Clamping Modeling - State-of-the-Art and Future Trends

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Abstract. Automated assembly is generally confined to mass production environments such as the manufacture of cars and white goods. Even in this environment high-level automated assembly is restricted to the OEMs where production volumes are high and flexibility and the ability to quickly reconfigure systems are not major drivers. In the aerospace industry the problem is further complicated by the move to thin walled monolithic parts and the increasing use of composite structures. Monolithic structures have been introduced to reduce the costs of assembling large numbers of components. Although the benefit of using monolithic parts is a large reduction in overall manufacturing costs the downside is a more difficult component to handle and assemble. In addition, there are thin walled components with sometimes-internal stresses and in our case made of nickel based alloys, which only can be cut with difficulties. Machining the flexible structure and maintaining close tolerance is difficult, transferring to assemble is difficult as well. Machining fixtures are used to locate and constrain a workpiece during a machining operation. To ensure that the workpiece is manufactured according to specified dimensions and tolerances, it must be appropriately located and clamped. Minimizing workpiece and fixture tooling deflections due to clamping and cutting forces in machining is critical to machining accuracy. An ideal fixture design maximizes locating accuracy and workpiece stability, while minimizing displacements. In this paper, a review of the state of the art approaches of Clamping modeling is provided. The current drawbacks of the existing approaches and the research areas to focus on in the near future are also identified.

Keywords: Clamping, Fixing, Modeling, Simulation, FE-Analysis, Multiphysics.

1 Introduction

A fixture is a mechanism used in manufacturing to hold a workpiece, position it correctly with respect to a machine tool and a cutting tool, and support it during machining. Typically, fixture design involves the identification of clamp, locator, and support points, and the selection of corresponding fixture elements for their respective functions. The automation of fixture design activities in manufacturing is an important research area, which must be addressed to achieve the integration of design and manufacturing. Fixture design is a complex task, which is as a critical design–manufacturing link, especially in a modern computer integrated manufacturing environment [1,2,3,4]. The computer- based automation of the fixture design activities is

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commonly referred to as computer - automated or computer - aided fixture design (CAFD).

The quality of a fixture design is defined through the requirements from design and manufacturing engineers. The main four commonly required areas are:

- Locating Performance Analysis. Studies workpiece DOFs (degree of freedom) constrained by locators, workpiece constrained status, locating performance index, and locator layout optimization.
- Tolerance Analysis. Studies machining accuracy provided by the fixture and locator tolerance assignment based on machining surface tolerances.
- Stability Analysis. Studies workpiece stability and minimal clamping forces.
- Accessibility Analysis. Studies point and surface accessibility.

To measure the quality defined above, two models – one geometric and one kinetic – will ne normally created to describe the fixture and workpiece relationship (Kang, 2001). The geometric model describes the relationship between workpiece displacement and locator displacements, and it is based on the Jacobian Matrix. The properties of the Jacobian Matrix can be used in finding locating performance and locating accuracy. The Jacobian Matrix is generally used to formulate the relationship between a 3D object and its locators, and it is also used in robotic hand grasping problems [5].

1.1 Initial Fixture Design

There have been many published papers in the area of fixture design. Attempts to automate the fixture design process are not new. In the initial work of Markus [6] and Miller [7], the locator and clamp positions were not determined automatically. The approach adopted was interactive where the user specified the clamping, locating, and support points, and then selected the appropriate fixturing components in the desired positions. In [8], the primary locating surface and its related locator positions are assumed as a given, and the problem was reduced to determining the secondary and tertiary planes with their respective locator positions. The work of Chou [9] focused on the clamping aspects of fixture design. A fixture clamping procedure was developed based on the twin criteria of workpiece stability and total restraint requirement. The total restraint requirement was ensured by restricting the degree of freedom of a given workpiece using clamps and balancing the cutting forces.

1.2 Expert Systems

Researchers have long recognised the importance of developing computer-automated fixture design (CAFD) approaches, in which the clamp, support, and locator design attributes are generated automatically for varying part designs. The use of artificial intelligence (AI) approaches, as well as expert system applications in fixture design, has also been reported. An expert system approach was adopted by Nee et al. [10] to perform the fixture design task where a heuristic rule base was used to generate a list of fixing recommendations including the locating and base elements for the fixture. A CAD model of a given product design was used as an input to the fixture design task. A heuristic rule base was used to generate a list of fixing recommendations including the locating and base elements for the fixture. In [11], a rule-based expert system is described, which identified the locating and clamping faces for rotational parts. Gandhi et al. [12] discussed an expert system architecture to perform fixture design using modular fixture components. Other expert-system oriented fixture-design methods include AIFIX [13] in which the fixing problem is solved as sub problems leading to the final workholding goal. Wright and Hayes [14] described the development of Machining Planner, which is an expert system for the set-up planning of rectangular parts in parallel-sided vices on a three-axis milling machine; later, an automated toe-clamp fixture was also used as a clamping device. Based on this study, the relationships between the force of the vice and the cutting forces were proposed. Markus [6] developed an expert system which configures clamps about a part using design specifications and rules related to geometrical constraints; Asada and By [15] implemented conformable clamps for assembly operations using magnetic tables, locators, and a robot. NIST has designed and implemented a programmable vice including a variable-depth jaw, to hold varying part shapes and sizes using controlled pressure [16]; fluidised beds have been reported [17] to hold parts of unusual shapes. Case-based reasoning has also been used to aid in automated fixture design activities [10,18].

1.3 Recent Approaches to CAFD

In [19], a semi-automated system is described where (when fixture points and planes are selected) modular components are automatically identified and assembled. However, the identification of the clamp, locator, and support (CLS) points is not determined within the system (they are provided as inputs to the system). In a related paper [20], the focus is on geometric analysis, which uses analysis of the geometric relationships between the CLS components and the workpiece, the initial conditions for fixture assembly are developed automatically. Dai et al. [21] described a modular element database creation method, which can be used effectively for integrating with a CAD system and for modelling fixture subassemblies. In [22], an innovative approach to fixture design based on genetic algorithms (GA) and neural networks (NN) is described. The GA searches among a population of fixtures, and each feasible fixture chromosome is evaluated using a defined objective or fitness function; the major drawback of this approach is that the design space (or search space) is very large even for fixture problems corresponding to simple part designs. In [23], fixing surfaces and points are automatically determined based on fixture surface accessibility, stability and feature accuracy. In addition to this, some investigations has been directed to tolerance analysis of locators, source errors analysis and fixture loading techniques [24, 25].

1.4 Summarized Methods Applied to Clamping Optimization

Although numerous CAFD techniques have been proposed and implemented, fixture design still continues to be a major bottleneck in the integration of CAD and CAM activities. One reason for this is that fixture design approaches being developed are not fully integrated with other product and process design activities. Future fixture design approaches must focus on methods which not only serve as a bridge between CAD and CAM, but, more importantly, seek to support cross-functional participation and concurrent engineering approaches. In today's virtual enterprise oriented manufacturing environment, the planning and process design resources may be physically distributed around the globe. There is a need to develop fixture design methods for this changing international manufacturing landscape.

The main activities of Clamping optimization are summarized in Figure 1.

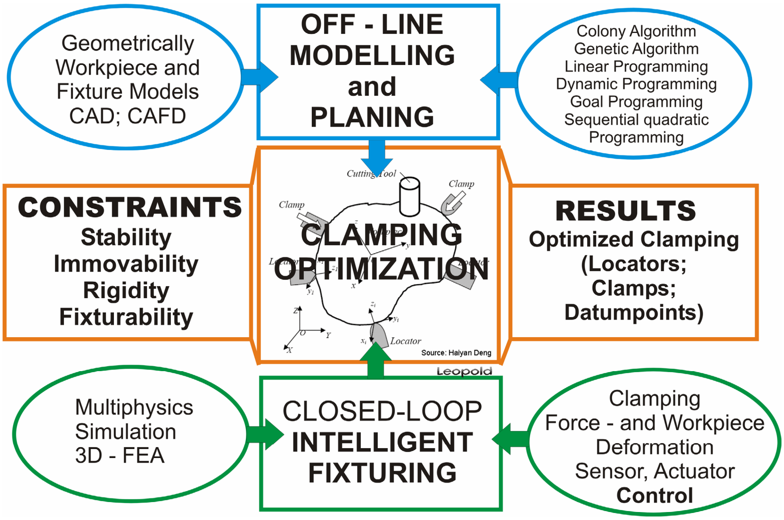

Fig. 1. Methods applied to clamping optimization

2 Modular and Intelligent Fixing Systems

Other computer-automated fixture design work includes Sakurai [26], Boerma and Kals [27], and Rong and Zhu [28]. In [26], the development of a system is described to automate set-up planning and fixture design. Both algorithmic and heuristic methods were developed to generate and analyse the set-up plan and fixture configurations. A solid model of the component (part) is used as the input for the fixture design task. The requirements for set-up planning and fixture design included accurate location of the workpiece, total restraint of the workpiece during machining and interference aspects between the cutting tool, workpiece, and fixture components. Another related aspect studied was the deformation of the workpiece during machining. Features occurring in part design have also been used by other researchers to develop fixture designs [29]. In [30], a mathematical model is used to determine the fixture locator and clamps; kinematic analysis based fixture design is described in several publications, including [8,11,31]. Other researchers, including DeVor et al. [32,33], have analysed the cutting forces and built mechanistic models for drilling, and other metal cutting processes, which can be used to determine clamping requirements. In [34], assembly constraints are defined to model spatial relationships between modular fixture elements. Modular fixture design elements are described in detail in [35]; the use of standardised fixtures or modular fixture components is intended to eliminate the need for single-purpose fixtures. It is an alternative to custom-built fixtures, which are more expensive. A predetermined grid of holes and components such as studs, clamps, etc. can be used to build a fixture. Several researchers have employed modular fixing principles to generate fixture designs [1,3,12,28]. Fixing is process-specific. At some positions along the tool path, small forces may be adequate, but large forces may be required at others. The minimum clamping forces to secure a workpiece are different as the cutter moves along its intended tool path. Hence, our attention is focused on the force distribution. We attempt to design an Intelligent Fixing System such that the fixture elements can be manipulated to provide dynamic clamping forces during the entire machining and fixing process. For the Intelligent Fixing, the clamping forces are adaptively adjusted to optimal values according to the cutter position and the cutting forces during machining with the objective of minimizing workpiece distortion while ensuring that it is adequately secured. Since adaptive clamping forces appropriate to the dynamic machining environment are provided, the proposed IFS offers higher quality of machined parts and greater robustness to disturbances. The developed Intelligent Fixing System [37] is characterized by on-line monitoring, dynamic clamping forces, and real-time fixing process control (Fig. 2).

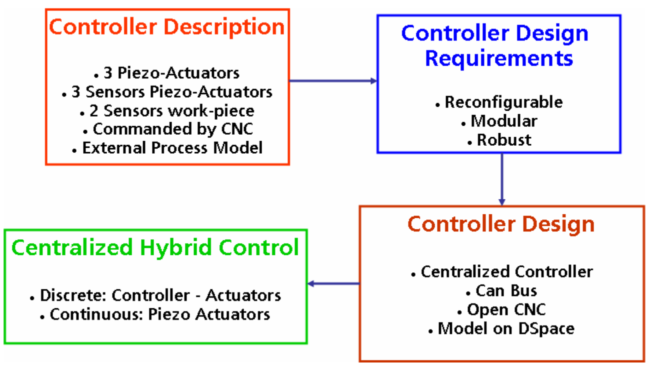

Fig. 2. Requirements for Intelligent Fixing Systems (IFS) [37]

2.1 Design Requirements

The general design requirements pertinent to ordinary fixtures also apply to the intelligent fixing system. The functional requirements of a fixture include total restraint, positive location, repeatability and rigidity. Since the IFS still needs to adjust the clamping forces at different cutting tool positions and the magnitude of the cutting forces vary during machining, sensor feedback, clamping control and programmability are required to realize its functions.

2.2 Open- and Closed-Loop

In an open-loop IFS, the optimal clamping forces with respect to the different cutting tool positions are pre-computed before machining. During machining, the control unit of the IFS adjusts the clamping system – based on a database - according to the deformation of the workpiece. In a closed-loop IFS, the optimal clamping forces with respect to the different cutting tool positions are calculated in real-time during machining. Cutting forces acting on the workpiece are obtained from sensors in the system and optimal clamping forces are then deduced and applied. Unlike the mechanism of open-loop IFS, the optimal clamping forces provided by the closed-loop IFS are continually adjusted by monitoring and measuring forces on the workpiece. To ensure that the controller has a sufficiently short response time, the models and algorithms should be as simple as possible.

2.3 Sensor Feedback

Sensor feedback is most important for the design of an intelligent system. Sensors allow real-time information to be transferred between the fixing system and its controller. In [APT] piezoelectric sensors are mounted on the locators to monitor and easure the reaction forces during machining.

2.4 Clamping Control

Clamping devices are designed to apply variable clamping forces to the workpiece during the machining process. Through a remote interface circuit, a CPU controls the clamping system to apply the required clamping forces as the cutting tool moves to different locations on the workpiece. The objective is to minimize the deformation of the workpiece caused by the clamping forces.

2.5 Programmability

The sensing and clamping operations of the IFS are controlled by a CPU through a remote interface circuit using customized programs for the processing of the input/output signals, monitoring and control of the fixing process.

2.6 Fixturing Stability

A stable fixturing system must hold a workpiece stable in place during machining. Positive reaction forces at the locators ensure that the workpiece maintains contact with all the locators from the beginning of the cutting operation up to the end. A negative reaction force at the locator must be avoided. If one or more of the reaction forces should go to zero, this indicates that the workpiece is no longer in contact with the corresponding locators and the fixing system is considered unstable. Hence, a fixing stability criterion is considered here and it states that all the reaction forces at the locators must be positive during the entire machining process.

2.7 Initial and Optimized Clamping Force

The optimal clamping forces are defined here as the minimum clamping forces necessary to keep the workpiece in static equilibrium throughout the entire machining process, but on the other hand, some thin-walled workpieces can be deformed due to the clamping forces. So, in addition to the initial clamping forces, process depending clamping forces should be used.

2.8 Control-Clamp at Datum Points

The control-clamp of a locator refers to the clamp that has the greatest influence on the reaction forces at the locator. All the clamps in a given fixing system are labeled as the control-clamps of a certain locator. If a reaction force at a locator is near or equal to zero during machining, its control-clamps will be adjusted to increase the clamping forces so that the reaction force will not reach the critical state.

2.9 Intelligent Controller

A model-based control scheme is proposed for the IFS - as illustrated in Fig. 3. Three different models are employed: fixture–workpiece model, stability monitoring model and process model. At the start of the machining process, the reaction forces are measured through the sensors embedded in the locators. According to the fixture–workpiece model, the cutting forces are estimated, and from the estimated cutting forces and the optimization model, the required optimal clamping forces are predicted. The predicted optimal clamping forces are then applied in real-time to the workpiece using the specially designed clamping system. Once unstable phenomena are detected, the stability monitoring model issues a command to the clamping system to increase the appropriate control-clamp until stability is restored. These processes are repeated until the completion of the machining process. In this way, reaction forces at the locators are monitored and serve as feedback information as the clamping forces are varied automatically throughout the entire machining process. The computation times of the fixture–workpiece and optimization models must be fast enough for real-time control.

3 Fixture - Workpiece Model and Simulation

For the Application of Intelligent Fixing Systems it is important to distinguish three families of workpieces – machine tool – cutting tool - clamping systems (Fig. 4)

a.) stable workpiece – unstable cutting tool
b.) unstable workpiece – stable cutting tool
c.) flexible sheet metal parts with internal stress situation (spring back)

A fixture–workpiece model aims to relate the interaction between the fixture and the workpiece during the machining operation. Several kinds of fixture–workpiece models have been developed in the past decades [38-43]. Different forms of fixture–workpiece model have been derived in order to make its application more convenient for the subjects under study. Many thin-walled structure components widely used in aero industries not only have complex structure and large size, but also need high machining accuracy. However, because of their poor rigidity, it is easy to bring machining deformation caused by the existence of the initial residual stresses, the fixing stresses, cutting forces and cutting heat. The difficulty in ensuring their machining accuracy becomes a big problem, so that how to effectively predict and control the machining deformation has become an important subject in the development and production of aero parts [44,45].

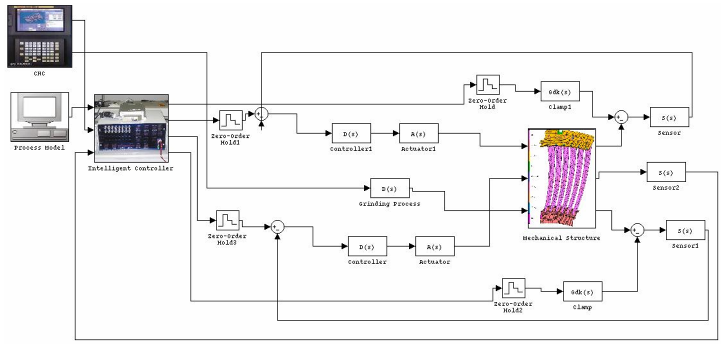

Fig. 3. Intelligent Controller for a Clamping System of Nozzle-Guide-Vans [37]

The FEM is most suitable to analyze the elastic deformation of a workpiece-fixture system in the presence of clamping and cutting forces. The finite element model built in this work includes contact stiffness, element stiffness, spring-damping properties and frictional force as well as grinding forces.

To realize the proposed Intelligent Fixing System Principle, a multiphysical simulation has been developed [ ]:

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1. The Workpiece Model (material properties; friction conditions; boundary conditions for fixing)
2. The Machine Tool and the Cutting Tool Model – including instability charts
3. The process model for the applied machining operation (milling, drilling, grinding) – machining simulation based on FEA; cutting force predicition by simulation or predictive modelling
4. Sensor – Actor – Models - based on hybrid mechanical-thermal-electrical simulation

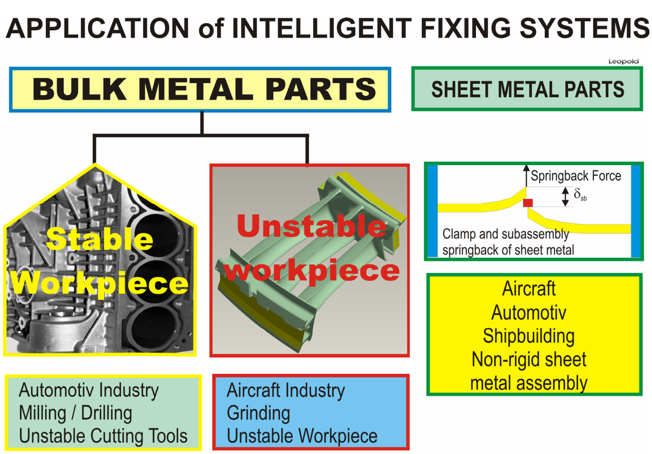

Fig. 4. Intelligent Fixing Systems for three different industrial applications

To realize a near real-time simulation, the proposed model for the Intelligent Fixing System is based on a reduced mechanical model, started with a full FE-Model, a parametric model up to an analytical model [37].

For the mechanical modelling, the following conditions must determine.

3.1 Cutting Forces

The thermo-mechanical phenomena of machining are so complex with so many elements involved that even for single-point cutting it is not simple to estimate the cutting forces accurately. A number of validated models have been reported in the literature for milling, drilling, and grinding.

3.2 Friction

It is well known that the frictional force between two objects is indeterminate until slippage occurs. Due to such uncertainty, the analysis of friction in a fixing system is difficult. Coulomb friction force between the workpiece surfaces and the fixture elements are usually assumed. This is considered to be the simplest and effective way to deal with friction. For some machining fixtures, unlike the problem of robot grasping, frictional forces are not relied on or necessary to hold the workpiece because the cutting forces can be very large and are inherently dynamic. Friction shows no significant influence on the fixturing system. Other machining fixtures, such as vises, chucks or strap clamps, rely mainly upon friction to maintain the fixturing stability. The friction coefficient is depending on the working environment, such as the use of cutting fluid. Since the objective is to obtain the minimum clamping forces, the critical situation of slippage should is assumed.

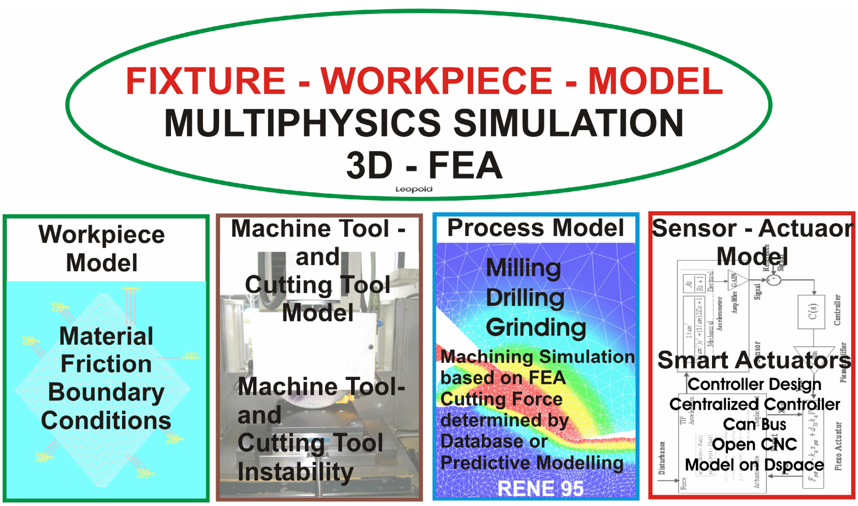

Fig. 5. Multiphysics approach to investigate intelligent fixing systems

3.3 Spring-Damping Properties

In order to produce a more accurate model for predicting the behaviour of the fixture–workpiece system, the FEM model must includes fixture stiffness [46, 47], which past models have assumed as rigid bodies. The spring-damping properties of the clamping devices have a strong influence on the dynamically behaviour of the intelligent fixing system [48].

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