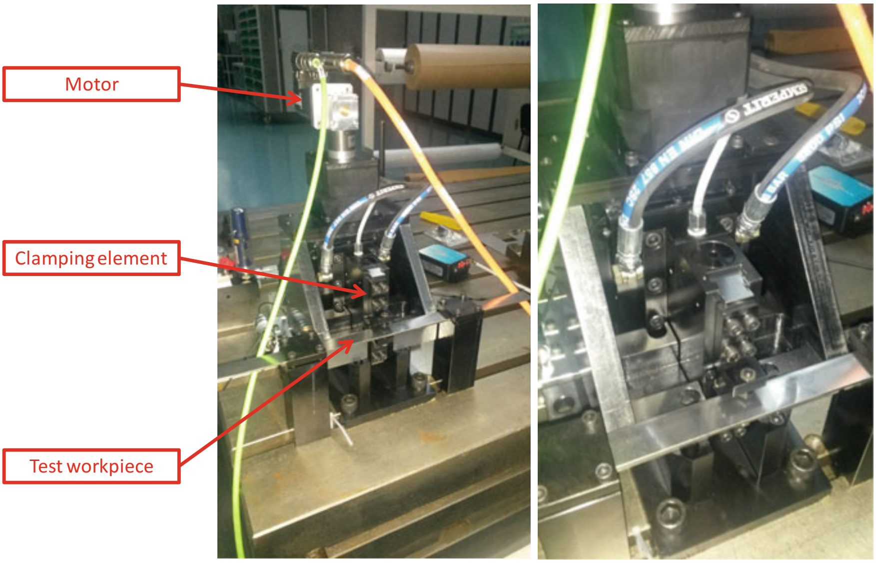

Fig. 7.9 Detail of the test bench

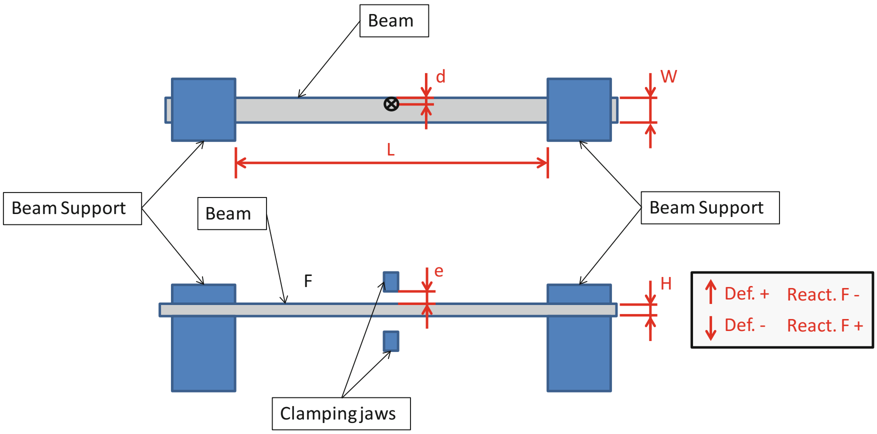

Fig. 7.10 Schema and main parameters of the test bench

The beam stiffness can be modified by changing the distance between both supports (beam length L) or by changing the section of the beam (width and height). In this case, three different beams have been used.

The objective of the verification tests was to evaluate the different functionalities of the clamping system, so three different test types were arranged:

- Clamping Precision Test: Capability of the floating stage (Flexible position) to effectively clamp the workpiece with reduced deformation. Repeatability of the floating clamp process.
- Force Loop Test: Capability of the repositioning stage to achieve a target reaction force in the clamping system modifying the workpiece position. Repeatability of the positioning stage and sensitivity of the load cell to measure the reaction force and its changes.
- Position Loop Test: Capability of the repositioning stage to achieve a target position once the workpiece is clamped. Repeatability of the positioning stage.

The tests allowed the identification of the following behaviour of the clamping unit: (1) the deformation produced depends on the initial stiffness of the workpiece; (2) higher clamping pressure means higher deformation; and (3) the initial distance between the workpiece and jaws, and the differences of stroke in both jaws affect the deformation of the workpiece. The verification tests allowed establishing the main capabilities of the clamping unit:

- The precision of the floating clamp depends on the working pressure, the orientation of the clamping unit (gravity load of the jaws), and the stiffness of the workpiece (with 4.54 N/µm, the deformation is lower than 0.02 mm).
- The working pressure has been established in 120 bar to limit the deformation below 0.005 mm, see Fig. 7.11.

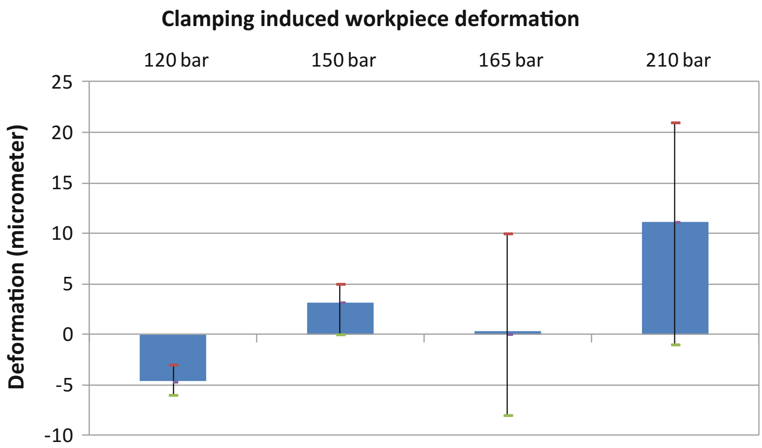

Fig. 7.11 Results of the induced deformation for different clamping pressures using a beam with section 25 × 10 mm

- Using the force loop, the clamping unit can achieve a reaction force precision of ±8 N, with a positioning repeatability of 0.01 mm (see Fig. 7.12).
- Using the position loop, the clamping unit can achieve a repositioning repeatability of 0.007 mm.

7.3.2 Validation tests

On the other hand, the validation tests were performed in the real fixture in the workshop, to obtain data about the real performance and to avoid distortions in the workpiece during clamping.

The tests were performed at the rotating table to control the key operation (see Fig. 7.13): axial clamping and levelling of the workpiece. This operation is done statically and it is required to fix the workpiece before the machining operation in the machining centre. So, the objective of the developed clamping unit is to improve the positioning and to reduce the set-up time compared to the currently used mechanical clamping elements.

The clamping unit was used in two configurations:

- Hydraulic/Electromechanic clamping unit: As originally designed with the floating clamp and the repositioning stage, see left hand side of Fig. 7.14.
- Hydraulic clamping unit: In a simplified way using only the floating stage without the repositioning stage, see right hand side of Fig. 7.14.

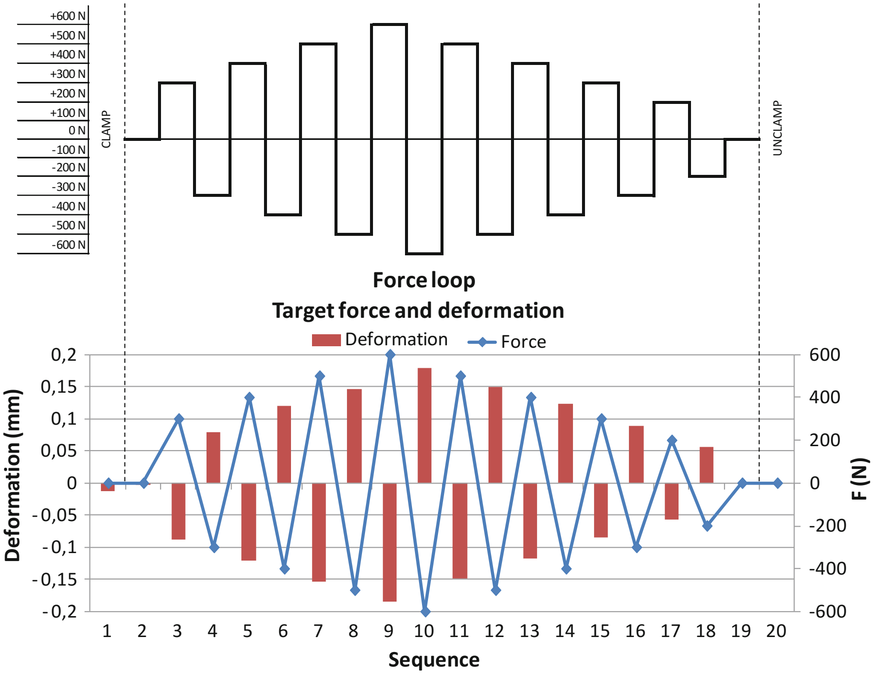

Fig. 7.12 Results of the induced deformation with a target reaction force sequence for a beam with section 18 × 8 mm

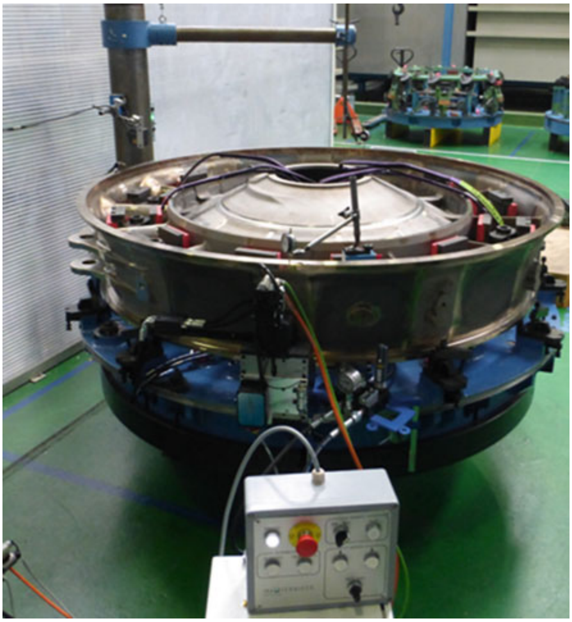

Fig. 7.13 General view of the test assembly

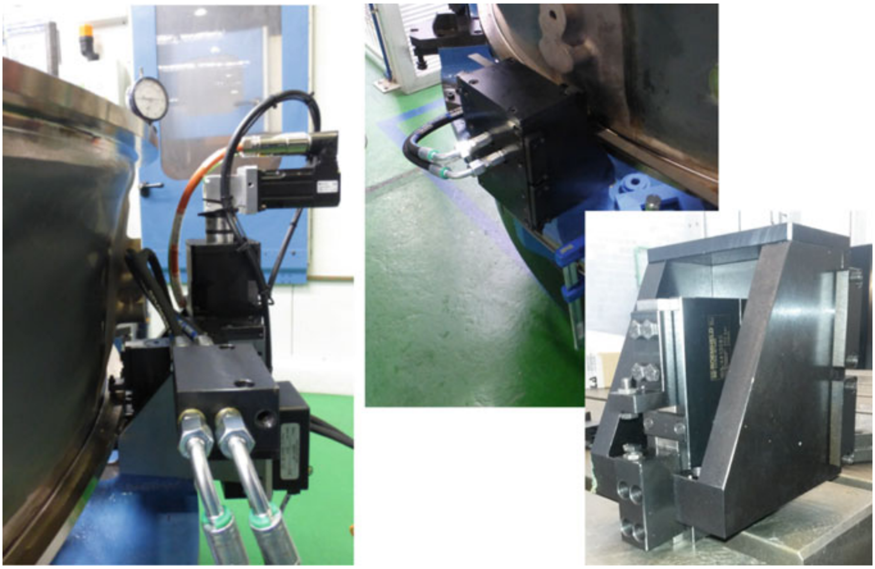

Fig. 7.14 (*Left*) System with repositioning stage. (*Right*) System without repositioning stage

The tests in the pre-setting station consisted in:

- Substitution of one of the mechanical clamps by the developed clamping unit.
- Adjust the jaws (hydraulic/electromechanic + mechanical) until correctly fix the workpiece following the usual clamping sequence of the eleven clamping elements.
- Intermediate measurements with the laser sensors to assess the workpiece deformation (clamp in the lower flange; measurement in the upper flange).

The validation tests allowed to assess the main capabilities of the clamping unit in a production environment and to evaluate the suitability of the clamping unit developed to be used in the current fixture. The main conclusions obtained are:

- Currently neither the conventional mechanical clamping nor the clamping process with the new clamping unit produces significant deformation in the workpiece, see Fig. 7.15.
- The hydraulic/electromechanical clamping unit behaviour is suitable for the application according to the specifications related to precision. This can be maintained well below the tolerance of 0.01 mm.
- The hydraulic clamping unit also meets the specifications related to precision.
- The clamping unit allows correcting the position of the clamping element to minimize an undesired deformation of the workpiece or an excessive reaction force.
- The reaction force measurement capability of the clamping unit has allowed identifying that undesired reaction forces appear with the conventional mechanical clamping unit, see Fig. 7.16.

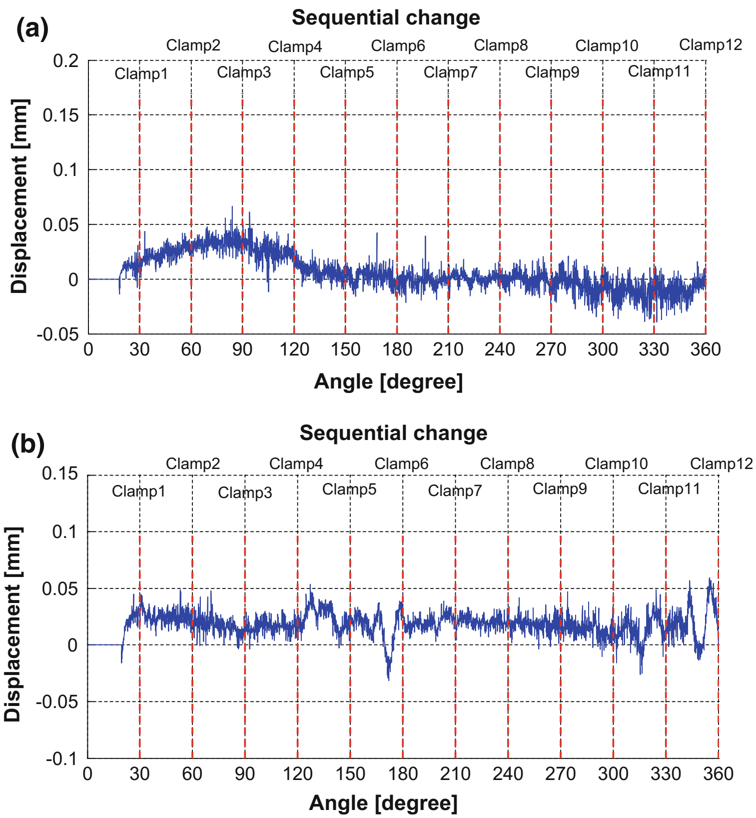

Fig. 7.15 (a) Typical incremental deformation after fixing one of the mechanical clamping elements of the fixture. (b) Typical incremental deformation after fixing the intelligent clamping unit

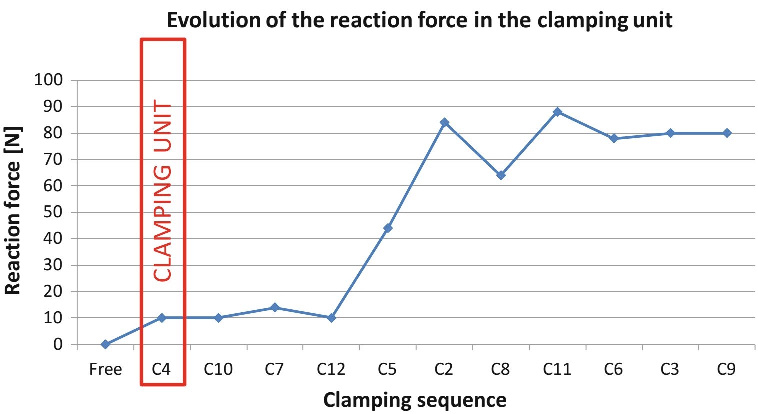

Fig. 7.16 Evolution of the reaction force during clamping process

- The conventional clamping process has several uncontrolled issues due to the manual work.
- The actuation of the hydraulic floating stage takes just 4 s, and it is independent of the number of clamping units used. Meanwhile, the mechanical clamping of the workpiece with 11 clamping elements involves between 15 and 20 min.

7.4 Summary and Conclusion

The workpiece in this case study is a structural component made by welding different forged and casted components that are machined afterwards. The welding produces deformations and distortions, so the fixture must adapt the clamping of the workpiece to avoid additional deformations and hyperstatic load states.

In order to achieve workpiece clamping without its deformation, an intelligent clamping unit was developed to be able to clamp the workpiece in a floating mode adapting the position of the clamping unit to the shape of the workpiece, avoiding the generation of hyperstatic stress states in the clamped workpiece. The capabilities of this clamping unit were tested in the laboratory and the workshop enabling the work in the planned mode and achieving a suitable result attending to the deformation of the workpiece.

The solution comprises a series of intelligent clamping units able to detect and correct the position of the workpiece, with the following characteristics:

- Integration of sensors (displacement and force) in the clamping unit to detect undesirable deformations.
- Integration of actuators in the clamping unit to counteract the deformations by modifying and adapting the position of the yaws and the clamping force.
- Achieve an automatic closed-loop position correction based on the measurement of the position and force sensors.

The main contributions of this case study to the clamping technology are these two aspects:

- Adaption of the clamping unit to the current shape of the workpiece, correcting problems with previous deformations or misalignments.
- Correction of the clamping position with an actuated movement stage controlled in close loop, able to produce known deformations or achieve a target reaction force in the clamping point.

This kind of solutions is mainly oriented to large components with complicated clamping process when deformations must be avoided to achieve a good clamping of the workpiece and a good processing during the subsequent machining. Another important aspect of this development is the automation of the clamping process that enables removing manual operations that mean a long set-up time that are also a potential source of clamping problems and errors.

Attending to the requirements of the case study and the industrial application analysed in the case study, the main conclusions of the work can be summarized as:

- The achievement of an automatic clamping and position correction based on the measurement of the displacement and reaction force in the clamping unit is enabled.
- Using the force control in the clamping unit, the reaction force in the clamping point can be controlled within ±8 N with a positioning repeatability within 0.01 mm.
- Using the position control in the clamping unit, the system can achieve a repositioning precision of 0.007 mm.
- This kind of system allows the reduction of the workpiece fixturing set-up time, being independent of the number of units. In the application of the case study the time for clamping can be significantly reduced.

This development can be used in many different applications, being the target companies those dealing with machining processes of complex and flexible workpieces; but it can also be applied to other processes like welding, metrology or complex assemblies where precision fixtures are also required because of the flexibility and deformation of the workpiece during the process.

Part III
Positioning

Chapter 8
Case Study 3.1: Fixture System for Workpiece Adjustment and Clamping with/without its Pre-deformation

Jiri Sveda, Petr Kolar, Jan Koubek and Jose de Dios

Abstract The Case Study is focused on the improvement of the productivity and accuracy of large workpieces production thought the shortening of the setup and clamping time. Current situation in the workpiece adjustment is based on extremely time demanding manual setting, when the operator has to find optimal zero point of the workpiece manually—scribing operation and to fix the workpiece. The main goal of the Case Study is the development of a low time consuming clamping system with low requirements for the operator. This objective was achieved by the development and testing of a comprehensive solution that automates the workpiece adjustment process by active fixture units with centralized control and uses a machine tool touch probe for workpiece current state automatic inspection. This approach is more effective than manual setting and also reduces the risk of errors. In addition, the developed solution allows the workpiece automatic clamping in an adjusted position and with a pre-deformation if necessary.

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DOI 10.1007/978-3-319-45291-3_8

8.1 Introduction of the Case Study

The case study deals with the manufacturing of large flexible workpieces with time-demanding clamping process. The main objective of the case study is the improvement of the productivity and accuracy of large workpiece production through the shortening of the workpiece setup time during the scribe operation and increasing the process automation and the operator safety. This includes the development of modular active clamping systems for the automatic leveling the workpiece in support points, self-adjusted clamping units with integrated sensors for workpiece support in additional points, self-adjusted clamping units with integrated force sensor for controlled workpiece pre-deformation for machining in the specific set (e.g. simulation of gravity on the train side part when machining in horizontal position) and the control software with human-machine interface.

Current situation in the workpiece adjustment is based on time demanding manual setting when the operator has to find optimal zero point of the workpiece manually—scribing operation. Especially in large machine tools, it is extremely important to do it precisely for the subsequent workpiece setup and machining. The workpiece has to be set in such a way that the machining allowance will be sufficient for the machining of all features. The main problems of the described process are the long set-up time, manual operation and the need of highly skilled operators. Furthermore, a high precision process is required in order to maintain accuracy of the component, meeting the requirements of parallelism and perpendicularity of the key surfaces in different planes.

The solution proposed in the case study is a comprehensive solution that automates the workpiece adjustment process by active fixture units with centralized control and uses a machine tool touch probe for the workpiece real position and shape identification. This approach is more effective than manual setting and also reduces the risk of errors.

The second solution deals with additional workpiece clamping and its pre-deformation if necessary. The proposed solution uses the same fixture units used for the automatic workpiece adjustment with small differences. The clamps are equipped with deformation force monitoring in order not to exceed the force limit given for the workpiece damage and a system for automatic clamping the workpiece in current state without its deformation. In addition, the system is equipped with automatic workpiece inspection for controlling the pre-deformation.

The demonstration part for the fixture system proposed in this case study is an assembly frame made of steel Ck45 and profile section of 80 × 80 × 3 mm, being the overall size 1680 × 1800 × 500 mm as shown in Fig. 8.1. The proposed positions of leveling units and additional clamping units including active vibration reducers are also shown in the figure. Based on the demonstration part parameters, the case study key performance indicators were defined in Table 8.1.

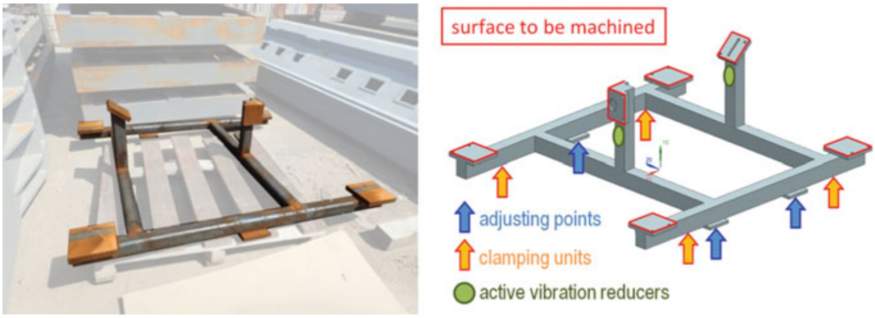


Fig. 8.1 Demonstration part for the case study and its clamping scheme

Table 8.1 Specific requirements of the fixture system—key performance indicators

Parameter	Comment
1. Minimum fixture automatic stroke: **20–50 mm**	The stroke is defined by the manual raw positioning step
2. Positioning accuracy: **0.01 mm**	The position measurement system should be integrated in the fixture for position check via the superior control system. The requested accuracy follows the requested workpiece accuracy
3. Maximum load during positioning and pre-deformation **5000 N**	This is the maximum force that consists of workpiece weight reaction and pre-deformation force
4. Maximum load during machining **5000 N**	This is the maximum machining force when the fixture units are locked

8.2 Developed Solution Overview

The automatic leveling system allows autonomous setting of workpiece position maintaining sufficient machining allowance in all machined surfaces. Manual leveling is extremely difficult and time-consuming because all surfaces for machining have to be inside the machining allowance. It means that all surfaces have to be checked. Linear translation and Z-rotation of the workpiece can be compensated in the machine tool control system directly, but other rotations have to be compensated by workpiece leveling.

The automatic leveling system computes suitable alignment of the final workpiece shape and real blank in machine tool working volume. The suitable position is implemented by coordinate system transformation and also the workpiece physical movement. The workpiece has to be aligned with a plane perpendicular to spindle axis in case of three axes machine tool because the machine tool has not kinematics for the cutting tool angle compensation as shown in Fig. 8.2. This is important to achieve a highly effective face milling process.

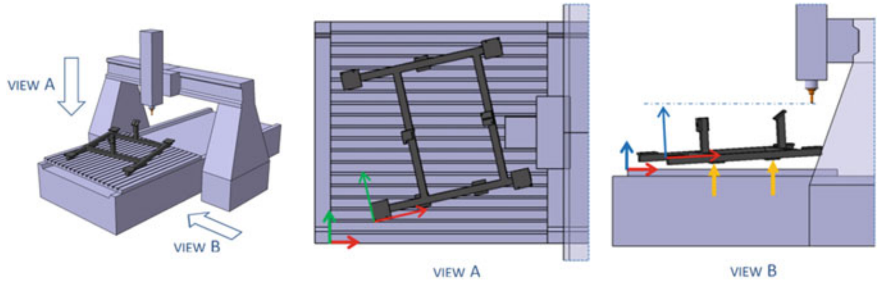


Fig. 8.2 Workpiece position on three axes machine tool—linear translation and Z-rotation of the workpiece can be compensated in the CNC, other rotations have to be compensated by workpiece leveling

A system was designed, where the rotations of the workpiece are performed by newly developed motorized leveling units (three positioning units). The current state of the workpiece is measured first; it is done automatically with a touch probe using the newly developed software that controls the machine tool movement during measurement. Then the workpiece adjustment is computed taking into consideration the machining allowance (optimization of a defined target function), and the workpiece is automatically adjusted. The workpiece is locked in this position by a number of automatic clamps for better stiffness during upcoming machining. Optionally, the workpiece can be equipped with the developed active vibration reducer (dynamic fixture) for vibration reduction in points where common fixtures cannot be used. The workpiece can also be pre-deformed by other positioning units with a similar design.

The clamping system hardware components consist of static and dynamic fixtures as key elements. The fixtures are centrally controlled by the main control unit connected with the machine tool control system. The static units are used for workpiece automatic leveling in the machine tool working volume, for workpiece clamping without deformation in desired position and for workpiece controlled pre-deformation if necessary. They are equipped with an electrically operated positioning unit including the required sensors and hydraulic clamps. The dynamic units are used for the reduction of workpiece structural vibration in points where it is not possible to use common clamps. They consist of active vibration reducers with a specific control algorithm. Figure 8.3 shows an overview of the different units and their functions.

The main control unit is equipped with the newly developed software LECLIN (**LE**veling **CL**amping **IN**spection) that implements all the functions in a PC application. The software is developed in C# language and consists of four basic modules:

- Alignment—setting of the workpiece coordinate system
- Leveling—automatic leveling of the workpiece
- Inspection—workpiece actual state measurement (deformation, geometric errors etc.)
- Clamping—control of the static and dynamic fixtures.

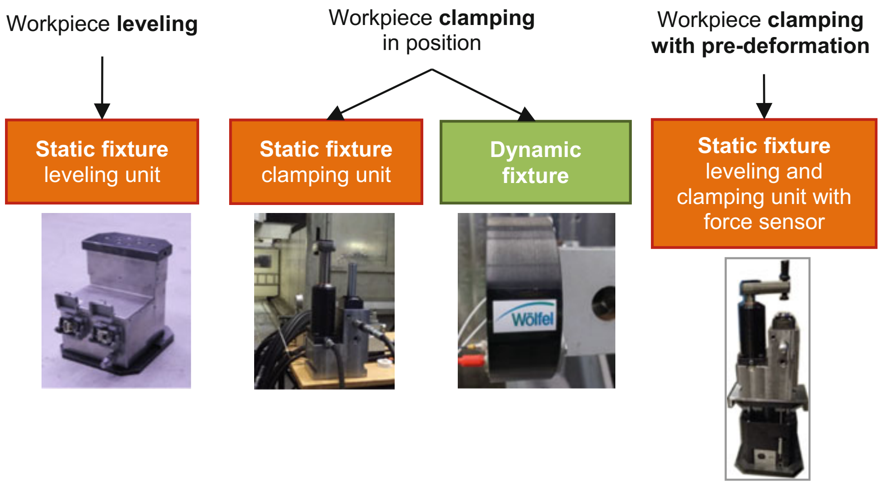


Fig. 8.3 Overview of clamping system key elements and their functions

The software includes a direct online communication with Heidenhain iTNC530 control system that allows controlling the machine tool during the workpiece current state measurement by a touch probe and sharing the machine tool corrections and other variables. It also includes a communication protocol with the internal PLC to operate the clamping units and to control the positioning.

8.3 Fixture Design

8.3.1 Static Fixture—Leveling Unit

The active leveling unit is designed as a mechanism equipped with a ball screw connected to a servo motor and a gearbox; the ball nut is directly connected with the movable part of the unit. The mechanism is also equipped with linear guideways for better stiffness and a brake located on these linear guideways. The conceptual scheme of the leveling unit is shown in Fig. 8.4.

The motorized leveling unit is equipped with a Beckhoff servomotor DC48 V/0,16 kW including an absolute measurement system, a small integrated servo drive, a worm gear unit with a ball screw, two linear guideways with an integrated controlled hydraulic brake for stiffening in target position, and a direct measurement system for high positioning accuracy. The brake is integrated in the unit body as an insert and it is hydraulically actuated. The stroke of the unit is 50 mm and the maximum loading force during movement can reach 5000 N. The positioning unit is connected to the control system using an EtherCAT bus and collective supply power. The active leveling unit is shown in Fig. 8.5.

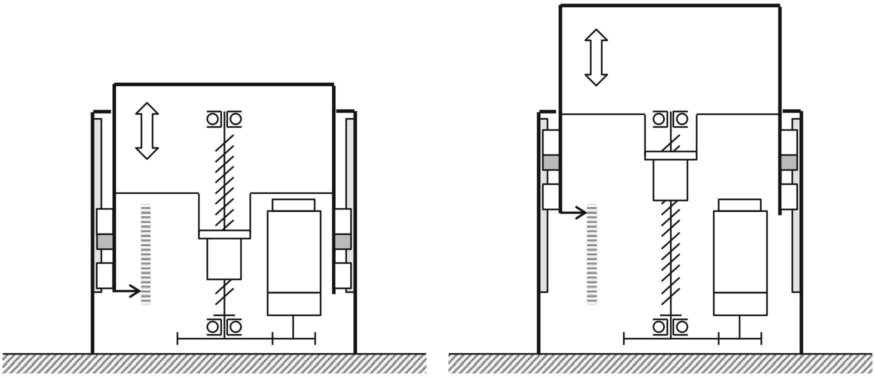
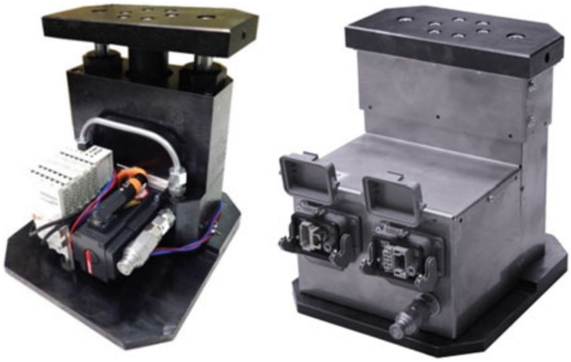


Fig. 8.4 Levelling unit mechanism conceptual scheme with an electrical servo motor and a gearbox

Fig. 8.5 The active levelling unit without and with covers



The experimental tests were performed to verify the positioning accuracy. In these, the actual position of the unit was measured with a length gauge Heidenhain ST1278. The accuracy was evaluated based on different tests including the direct and inverse movement, incremental movement in one direction and small movements. Considering the results it can be concluded that overall accuracy of the unit is ± 6 μm.

8.3.2 Static Fixture—Clamping Unit

The unit for clamping in additional points consists of two main parts and is shown in Fig. 8.6. The first part is represented by a hydraulic support that can touch the workpiece with very low contact force and it can be fixed in that position. So, it works as a locator for the workpiece in the current position without its deformation. The work support consists of a Roemheld clamp type B 1.950 [1]. The second part is represented by a swing clamp that can fix the workpiece on the work support by

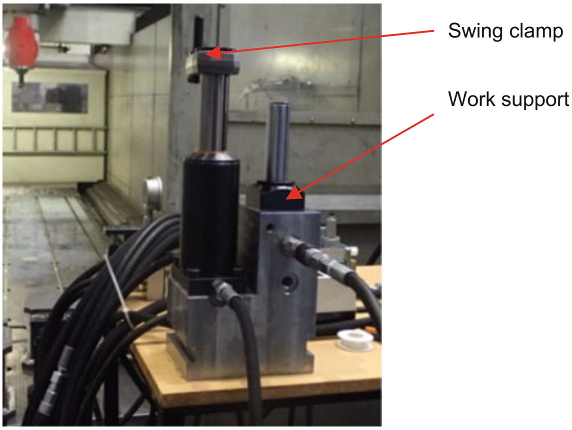


Fig. 8.6 Unit for clamping in additional points

closing the clamping force circuit. The swing clamp consists of a Roemheld clamp type B 1.881 [1].

Units for clamping in additional points without deformation are actuated by a hydraulic circuit controlled by the main control system using EtherCAT distributed IO. The hydraulic circuit is powered by two hydrogenerators: a low pressure tandem spur-gear pump pressurizes two separated lines for swing clamping units and support units respectively.

8.3.3 Dynamic Fixture

The developed automatic clamping system can provide additional stiffness and damping to the workpiece in regions close to the assembly positions. But there are regions, especially in large workpieces, where the stiffness and damping provided by the clamping devices is not enough or directly these cannot be used. These regions can change from workpiece to workpiece and machine operations.

Therefore, a portable device able to introduce some damping and improve dynamic stiffness in the structure is needed. This portable device can be placed in regions where the operator knows that vibrations are prone to occur. The Wölfel Active Vibration Reducer (AVR) is a device which can be easily transported and attached to different structures, reducing the vibrations in the region where it is located. Left-hand side of Fig. 8.7 shows the scheme of the AVR.

The AVR is a device composed of one acceleration sensor and one inertial shaker, within an enclosure which can be seen in right-hand side of Fig. 8.7. This device can be attached to a vibrating structure and it modifies the mechanical impedance of the structure, thus reducing vibrations. Only two cables are needed, one for the sensor signal, and one to drive the actuator. The size and weight of this device allows transportability.

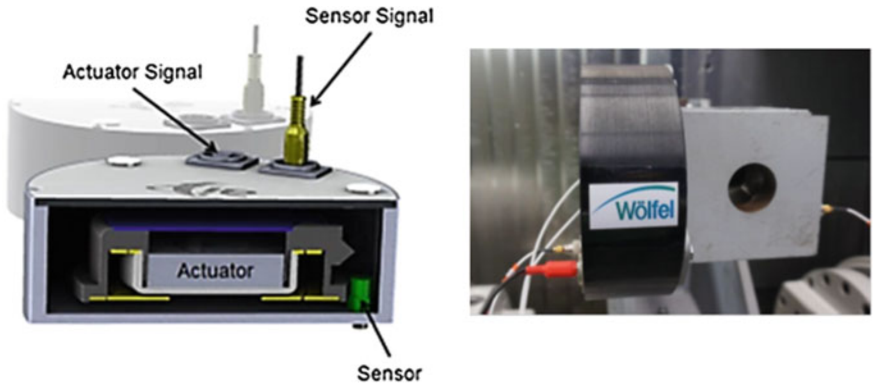


Fig. 8.7 Scheme of the AVR (*left*) and laboratory tests (*right*)

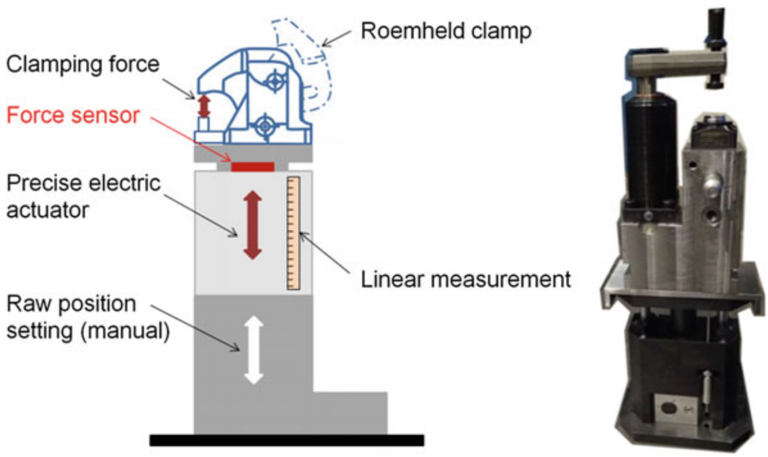


Fig. 8.8 Scheme and photo of the unit for workpiece pre-deformation

8.3.4 Static Fixture for Clamping with Pre-deformation

This system is almost identical to workpiece leveling unit and it is used for controlling the pre-deformation of a workpiece. Compared to the previous design of the leveling unit, the active positioning unit is equipped with a force sensor and clamping part (see Fig. 8.8). The force sensor is integrated between the ball screw nut and the movable flange which is fixed by guideway (guide bars) with a hydraulic brake. The advantage of the solution is the possibility to perform an accurate measurement of the deformation force during a movement and immunity to high load force after the workpiece clamping. The force sensor is bypassed by the braked guide bars in this case and a danger of the sensor destruction by high cutting force is minimized. Implementation of the force sensor inside the positioning unit is shown in Fig. 8.9.

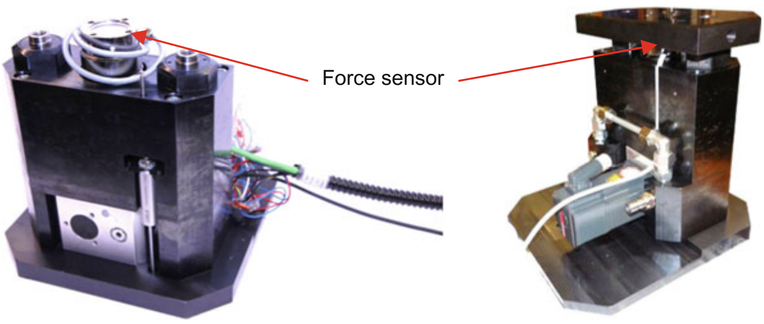


Fig. 8.9 Unit with force sensor for pre-deformation force measurement and control

8.4 System Integration

The whole clamping system control scheme is shown in Fig. 8.10. It consists of the main electrical cabinet with the main control PC (Beckhoff industrial PC) and I/O for control of static fixtures, dynamic fixtures, hydraulic circuit, portable screen with software LECLIN and connection with the machine tool control system. The main control PC is connected with I/O and also with the static fixtures (positioning and clamping units) by a real-time EtherCAT bus. It allows decreasing cost demands for each static fixture because the regulation is located in the central unit. The main control PC is also connected with the machine tool control system Heidenhain iTNC530, dynamic fixtures and remote operator screen by EtherNET.

The automatic workpiece leveling module of the developed software LECLIN is shown in Fig. 8.11. It consist of a 3D window with a CAD model of the workpiece and a menu toolbar. The machine tool and the clamping system are controlled by the software during the leveling. The real movement of the machine tool is shown in the 3D window simultaneously.

The complete leveling technique in LECLIN software is shown in Fig. 8.12. Identification of the workpiece position in the machine tool working volume is performed first. It is done by moving the machine tool with the touch probe manually to the highlighted points (Fig. 8.12—1).

The workpiece is aligned in the machine tool coordinate system (Fig. 8.12—2). Automatic measurement of the surfaces designated for machining is performed after workpiece position identification (Fig. 8.12—3). Then, the real shape of the workpiece is shown by the green volume on the CAD model to identify the allowance (Fig. 8.12—4). Next, a comparison of the reference planes from NC code (red color) with real workpiece material volume can be done (Fig. 8.12—5). Optimization of the workpiece position in the machine tool working volume is performed based on these data. If the position of the workpiece is suitable for machining, the red planes are located inside the green volume (Fig. 8.12—6). The translation of the leveling units and corrections of the machine tool control system can be activated directly.

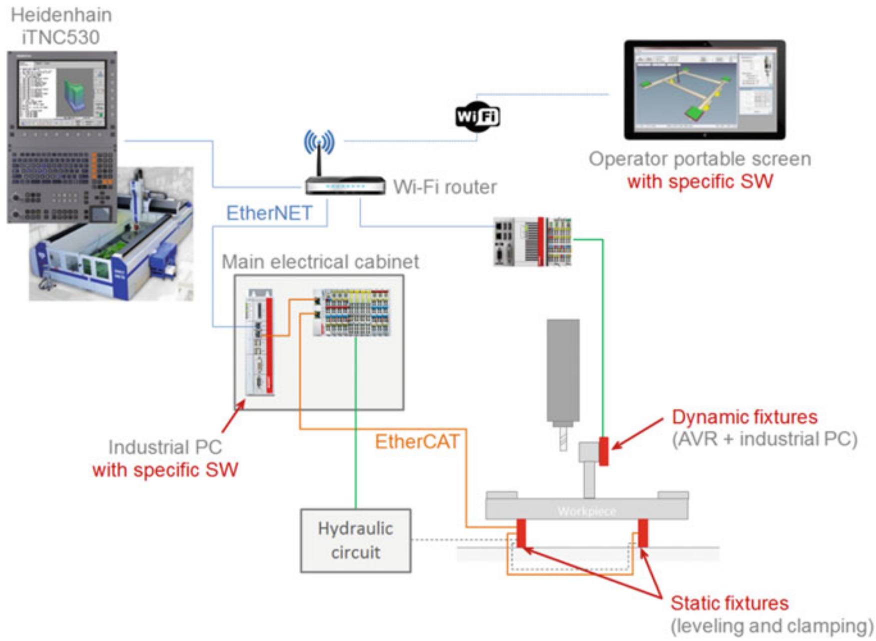


Fig. 8.10 Communication and connection scheme of the system

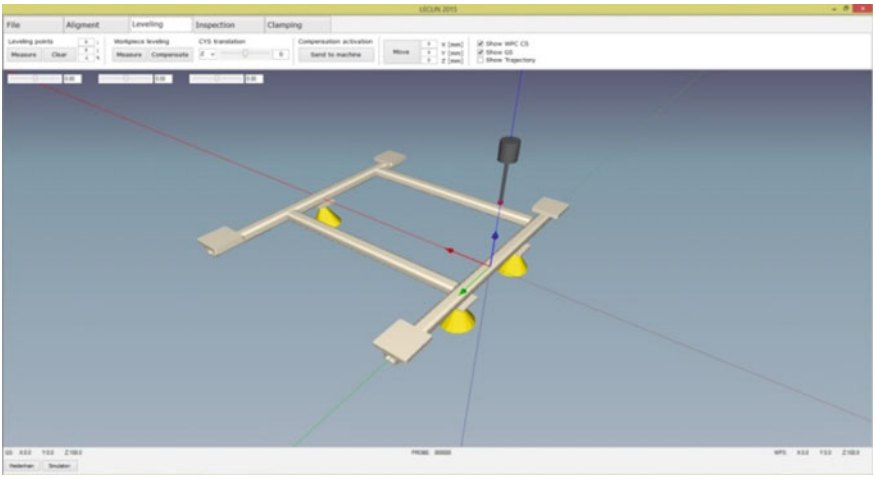


Fig. 8.11 Developed software LECLIN for automatic workpiece levelling

The workpiece inspection system is another module of the developed software LECLIN. Its main use is associated to the pre-deformation of the workpiece. This module allows inspecting the real shape of the workpiece directly in the machine

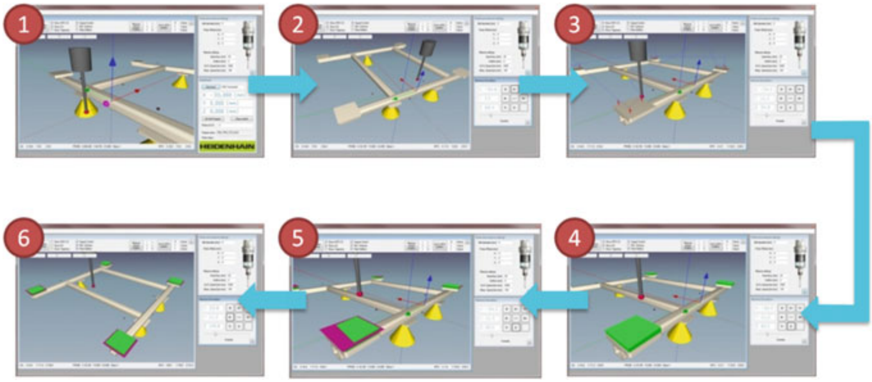


Fig. 8.12 Levelling technique in the developed software

tool working volume with the Heidenhain control system. It helps with the definition of the pre-deformation movement to be carried out by clamping unit. The developed software module consists of a 3D window with a CAD model of the workpiece where the results from measurement can be shown. The measured trajectory is set by the input file with demanded points and directions.

All the designed clamps are also controlled by the developed software LECLIN in the module "Clamping". It allows manual control of leveling units and activation of clamping units for clamping without deformation, with controlled pre-deformation and also dynamic fixtures.

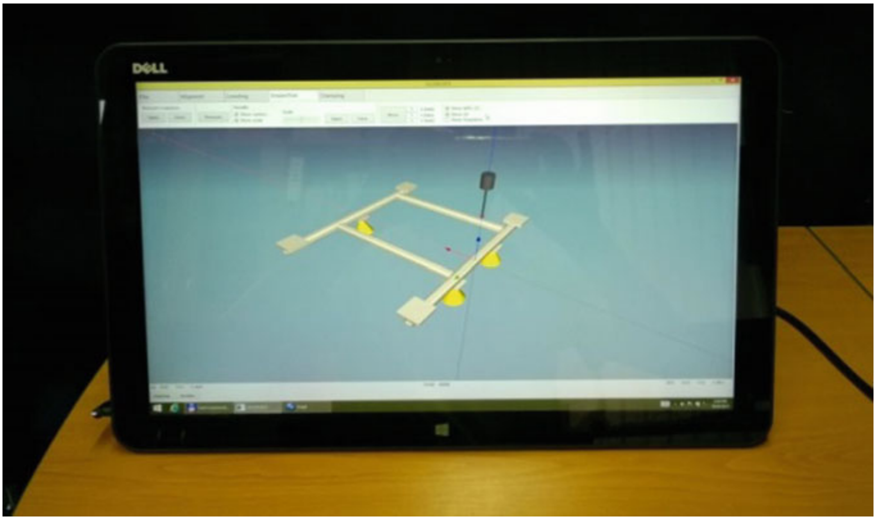


Fig. 8.13 LECLIN control software with HMI on operator portable PC

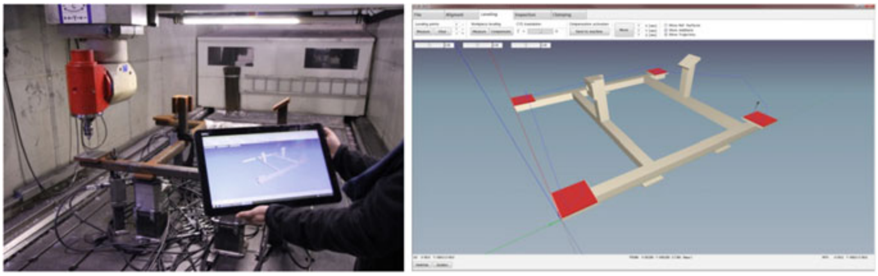


Fig. 8.14 Testing configuration of the fixture system in the machine tool and clamping system control by portable PC with software LECLIN

The developed software can be installed directly in the main control PC and visualized by standard industrial display or by an operator portable PC that allows remote control of the clamping system using WiFi communication. The interface of the software installed in the portable PC is shown in Fig. 8.13.

8.5 Validation under Real Conditions

Leveling and clamping tests were performed with the demonstration part on a TYC FPPC 250/6 CNC machining center with a Heidenhain iTNC530 control system. The final demonstration part is an assembly frame made of steel Ck45, section profile of 80 × 80 × 3 mm, and overall size of 1680 × 1800 × 500 mm. The final demonstration part in the machining center equipped with the developed clamping system is shown in Fig. 8.14.

Fig. 8.15 Demonstration part machining

The workpiece leveling and clamping tests have followed different steps controlled by the designed software LECLIN:

- Identification of rough workpiece position in the machining volume, performed with a touch probe in manual mode, operator is guided by LECLIN.
- Automatic identification of the workpiece current state, all surfaces for machining are measured by touch probe.
- Automatic optimization of the workpiece position, all surfaces for machining are fitted to the current workpiece volume, movement of active leveling units is computed.
- Setting of suitable machining allowance and activation of active leveling units movement (see Fig. 8.14 on the right).
- Optionally checking of the leveled position by the automatic identification cycle mentioned above.
- Clamping of the workpiece in additional points without deformation and start machining (see Fig. 8.15).

The whole process of leveling and clamping the demonstration part was performed in very short time, approximately 15 min including rough workpiece position identification with operator movement. Conventional leveling, scribing and clamping operation of the demonstration part took about 45–60 min depending on the operator skills in case of the demonstration part.

The pre-deformation test was performed in a machine tool where the workpiece was deformed. The workpiece was deformed in defined steps; the deformation force measured by the internal force sensor and the servomotor torque were observed as shown in Fig. 8.16. It was evaluated that the pre-deformation error didn't exceed 10 μm and the pre-deformation force identification accuracy is in the tens of Newton using the direct force sensor inside the positioning unit. The deformation force computed from the servo motor torque is not suitable for precise monitoring of these aspects in the workpiece.

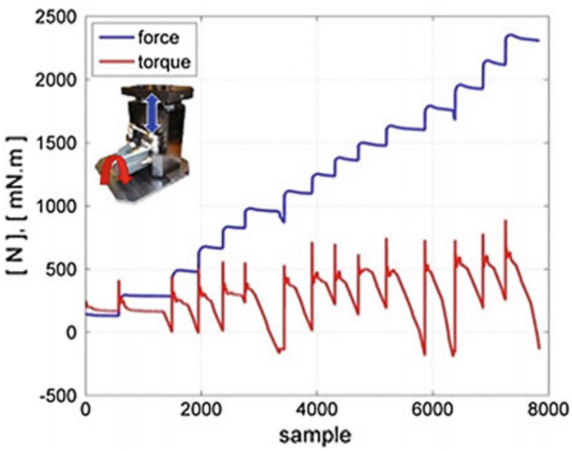


Fig. 8.16 Deformation force measurement by internal force sensor and servo motor torque

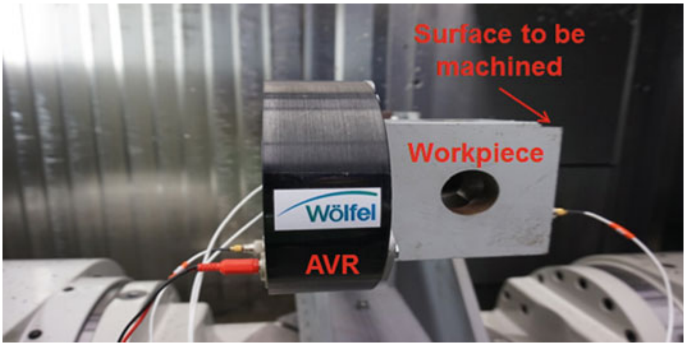


Fig. 8.17 AVR testing in machine tool

The dynamic fixture (Active Vibration Reducer—AVR) prototype functionality was tested on a machine tool under real conditions as shown in Fig. 8.17 applying different cutting conditions. After the previous set of measurements, the modified multi-tonal control algorithm was adapted and new parameters were applied. The random behaviour of the cutting operation led to difficulties in analysis, if only the acceleration signals were checked. Therefore, not only the time signals were analysed, but also the surface quality was checked by inspection using surface roughness gauges.

The average roughness of the uncontrolled part is Ra = 1.22 μm; whereas the average roughness of the controlled part could be decreased to Ra = 0.72 μm. In general, the measures to increase the surface quality depend on the designer requirements. It can be concluded that using the AVR, tighter design requirements could be fulfilled without modification of the machining process. The time signal of the acceleration values was monitored too, the acquired data can be seen in Fig. 8.18, being the red curves those of the uncontrolled operation and blue curves those of the controlled operation.

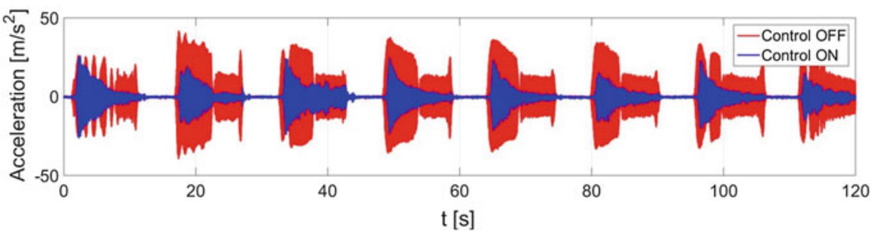


Fig. 8.18 Cutting at 5000 rpm with one cutting edge. Several consecutive paths machined. Control with modified feedback control. Accelerations measured with control OFF (*red*) and with control ON (*blue*)

Table 8.2 Case study results compared with key performance indicators

Parameter	Requirements	Developed solution	Status
Minimum fixture automatic stroke	20–50 mm	50 mm	**OK**
Positioning accuracy	0.01 mm	0.006 mm	**OK**
Max. load during positioning and pre-deform	5000 N	5000 N	**OK**
Max. load during machining	5000 N	>5000 N	**OK**

Table 8.3 Case study results

Parameter	Existing solution	Developed solution	Comparison
Solution	Manual workpiece leveling	Automatic workpiece	
Total price	EUR 5500	EUR 10,200	**+85%**
Idle time	60 min	15 min	**−75%**
Investment return period	42 pieces with the same number of units		

8.6 Summary and Conclusion

The presented case study demonstrated the benefits of automatic workpiece adjustment and clamping system in of the selected demonstration part. The main KPIs are compared with the results obtained in the demonstration part in Table 8.2. As can be seen, the proposed solution fulfils all KPIs and enables precise positioning and clamping of large workpieces. The main results of this case study are shown in Table 8.3 where the time reduction for the demonstration part is highlighted. It was achieved a saving of 75% in adjusting and clamping process time. Despite the fact that the initial investment is relatively high, the proposed leveling and clamping system is cost-effective. The key financial benefit is the ability to reduce clamping time significantly and an universal design suitable for different types of workpieces, so the return of investment can be rapidly achieved.

Reference

1. Römheld GmbH Product catalogue. Available on-line. http://www.roemheld.com/EN/ (2016)

Chapter 9
Case Study 3.2: Semiautomatic Tool Reference for Application on Large Parts

Jose Zendoia, Harkaitz Urreta, Alberto Mendikute and Ibai Leizea

Abstract For large parts machining, workpiece set-up is a time-consuming and usually an error prone process. Large parts of unitary or very small batches are located in the machine using previously designed references in its surfaces according to machining specifications (marking out process). Both, the marking out process and the alignment in the machine are normally manual processes. The part has to be aligned according to machine axes. This process is done normally for each workpiece using touch probes or dial indicators. Zero point systems are conventionally not used in large parts machining. A 3D metrology system based on photogrammetry technology has advantages with respect to the marking out process: quick response, high precision in the captures, and the easiness to use. A photogrammetric application was developed here with the goal of producing parts with minimum material removal. An on-board solution was developed to control positioning of the part in the machine according to photogrammetric application requirements. Also, a kinematic alignment table was developed with the ability to rotate in three degrees of freedom simplifying the alignment process of the part in the machine. Finally, the developed system was validated in an industrial environment.

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9.1 Introduction of the Case Study

For machining large rough parts, the set-up is a time-consuming and non-efficient fixation process [1]. For large prismatic parts (Fig. 9.1), the set-up time is of the same order of magnitude than the machining process time itself, ranging from half an hour to several hours of alignment time.

Large part alignment according to the machine translational axes is a complex and manual task. The traditional process comprises at first that the rough part is marked out according to machining allowances (excess of material to be cut). The rough part is positioned on a surface table and by means of scribers, blocks, indicators, punches or compasses some datum or references (fiducials) are marked in the rough part. Once the datum are defined in the marking out process, the part is aligned according to the machine axes. Zero-point clamping systems are not used for large prismatic parts (very small batches or loose units). Therefore, workpiece alignment in-machine is necessary for each unit. Using dial indicators or machine touch probes incorporated in the machine spindle, the rough part is measured with reference to the machine axes (using the previously defined datum) and the part misalignment is obtained. This part misalignment error value is used to orientate the part. The orientation of the part is a manual process. The part is aligned using clamps and fixtures as for example steel studs or variable locating feet supports. This process (measurement + alignment) is repeated until the alignment of the part's fiducials or marks is achieved in respect to the machine axes (Fig. 9.2).

Fig. 9.1 Large prismatic part in a milling machine

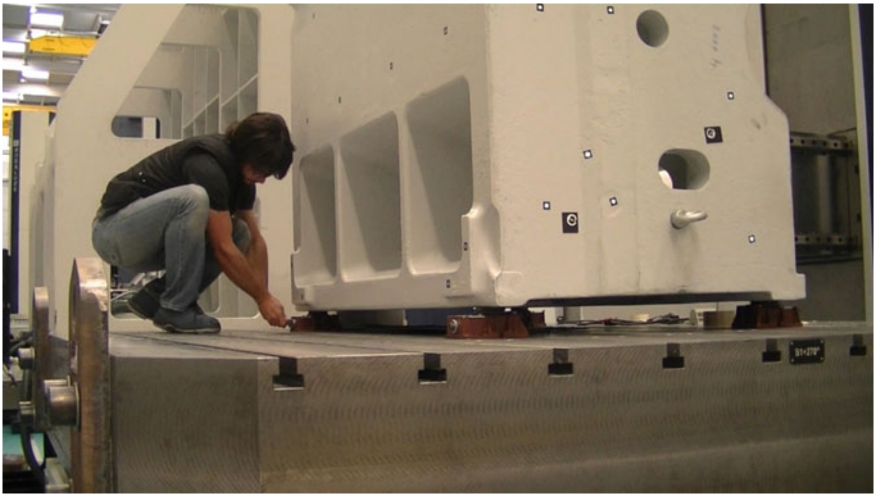

Fig. 9.2 Manual alignment of a workpiece in a milling machine

The case study described here is to define a new system which can be integrated in a milling machine. The system should allow an automation of the first positioning of a workpiece in the machine simplifying the complex and time consuming task of alignment of the workpiece. Alternatively to the marking-out process, photogrammetric measurement was implemented to define corresponding references at the workpiece. This technology is less time consuming and can provide the best fit between the finished and rough parts volumes. Alternatively to the dial indicators or touching probes, a 3D vision system was utilized. Using references as coded targets, part misalignment was measured using a novel vision system measurement procedure. Alternatively to the manual alignment process using variable feet supports, a 3 DoF tilting table was developed.

The specific functionalities and requirements of this case study are:

- Out-of-machine photogrammetric process for characterisation of the raw part's 3D geometry.
- Software for alignment of the characterised 3D geometry. Alignment is computed minimising the amount of excess material to be machined and ensuring that no surfaces have material shortages.
- On-machine photogrammetric process for measurement of the misalignment between the part and the machine's axes.
- Integration of a three tilting axis table in a three translational axis machine for automatic first alignment of the workpiece with the following design specifications:
  - Precision of the Table 0.1 mm/m
  - 3 Degree of Freedom (3DoF) table Parallel kinematic table with maximum stiffness and compactness

– Amplitude of rotary angle stroke, up to ±1.5° (±26 mm/m)
– Mass on the table, max. 5 t with a preload of the table with clamping fixtures using a force of max. 15 t.

The photogrammetric process consists of the 3D reconstruction of a set of points of the workpiece, marked with attached fiducials on its surfaces. The point positions in space are computed from a set of photographs of the workpiece, taken at multiple positions and orientations. As well as the fiducial markers, the workpiece should be previously equipped with a reference cross—which marks the reference coordinate system—and calibrated scale bars which provide reference lengths for correct dimensioning of the reconstructed scene.

The system was designed to obtain uncertainty levels of 0.5 mm or less, for which the use of self-calibration algorithms is crucial [2]. In addition, auto-guidance features were implemented to prevent operator errors and reduce measurement time which should be kept below 30 min, including time spent for fiducial attachment, photograph acquisition and 3D reconstruction.

The software for workpiece optimum alignment was developed to be able to decode the machining trajectories contained in a standard CAM file in order to minimise part geometry interpretation and dependence on the operator for the optimal alignment computation. The software was developed providing the most efficient algorithms available in order to reduce processing time below a couple of seconds. Furthermore, additional development effort was made to reduce the dependency on the initial alignment point, which is a notorious weakness of geometrical alignment algorithms of this kind.

The software receives two inputs: a 3D point cloud of the workpiece geometry—produced by the out-of-machine photogrammetric system—and a CAM file containing the machining plan. The software then computes the optimal alignment between the workpiece geometry and the CAM data, ensuring that

1. no surfaces have shortage of material (the amount of excess material must not fall below a threshold set by the user) and
2. the distribution of excess material must be kept to its minimum possible levels across all surfaces to be machined.

After fixation of the workpiece—to a separate baseplate or directly to the machine table—an on-machine photogrammetric process is expected to measure the part misalignment with respect to the machine axes. This is computed with respect to the optimal alignment obtained with the alignment software and it will be used later as a reference signal for the active fixture system for correction of the 3 alignment angles. The core of the on-machine process is a spindle integrated 3D vision system for measurement of the 3D coordinates of a set of fiducial markers attached to the workpiece.

The spindle integrated system should meet the following design criteria:

- Standard interface for spindle integration (ISO and/or HSK).
- Measuring time for each fiducial marker of 2 s or less.
- Measuring process automation from the CNC program, compatible with Siemens and Heidenhain CNC models.

9.2 Photogrammetry System

The first step of the photogrammetric process is the targeting, as the mounting of reflective targets on the part surfaces. These targets are designed so that they can be easily identified by the image processing software and they are made of a highly reflective material. Targets can be of two different kinds: coded and non-coded (Fig. 9.3). Coded targets have associated an individual number which can be automatically read by the image processing software. Each coded target is unique—two different targets cannot have the same code in the scene—and they provide the necessary information to determine the part's location and orientation as well as the camera's pose in the moment that a photograph is taken. In addition, non-coded targets are placed on the part's surfaces. These markers have no code and are indistinguishable from each other, so specialised software methods are needed to calculate their position. Their purpose is to mark all surfaces of interest, providing the necessary information to reconstruct their geometry.

The developed markers identification algorithm is executed in the second step of the photogrammetric process, which is the incremental adjustment (Fig. 9.4). This is a continuous process which runs at the same time as photographs are taken. As soon as a new photograph is acquired, a WiFi transmitter sends it to a host computer which takes the new photograph, detects its markers and adds the new data into the point cloud reconstruction, adding new points or refining the positions of already reconstructed ones. If the process fails at some point, an auditory signal is sent to the operator, who is warned that the last photograph should be repeated.

The core of this stage is the algorithm known as bundle adjustment, widely used among photogrammetric software. Basically, this algorithm makes a simultaneous

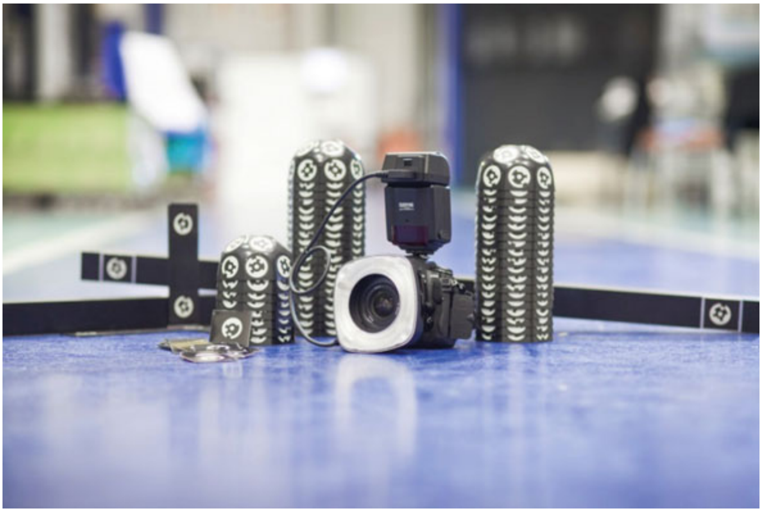

Fig. 9.3 Markers and a photogrammetric camera

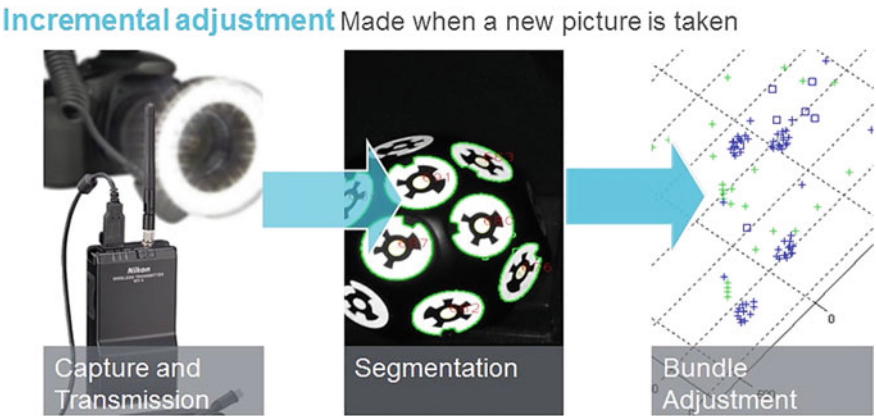

Fig. 9.4 Capture of image, and treatment for markers detection

optimisation of the markers' coordinates and the camera poses by minimising the re-projection error. The latter is the difference between the segmented markers' coordinates and the projections of the reconstructed 3D points onto the image planes.

9.2.1 *Software for Minimisation of Material to be Removed*

In this task the activity was focused in the model to align and fit the parts in the machine axes in order to ensure that there is material to cut in all machining surfaces and also the optimization of material removal to reduce machining time. The main work was the modelling for optimization of the overstock distribution. In Fig. 9.5 a screenshot of the proprietary software is shown. The calculation of overstock is shown in control points with colour dots.

The core of the process is the ICP algorithm (Iterative Closest Point) [3]. The ICP algorithm generates transforms which minimise the distances between the cloud points and the CAM surfaces. However, this transform may not meet the sought criteria in terms of overstock, generating solutions with lack of material in one or more zones. Therefore, the point cloud should be adjusted to ensure that positive overstock is present on all points. The computation of this transform is made via the Minimum Overstock Transform (MOT) algorithm.

9.2.2 *On-machine Photogrammetric Process for Measurement of the Misalignment between the Part and the Machine Axes*

There are two alternatives to take the photographs of the raw part. In Fig. 9.6 a set of photographs of the workpiece is taken outside of the machine and after using a set of references, the part is located in the machine.

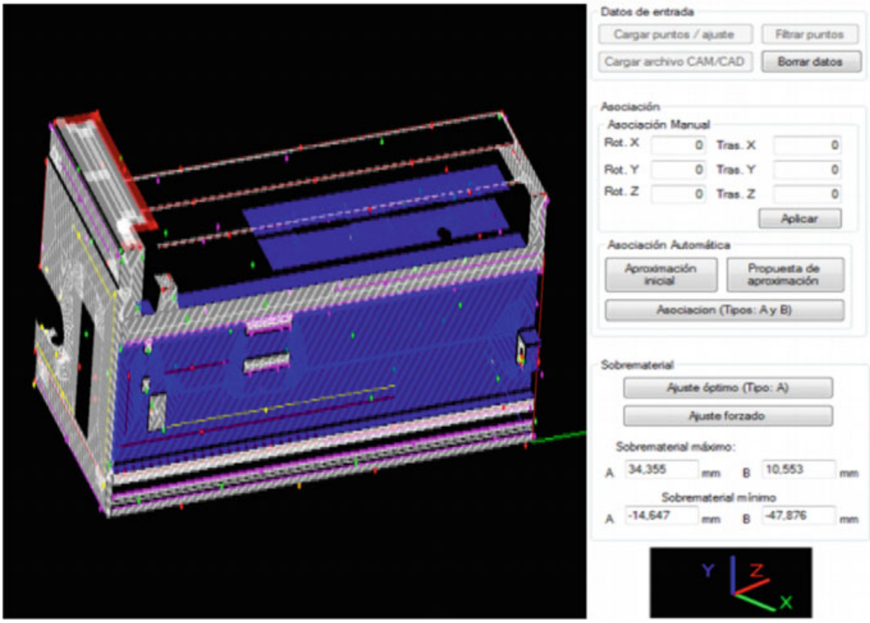

Fig. 9.5 Capture of image for calculation of overstock software

Fig. 9.6 Out-of-machine photogrammetry setup

For the cases when on-machine measurement has to be carried out, an on-board camera system was developed. This camera is clamped like a tool (using standard systems like ISO tappers or HSK). The image is captured by an external software, that is synchronized with the machine, from different points and orientations, using the axes of the boring or milling machine. The information is sent by WiFi

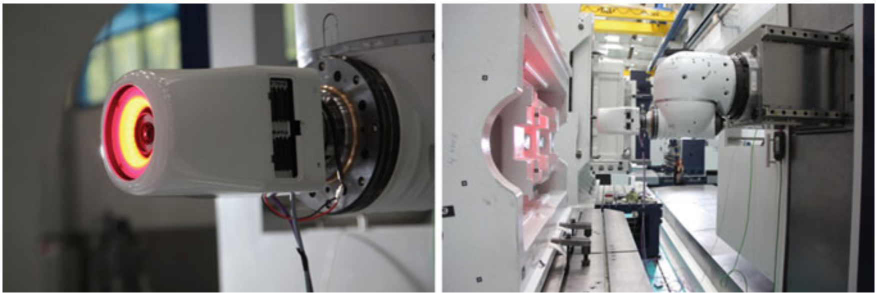

Fig. 9.7 On-machine photogrammetry set-up, developed WiFi camera clamped to working head

connection to the laptop where the photogrammetry software is running. The results are analysed by the operator.

In Fig. 9.7 the camera mounted in the working head of a milling machine is shown. This setup is very useful for applications where a full automatized solution is demanded, being the machine who takes the pictures and set up the large parts at the table.

The 3D metrology system based on photogrammetry technology has three main advantages: Agility in the measurement (quick response), high precision in the captures, and finally the easiness to use with incremental adjustment method, making it able to be used by any kind of operators without experience in photogrammetry. The basic algorithms and adjustment bundle was resolved and two main applications was developed:

- Large parts measurement and adjustment with CAM program. Optimization of material to be removed.
- On-machine implementation of photogrammetry system with an on-board camera solution.

9.3 3-DoF Alignment Table Design and Fabrication

In addition, a 3-DoF alignment table was developed. The table is able to rotate in the three degrees of freedom, aligning the raw large part with the coordinate system (X, Y and Z axis) of the machine itself. The table was designed with hydraulic actuators and inductive extended range sensors to close the control loop. The kinematic of the table is parallel, with high compactness of the system, able to be used in a large range of milling and boring machines. To increase the stiffness and load capacity of the table, four clamping cylinders are used in the corners of the table.

After setting requirements based on photogrammetric specifications, different design options were analysed and a consistent design option was selected where the architecture is a parallel kinematic mechanism together with hydraulic actuators and

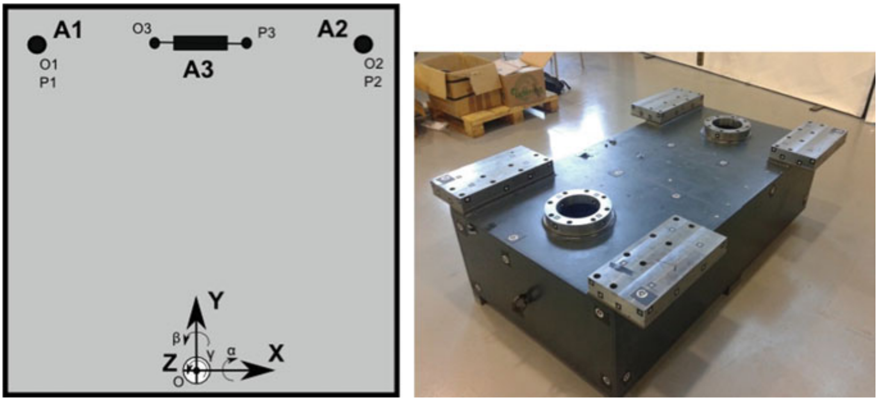

Fig. 9.8 *Left* Basic mechanism of the alignment table. *Right* Demo part

close loop control. In Fig. 9.8 (left), the scheme of the mechanism is shown. There are three actuators (A1, A2, A3). One end of each actuator is fixed to the machine base (non-movable) (O1, O2, O3) and the other end is in contact with the table (movable) (P1, P2, P3). The contact between actuators and movable table is using spherical bearings to allow different movements of the table. The movable table is pivoting in Z with a spherical bearing with some degree of tilting ability. The table rotates around Z, using the movement of the actuators. These are the rotations:

- rotation around X; movement is created using A1 and A2 synchronized actuators.
- rotation around Y; movement is created using A1 and A2 synchronized actuators (movement of A1 and A2 in opposite directions).
- rotation around Z; movement is created using A3 actuator.

In Fig. 9.8 (right) the demo part used in the project to demonstrate the alignment process is shown.

In Fig. 9.9 two 3D models of the final design of the table are shown. In the models, the demo part is fixed to the table using the clamps. The table is located in the T slotted machine tool frame. 8 work-supports are used to block the table after positioning. By means of a mechanical spring, the work-support end is always in contact with the bottom of the movable table. After positioning the work-supports are blocked hydraulically. When the work-supports are blocked, the positioning cylinders pull down the movable table, stiffening the system. All the actuators are controlled using hydraulics.

In Fig. 9.10 a photograph of the table assembly process is shown. Main elements are the spherical bearing Z (pos. 1) which is located in the white pillar as it can be seen in the Figure, A1 actuator (pos. 2) with its measuring sensor, A2 actuator (pos. 3) with its measuring sensor, A3 actuator (pos. 4) with its measuring sensor and 8

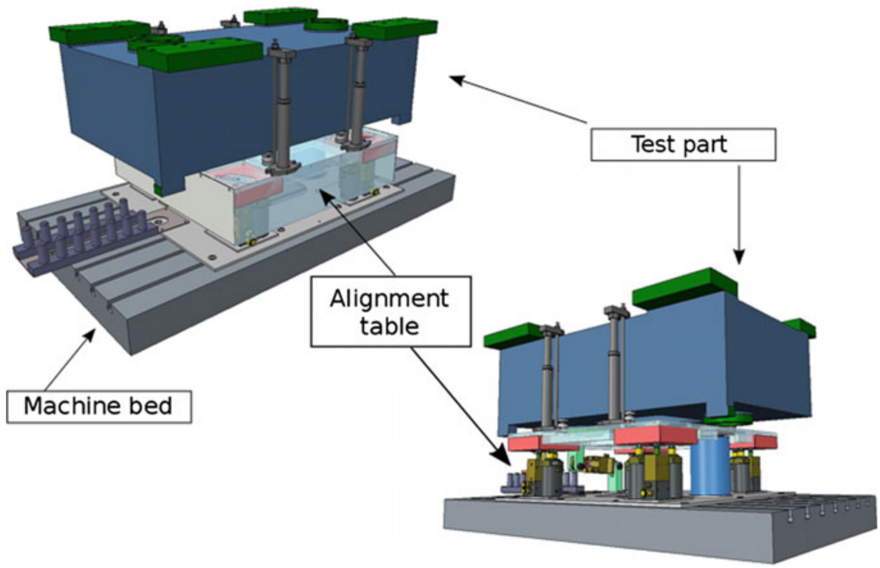

Fig. 9.9 3D Models of alignment table

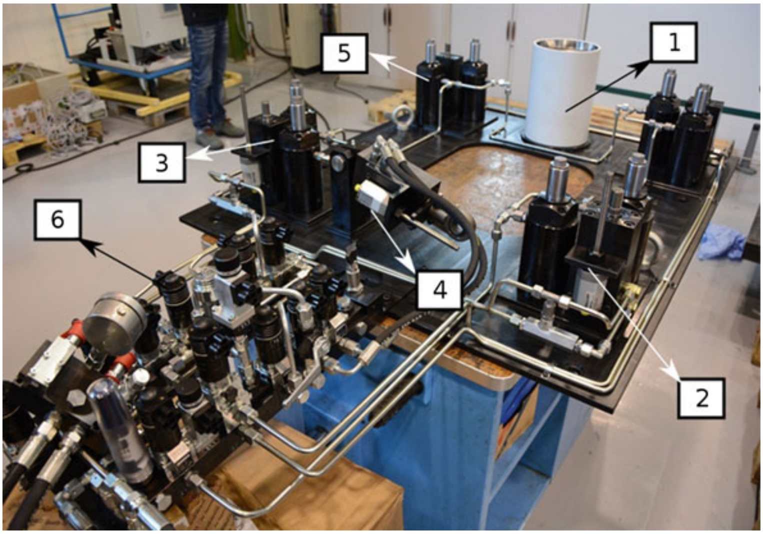

Fig. 9.10 Picture of alignment table assembly process

work-supports (pos. 5). Hydraulic valves, tubes and piping are assembled to the table (pos. 6), meanwhile hydraulic pressure units are not shown in Fig. 9.10. In Fig. 9.11 the final result of the mechanical assembly is shown.

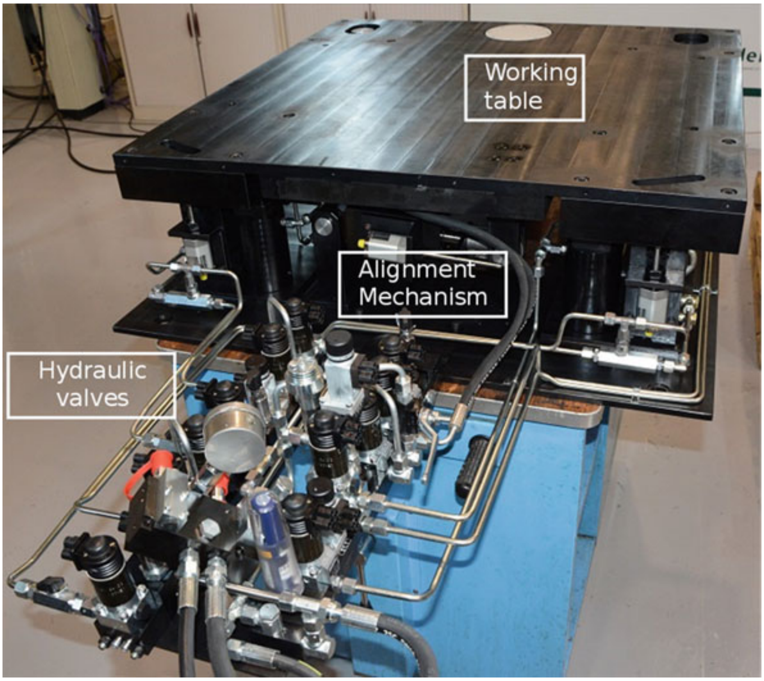

Fig. 9.11 Picture of alignment table after assembly

9.4 3-DoF Alignment Table Control

As mentioned in the previous section, the architecture of the adaptive alignment table is based on a parallel kinematic Therefore, a model to implement the control was derived. In Fig. 9.12, the model for the simulation of the movement of three actuators in the space for a given displacement of the rotary axes is shown. Looking at each degree of freedom, the simulation of the movement for a 15° rotation (10 times more than the real stroke for a better view of the effect) is represented in Fig. 9.13.

In Fig. 9.14 calculations in 3 DoF [β rotation angle is 1°; γ rotation angle is 1°; α rotation angle varies (0°, ±0.5°, ±1°, ±1.5°)] and α, β, γ errors are shown. The α errors are displayed in the first range of columns, the β errors are displayed in the second range of columns and the γ errors are displayed in the third range of columns.

9.5 Verification and Validation

The complete system was tested including the automatic location of the part and the system for minimisation of machined material.

$$Input: Correction\ Angles(\alpha, \beta, \gamma)$$

$$(\alpha, \beta, \gamma) \rightarrow \text{Rotation Matrix}[R] \rightarrow \text{New Points} \begin{pmatrix} P_1' \\ P_2' \\ P_3' \end{pmatrix}$$

Initial lengths:

$$A1 = \overline{O_1 P_1} \qquad A2 = \overline{O_2 P_2} \qquad A3 = \overline{O_3 P_3}$$

$$Output: \text{Commands for the actuators } (\delta_1, \delta_2, \delta_3)$$

$$\delta_3 = O_3 P_3' - A3$$

$$\delta_1 = \overline{O_1 \Pi_Z^1} - A1$$

$$\delta_2 = \overline{O_2 \Pi_Z^2} - A2$$

Being Π a plane that contains the points (O, P_1', P_2')

Fig. 9.12 Mathematical model for actuator movement in parallel kinematic architecture

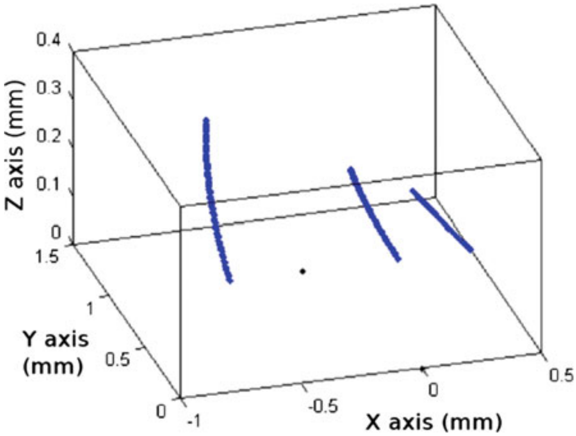

Fig. 9.13 Simulation of actuators in parallel kinematic architecture for 15° in each rotary degree of freedom

All those tests for validation were carried out in a manufacturing company using parts to be machined in the production systems. In Fig. 9.15 one of the parts used in the validation is shown. In this case, the workpiece is a column for a Gantry type machine. It can be seen how the markers are located and photographs taken outside

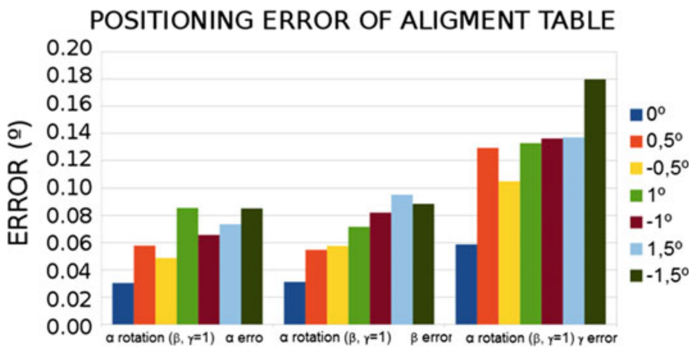

Fig. 9.14 Determination of α, β, γ errors based on 3-DoF rotation: α rotation (β = 1°, γ = 1°)

Fig. 9.15 Validation of system with gantry type machine column: characterization (*left*), screenshot of application for adjustment and calculation (*right*)

of the machine. The maximum and minimum overstock material is calculated and a specific first alignment of the part with respect to the machine is obtained. In Fig. 9.16 another example is shown. In this case, it is a machine column with its markers. The software calculates a best first alignment of the workpiece in the machine to avoid any leak of material for machining (negative values of overstock) or excessive overstock for machining. In Fig. 9.17 the validation of the on-machine solution is shown, where the part is measured directly using the machine axes.

Fig. 9.16 Validation of system with grinding machine column: characterization (*left*), screenshot of application (*right*)

Fig. 9.17 Raw part located on the machine table with markers

9.6 Summary and Conclusion

The main results achieved in this case study are:

- A 3D metrology system based on photogrammetry technology was developed and validated. The system was validated in a manufacturing environment with different real workpieces as described in previous sections. Algorithms and software were developed to create a 3D point cloud of the workpiece geometry using photogrammetric markers. The main application of this system is the optimal alignment between the workpiece geometry and the CAM data ensuring that there is no shortage of material or excessive material for machining. Finally an on-board camera solution for applications where a full automatized procedure is demanded was developed.

- An alignment table to support photogrammetric results was designed and constructed. The design of the table was a cooperative design activity between a manufacturing company, a hydraulic actuator supplier and photogrammetric technicians. Several conceptual designs were evaluated and one specific solution was developed. The alignment table has 3 Degrees of Freedom and it is able to align the workpiece in relation to the three rotation axes. The movable part of the table pivots around a spherical bearing and three hydraulic actuators controlled by LVDT sensors create the movements for rotations around that spherical bearing. After alignment, the system is automatically stiffened using several work support elements and actuators.

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Chapter 10
Case Study 3.3: Active Fixtures for High Precision Positioning of Large Parts for the Windmill Sector

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Abstract The fixtures are used to locate, clamp and support the workpiece during the manufacturing process. Their performance affects the results attending to the quality, cost and performance. Thus requirements like accuracy, reliability, short set-up time and cost-effectiveness are demanded for the fixtures. Within the INTEFIX project, the design of an active fixture is presented for the accurate positioning of a planet carrier with very strict requirements of tolerances and for an intelligent adjustment during the machining process when required. This device will allow the manufacturer to reduce the manual inspections, to automatize the adjustment tasks and to improve the machining process setup time. This will increase consequently the productivity and achieve the required accuracy and the required geometrical quality of the part. The development of the active fixturing focused mainly on the conception of a high precision actuator capable of moving the large part with the required tolerance. The active fixture was implemented into the machine and the obtained results proved that the proposed active fixture is able to centre the workpiece within the tolerance of 10 μm assuring the quality requirements.

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10.1 Introduction of the Case Study

Quality and productivity in a manufacturing process depend considerably on the toolkits used. A machining fixture has to meet two basic requirements: to position the workpiece to a right position in relation to cutting tools with the appropriate accuracy and to hold the component tightly so that it does not move during the machining operations. The costs associated with fixturing can account for 10–20% of the total cost of a manufacturing system [1]. These fixturing and tooling costs reach higher values in short batch manufacturing applications, since normally the fixturing is specific for each workpiece. Therefore, modern manufacturing environment imposes a continuous research to pull towards more flexible and efficient equipment in the field of tooling and fixturing.

Fixture procedure strongly affects the final quality of the workpiece. Workpiece surface errors and fixture set-up errors (called source errors) are inherent to the machining processes; the fixtured workpiece will consequently have position and/or orientation errors (called resultant errors) that will definitely affect the final machining accuracy. Current clamping procedures are carried out with traditional fixturing methods. Therefore it implies several steps and the success of the operation usually depends on the skill of the human operator. In order to avoid this human error, it is important to automatically clamp workpieces with the use of fixturing devices, for which firstly a search of the existing actuating technologies is required in order to find the most suitable solution for the fixturing operation.

10.2 Clamping Technologies

Different actuator solutions have been addressed by the literature in the search for the best solution to meet the fixturing requirements of each application in terms of stiffness of the solution, geometrical field of application (large or small part fixture), accuracy of the positioning and costs. The most commonly employed are: Electro mechanic actuators, hydraulic or pneumatic actuators and piezoelectric actuators.

Concerning electro-mechanic actuators, several mechatronic systems have been designed with the aim of developing adjustable and flexible fixture devices [2, 3]. In [4, 5] an adaptronic chuck is presented for precision positioning in lathes together with an optical measurement system and control algorithms. This solution offers the ability to compensate eccentricities by active clamping adjustment. For the best accuracy, synchronous motors are commonly used.

Hydraulic and pneumatic actuators make the actuator function via fluid energy (oil or compressible gas). As an application case of hydraulic actuated systems, in [6] the authors have proposed a numerical controlled fixturing system based on the double revolver principle which arranges locators, clamps and supports on servo-controlled turn-tables with repositionable hydraulic cylinders providing the clamping force.

One of the most innovative solutions on fixturing large and difficult-to-handle parts using pneumatic solutions are the pin-array type flexible machining fixtures

[7]. These fixtures feature an array of pins that hold parts by conforming to their shape. Hydraulic actuators show high level of stiffness, whereas pneumatic actuators have many distinct characteristics of energy-saving, cleanliness, simple structure and operation, high efficiency and are suitable for working in a harsh environment, but are not so suitable for accurate ultra-precision positioning.

The piezoelectric actuators convert an electrical signal into a precisely controlled physical displacement. New integrated piezo-actuators are controlled by micro-controllers, which communicate with an external control desk via Bluetooth. A positioning range of microns in two degrees of freedom can be achieved. In order to control pressure in the clamping cylinders of chucks, force sensors are also integrated [8]. Thus, the centripetal forces are compensated to make a sensitive clamping possible. Piezo-actuators are extremely accurate, but on the other hand it is not a suitable solution with large stoke demand applications.

In [9], the authors focus on automatically positioning by electromechanical actuators and flexible clamping based on magneto-rheological fluids properties. The fluid is in direct contact with the held part. A magnetic field increases the viscosity of the fluid and this allows the application of clamping forces. Additionally, in [10] a fixturing device with dynamic clamping forces is proposed for rotatory pieces.

Since a commercial solution that meets the requirements for the application under study in this work has not been found in the literature, a compact novel active fixturing device based on high precision electro-mechanical actuators have been developed. It features an active clamping for micro positioning of large parts with extremely high precision (under 10 micron in centering positioning).

Intelligent control is based on generalized HIL (hardware-in-the-loop) by combining multiple simulations and real components into a Hybrid Process Simulation (HPS) for positioning the workpiece to be placed, which is not in the same initial position, with high accuracy as it is described in [11].

10.3 General Overview of Requirements for Active Fixture Design Approach

The design of the fixturing should be determined to ensure stability, repeatability and immobility in the workpiece to be manufactured. Fixturing devices must satisfy two features, which seem to be opposite:

- to minimize the displacements of the workpiece during the machining process;
- to avoid excessive stresses and strains on the clamped workpiece.

In this case, the fixturing that has been designed is for the manufacturing of small lots of large parts (planet carriers) for the gearbox of wind mills, within the wind-power sector for the Gamesa Company. The machining of components such as the planet carrier is a very demanding process, which is becoming highly complicated as progressively larger parts are being required. Due to the very large size of wind power generation equipment, achieving quick setup times and high accuracy values is really a relevant challenge. Figure 10.1 shows the planet carrier,

Fig. 10.1 Gamesa's planet carrier for the gearbox

made of cast iron. The dimensions of the component go from 1000 to 2500 mm of diameter and the weight is up to 3000 kg.

The machining process on the planet carrier takes place in two phases:

- Phase 1. Machining of the upper side of the workpiece. Its orientation in relation to the currently used fixturing can be seen in Fig. 10.2a.
- Phase 2. Machining of the bottom side. The orientation of the workpiece (upside down) in relation to the currently used fixturing can be seen in Fig. 10.2b.

The active fixturing has been designed for the Phase 2, as it is the most critical one in terms of required tolerances. In this case, the fixturing has to center the planet carrier relative to the cutting tool with a maximum diametral run-out of 0.01 mm measured in the central hole of the planet carrier.

The lathe used for the machining of the planet carrier has double pallet and, while one workpiece is being machined, the operators are clamping a new workpiece in the other pallet, which is out of the machine, by means of the fixturing device. In order to develop a suitable fixturing, it has been taken into account that the centering tolerance is relative to the machine and not to the fixturing itself.

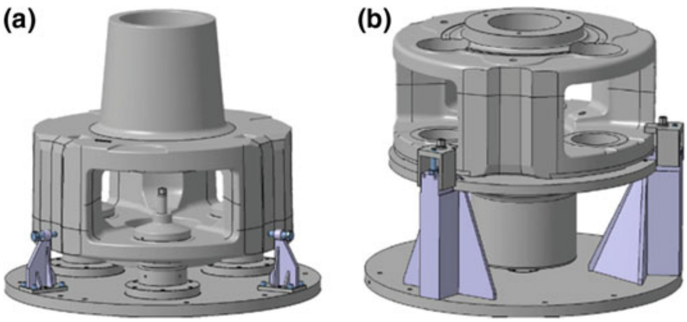


Fig. 10.2 (a) Phase 1 and (b) Phase 2 of the Gamesa's planet carrier machining process

Therefore, the setting-up process will have a first adjustment outside the machine, in which the workpiece will be pre-centered relative to the fixturing. A final adjustment will take place inside the machine by measuring the deviation between the vertical axis of the workpiece and the reference axis of the machine.

Currently the fixturing procedure is totally manual, which implies several steps and the success of the operation depends considerably on the operator skills. The drawbacks of the current clamping process can be summarized as follows:

- Locating operations involve a great deal of manual labour (manual inspections…) and introduce an amount of uncertainty as it depends on the skills of the worker.
- The procedure is time consuming: a large amount of time is spent checking the location of the workpiece and its dimensions before and after clamping, and after each machining operation, to assure a valid final workpiece.
- Skilled operators are needed for the locating, clamping and measuring processes.
- Low productivity due to the continuous machine inactivity to measure the areas of the workpiece with the most critical tolerances. Therefore, a large amount of time is spent.

With the purpose of solving the current inconveniences, an active fixturing has been designed with the following goals:

- To save time in the adjustment process: the new fixturing device will automatize the adjustment and measuring tasks achieving the required accuracy and quality with a reduction of the setup time.
- To increase the productivity, as there is more machining time available and the workpieces can be manufactured faster.
- To follow a modular design suitable for workpieces of different diameters.
- Considering these goals, the design, manufacture and validation of the fixturing have been performed.

10.4 Detailed Description of the Proposed Fixturing Solution

10.4.1 Clamping Technology

The most critical task that the fixture has to perform is the centering of the planet carrier with a maximum tolerance of 10 μm. Therefore, it has been decided to use electromechanical actuators because of its accuracy, high load capacity and enough stroke length. During the research carried out, it has not been identified any feed-drive suitable for this case study in the market, as the requirements of moving a workpiece of 3000 kg with a precision of 10 μm by means of electromechanical feed-drives are not usual. Therefore, a specific feed-drive has been developed for the application.

10.4.2 Designed Lateral Linear Feed-Drive

In order to adjust the planet carrier laterally with a diametral tolerance of 10 µm, the accurate and reliable feed-drive shown in Fig. 10.3 has been designed.

The feed-drive can be divided basically in three different sections:

- Driving components: synchronous motor, safety brake and gearbox, in charge of generating the torque necessary to move the workpiece.
- Transmission system. In order to get a very accurate feed-drive, the selected ballscrew has a very small lead of 1 mm and, therefore, a high torque per active volume unit is achieved.

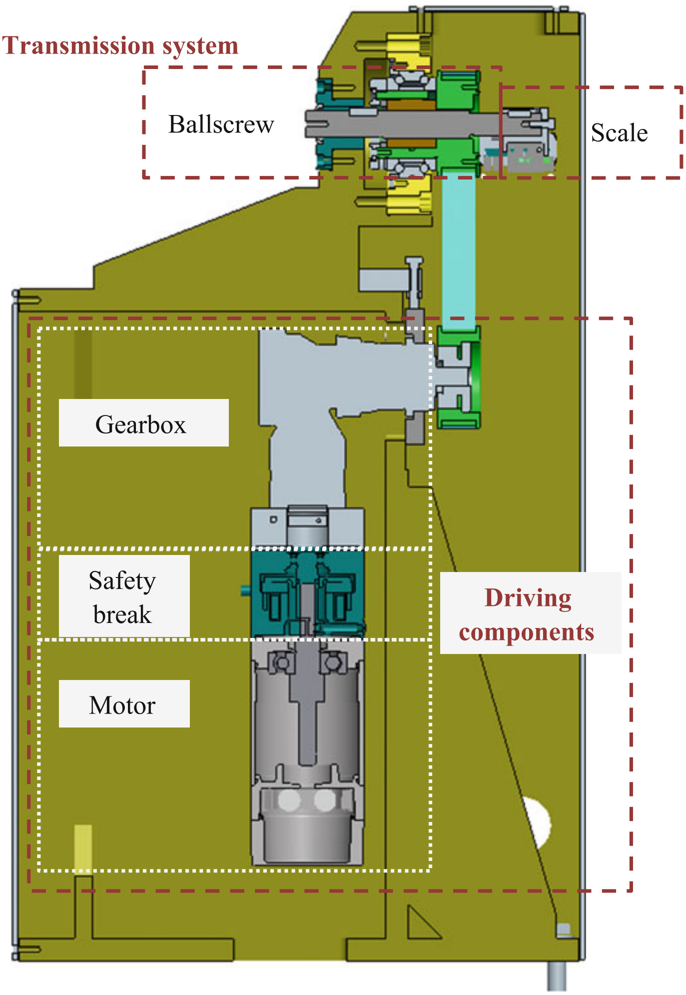


Fig. 10.3 Section of the feed-drive in charge of centering the workpiece

- Scale. As the centering tolerance is very strict and critical, apart from the encoder of the motors, additional magnetic miniature scales have been included for small-size linear stages. Their measurement range is 30 mm and they have a resolution of 0.1 μm.

From the point of view of the control of the position, the best option is to use a synchronous motor with an encoder. The resolution of the encoder and the relation between degrees and displacement will give to the control algorithm the relation needed to move the spindle. The minimum step given by the motor is lower than the accuracy needed in the positioning of the piece.

The fixturing has three actuators, placed in circular shape with an angle of 120° among them. They are independent modules and can be clamped and unclamped from the base of the fixturing; therefore the modular system can be easily adapted to workpieces with different diameters changing radially the position.

10.4.3 Design of the Fixturing

With the lateral actuator and its supporting structure already defined, the whole active fixturing has been designed, as it can be seen in Fig. 10.4. This fixture is going to accurately position and fix the planet carrier automatically without the need of any additional help.

The system is composed of the following mechanical components (see Fig. 10.4):

- Pre-centering plate with a poka-yoke system to place the planet carrier in a known position following a quite conventional solution in fixturing systems.
- Vertical positioning columns with a very precise flatness. The planet carrier is placed over these columns and supported by them.
- Clamping bridles, just over the three columns in order to clamp the workpiece.

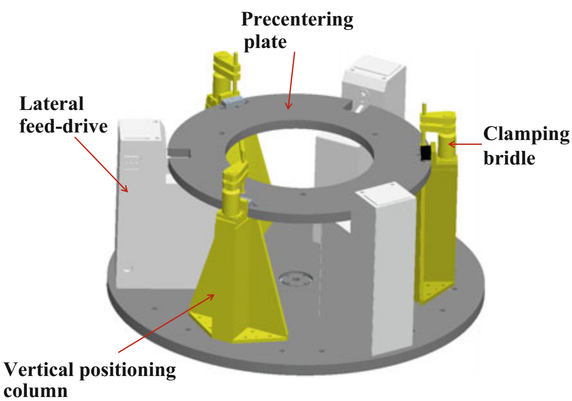


Fig. 10.4 Developed active fixturing with the workpiece and its components

- Lateral actuators. Linear electromechanical actuator specifically designed in order to achieve the strict tolerances required.

The set-up process of the workpiece consists of the following steps:

- The base of the fixture device with the three columns and the lateral actuators is placed, centered and fixed to the external pallet of the machine.
- The planet carrier is placed on the fixture, over the columns. It is placed in a specific position defined by a poka-yoke system.
- The three bridles turn and fix the planet carrier. It is important that these bridles act upon the supporting elements in order to avoid undesirable deformations.
- The external pallet turns and the fixturing and the Planet carrier are introduced inside the machining area. From that moment on, the planet carrier has to be centered very accurately, having to reach a diametrical run-out of 0.01 mm maximum. For this purpose, the feed-drive is controlled by the developed control algorithms that are explained below.

10.4.4 Control of the Centering Process

The centering of the workpiece has two steps. Firstly, when the fixturing is outside the machine, the workpiece is pre-centered with the passive vertical columns and the bridles fixing the workpiece in that position. In this step there is not any active intervention of the actuators. In a second step, the pallet with the workpiece and the fixturing are inside the lathe and a new centering process is necessary because the workpiece center has to be in the same vertical axis of the machine. For this adjustment a controller has been developed. To control the centering movement of the planet carrier a PID control is used in position and a scheme of this process is shown in Fig. 10.5.

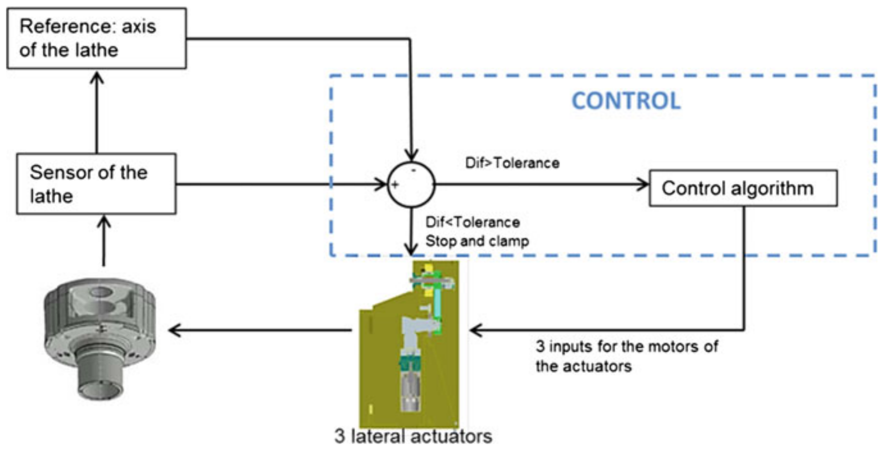


Fig. 10.5 Scheme for centering controller

For the control loop, the signals of the motor encoder and the scale of each actuator, along with the signal provided by the sensor placed in the lathe, are collected and confronted until having placed the workpiece in the required tolerance. The WRS system sensor is a high precision gauge composed by a probe/transmitter module and a receiver/interface one. It detects part coordinates and dimension during the manufacturing cycle. For this case a macro has been developed ("Eccentricity Measurement") that has to be executed before the machining in order to confirm the position of the workpiece.

To adjust the workpiece, all the three ballscrews go forward until each of them touches the workpiece. At that moment, the touch probe sensor measures the real position of the center of the planet carrier related to the vertical axis of the machine. The new values for each actuator are copied from GUDs to R variables and transferred from de CNC to an external PC. The position control algorithm calculates the movement that each actuator should induce to the workpiece. After the actuators have made this operation and the workpiece is in the right position, the clamping bridles fix it and the spindle of the actuators moves back, releasing the workpiece.

10.4.5 Intelligent Fixturing

Using the programmed control algorithms, the developed active fixturing allows an intelligent centering process of the planet carrier. Due to the weight of the workpiece and the fact that the time is not a constraint in this operation, it has been decided that the control of the feed-drives will be made in an uncoupled way, not centralised. As the feed drives will be placed each 120° around the prototype, one feed drive corresponds to the 'y' axis, and the other two will have components on the 'x' and 'y' axes. Furthermore, the assignment of the feed drives to an axis will

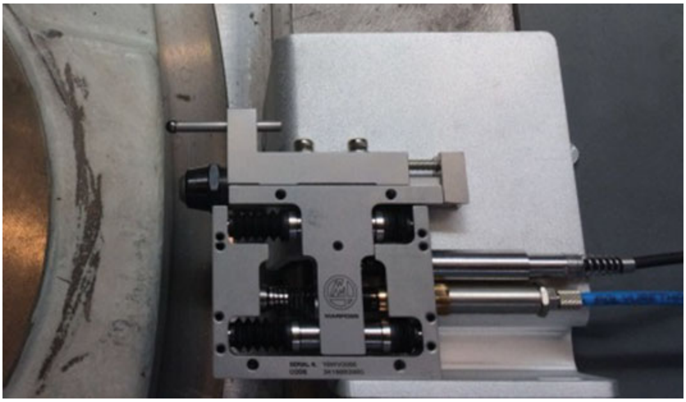
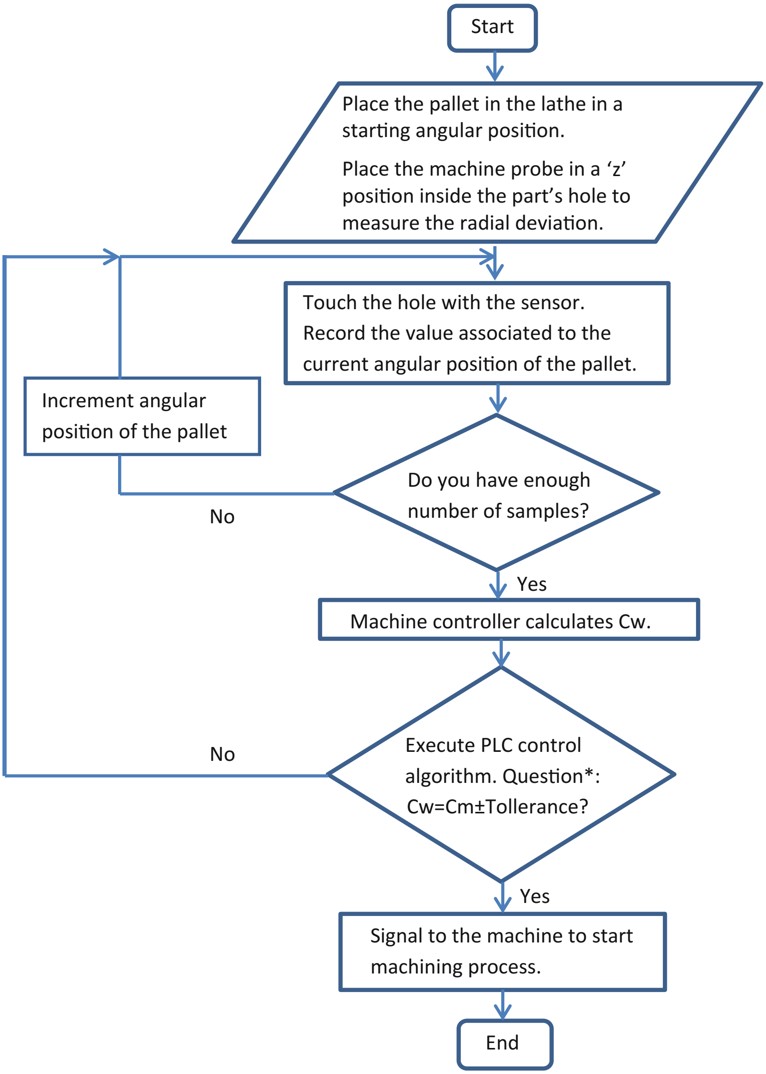


Fig. 10.6 Implementation of the inductive sensor into the active fixture



*** A watchdog is necessary to avoid malfunctions in the autocentering procedure repeatability.**

Fig. 10.7 Flowchart of the centering adjustment process

not be fixed; it will depend on the feed drive closer to the workpiece, which will be automatically assigned to the 'y' axis.

For simulation purposes, it has been programmed a Virtual Reality Model (VRM) using Matlab-Simulink. It is connected to the controller in order to provide a visualization of the centering process. In order to detect the workpiece and

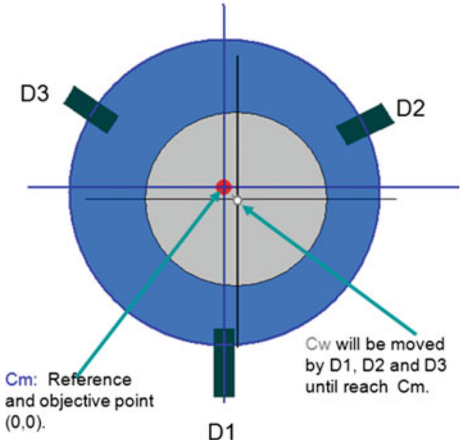


Fig. 10.8 Scheme of the centering of the workpiece

regulate the position relative to the surface of the planet carrier, an inductive sensor has been implemented into the active fixture in each actuator. With this implementation it is possible to detect the contact with the planet carrier and this connection closes the loop for each of the actuators (Fig. 10.6). A flowchart of the adjustment is presented in Fig. 10.7. Some variable definitions are: Cm is the center of the machine, Cw is the center of the workpiece, D1-D2-D3 are the feed-drives and the algorithm is executed by a PLC.

Figure 10.8 shows schematically the dynamic centering procedure to correct the misalignment of the workpiece.

10.5 Experimental Validation

The validation of the control strategies has been made in a Pietro-Carnaghi vertical lathe. For this purpose an active fixture has been designed and implemented into the machine, shown on Fig. 10.9a. These performance tests have allowed evaluating the accuracy and repeatability of the displacement following the real requirements. These values are indicators for the improvement made by the control system (in the accuracy case), since the repeatability is more related to the mechanical structure. Different trials have been planned in order to validate the viability of the controlled actuator of the fixture.

In the different planned tests a dedicated viewer has been used for the visualization of the PLC program. The program developed for controlling the spindle includes a screen that allows managing the two steps: control the displacements until touching the workpiece and then move the part to the commanded distance. The measurements of accuracy and repeatability have been done with an external/independent measuring system using a touch probe, shown on Fig. 10.9b, as well as the scale and the motor encoder.

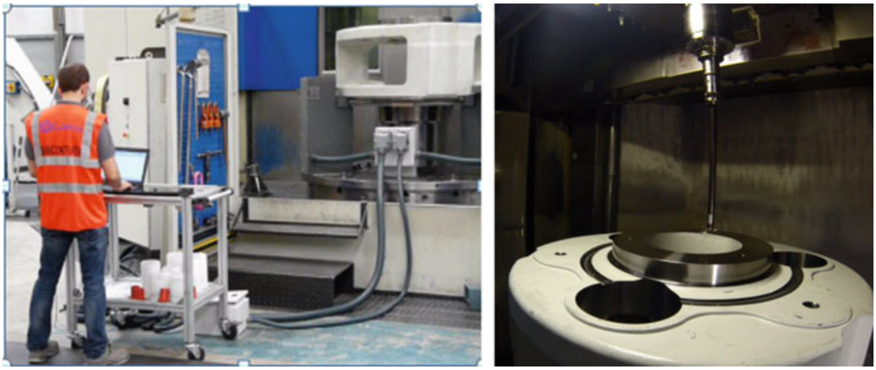


Fig. 10.9 Experimental setup: (a) Fixture implemented into the machine (b) Touch probe measuring system

The real displacement reached by the fixture into the machine has been tested in loaded movement (moving the workpiece). The analysis of the data is done between the displacements correspond to the motor encoder lectures and the real displacements obtained by touch gauge. The actuators have a linear relation along the whole working zone (±5 μm deviation) and a repeatability of a ±5 μm (Fig. 10.10).

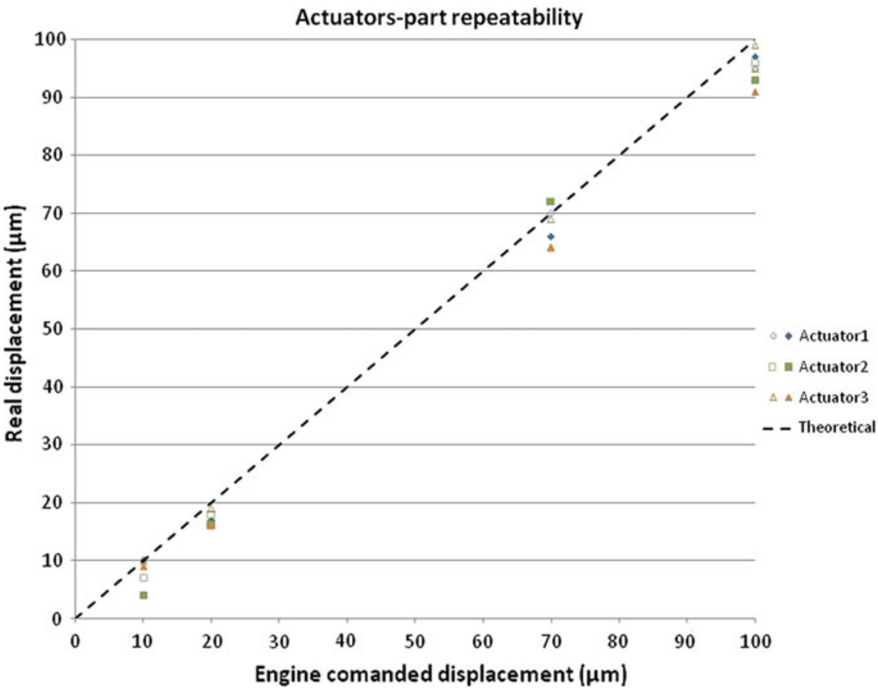


Fig. 10.10 Lineal relation between the commanded displacements with the touch probe indication

Table 10.1 Iterative experimentation in Pietro Carnaghi vertical lathe

	Self-acting	Test	Iterations	Total setup time
Current	No			13′
INTEFIX	Yes	1	4	8.8′
	Yes	2	5	9.5′
	Yes	3	4	9′
Total time reduction				≈30%

In order to obtain a part alignment below ±10 μm, an iterative process has to be followed. The main aim is to carry out laboratory tests to demonstrate the feasibility of the proposed fixture. Considering the requirements defined in previous tasks, several experiments has been carried out, which has allowed verifying that the system fulfils all specifications. In this sense, close-loop control tests have been performed. These close-loop tests, based on HiL (hardware-in-the-Loop) approach, have the aim of demonstrating and proving the overall performances against the initial specifications.

The obtained results have proved that the proposed active fixture is able to centre the workpiece within the tolerance of 10 μm assuring the quality requirements. This is possible due to the specific mechanical design of the actuators and the control of them by a PLC and a software program. Moreover, this new active fixturing system allows the manufacturer to reduce the setup time by 30% (Table 10.1).

10.6 Conclusions

An active fixture has been designed and implemented into a vertical lathe for the accurate positioning of a planet carrier. The repetatibility and the accuracy of the centering positioning reached by the fixture has been tested in loaded movement. The obtained results have proved that the proposed active fixture is able to center the workpiece within the tolerance (10 μm).

The fixture has been equipped with intelligent actuators that by means of a control system that communicates the information of the sensor with the driving systems, locates the workpiece in the right position. The active fixture acts on the positioning of the part during both setup time and machining process. To prevent the defects generated due to the bad positioning of the part, a new fixture control and a software platform has been developed in order to integrate the information gathered by the acquisition devices.

This new active fixturing system allows the manufacturer to increase the productivity, as the adjustment process is performed in an automatic way reducing the setup time by 30%.

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Summary and Conclusions

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The INTEFIX project results show exemplarily how the capabilities of fixtures for machining applications can be improved significantly. The general tasks and purposes of fixtures (i.e., to ensure a defined location of a workpiece within the workspace of a machine tool as well as to provide the required clamping forces to hold the workpiece in the defined location even under the influence of external loads and to support the workpiece in order to avoid workpiece deformations due to gravitational and process forces) can be enhanced by monitoring, corrective and compensatory as well as adaptive functionalities. For this, sensory elements and actuators are to be integrated into the mechanical structure of the fixtures, the supporting and clamping components and mechanisms, respectively. These elements are connected to appropriate control systems which can work autonomously or can be coupled with the machine tool control. This system integration leads to 'intelligent' fixtures which allow the detection and observation of workpiece-, fixture- and process-states during workpiece alignment and the clamping procedure

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as well as in machining operations. Major objectives of such intelligent fixtures are the precise positioning of parts and difficult-to-handle workpieces, the identification and compensation of workpiece deformations and distortions, and the detection and reduction of workpiece vibrations. In this book, research results are introduced and prototypes are presented which show exemplary approaches and solutions that reveal the high potential of intelligent fixtures with respect to these major objectives considering real manufacturing scenarios.

For target oriented and systematic design, layout and optimisation of intelligent fixtures, a new methodology is necessary. The interactions and interdependencies of workpiece characteristics, processing demands and process conditions, mechanical fixture properties, sensor sensitivity, actuator performance, control functionality, and quality requirements have to be considered in detail. For this, the development and utilization as well as the coupling of mechatronic modelling and process simulations possess a very high potential with respect to the achievement of an optimal fixture design and reduced layout times. Due to the complexity of intelligent fixtures, comprehensive modelling is a challenging task and computation times of sophisticated simulations are very long. A future task, therefore, is to investigate strategies for model order reduction and simplifications regarding an efficient optimisation of intelligent fixtures.

Some examples of the INTEFIX project already show the potentials of the use of CFRP and composite materials in fixture structures and sensory and actuation elements, respectively. Besides the lightweight properties, the high material damping compared to steel and the ability to design and produce function integrated structures with dedicated characteristics can be exploited in the development of intelligent fixtures. Furthermore, the use of 'smart' materials (e.g., shape memory alloys, magneto-rheological fluids, piezo-resistive materials, etc.) can enable a higher degree of functional integration. Based on microelectronic devices and micro electro mechanical systems (MEMS), distributed sensors and sensor networks providing multi criteria state information can be implemented.

On the basis of the experiences, results and findings of the INTEFIX project, intelligent fixtures can be developed and provided as functional core components of machine tools in innovative machining and production systems. Furthermore, intelligent fixtures constitute an important enabling element within a networked, self-organising and self-optimising production environment.

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