

Chapter 8

Behaviours Indicators of Machine Tools



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8.1 Introduction

The behaviour of a machine tool is the set of actions and operations made by the machine sub-systems in conjunction with themselves and the machine environment. The expected behaviour can be defined as the capacity of a machine tool to achieve its objective: to produce parts with specified quality at high production rates [1].

These concepts can be monitored through sensor measurements. The characteristics of the sub-systems allow to interpret the expected behaviour from the machine. However, raw data are highly influenced by external and internal conditions. The behaviour of the sub-system can influence the one of another sub-system from the machine tool. By computing contextualized, and comparable over the time, indicators, from sensors measurement and machine operating conditions, it is possible to

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monitor the machine behaviour and highlight its changes. The quality of the indicators and, consequently, of the monitoring requires a consistent acquisition that is representative of the system dynamics.

Behaviour indicators extraction of a machine tool can be done continuously by the exploitation of the workpiece program and existing machine sensors, or with specific characterization programs using existing sensors and/or additional sensors. Behaviour continuous monitoring using raw measurements is discussed in Sect. 8.2. The characterization tests of machine tools processed occasionally are discussed in Sect. 8.3. Finally, the conclusions are summarized in Sect. 8.4.

8.2 Extraction from Machining Raw Measurements

To continuously monitor the machine behaviour, it is possible to extract indicators from the raw existing sensors measurement during the machine workpiece production. Given the available collected data, it is possible to compute indicators representative of the machine and its sub-systems status. To give a sufficient representation of machine tool behaviour, it is recommended to have a minimal set of information that is synthesized in Table 8.1.

A machine is composed by a set of linear and rotating axes, at least one spindle and a set of auxiliary systems to ensure good machining conditions such as lubricant system, cooling system, air system, machining coolant system and hydraulic group. An overview of the machine behaviour is given by merging the results of its sub-systems. Therefore, information about each of them is required. The axis behaviour indicators can be built based on real position, drive current and temperature. In some cases, such as vertical axis, it can be equipped with a compensation system. The axis balance pressure has then to be considered. Behaviour indicators for spindle can be based on speed, current and temperature. The auxiliary systems can be mainly

Table 8.1 Minimal raw measurement set for behaviour monitoring

System	Sensor	Operating condition
Workshop	Temperature	
Machine tool		Cycle tool change
Axis	Real position	
	Current	
	Temperature	
Spindle	Speed	Tool Number
	Current	
	Temperature	
Pumps/tanks	Pressure	

described by the actions of their pumps and tanks where output pressure analysis gives a good representation.

Indicators should be computed from specific operating conditions. The knowledge of workpiece cycle start/end, tool changes and tools in use are then highly recommended for a more accurate analysis. The knowledge of the machine tool environment conditions, such as the workshop inner temperature, is a plus, especially for temperature- and current-based indicators.

8.2.1 Indicator Extraction Process

When it is working, a machine tool and its sub-systems are solicited from various ways and with intensive efforts to produce a part. The solicitations depend on the different machine tool operating conditions. To observe machine behaviour, it is convenient to isolate and observe sensors measurements according to these conditions. The observation is available by extracting business indicators from isolated sensors measurement as depicted in Fig. 8.1.

Collected raw sensors data are, first, consolidated and made reliable, and then, the operating conditions of the machine tool are computed as explained in Sect. 8.1.1. Indicator extraction process from these conditions is detailed in Sect. 8.1.2.

8.2.2 Machine Operating Conditions

A machine tool operates in a workshop and aims at performing successive operations to a raw material to produce a finished workpiece. Each operation may involve the use of a specific tool and axis movements with optimized machining parameters, such as spindle speed or feed rate, for instance. The structuration of machine operating conditions is illustrated in Fig. 8.2, containing the following layers: production, cycle, step, tool change (TC) and move (M).

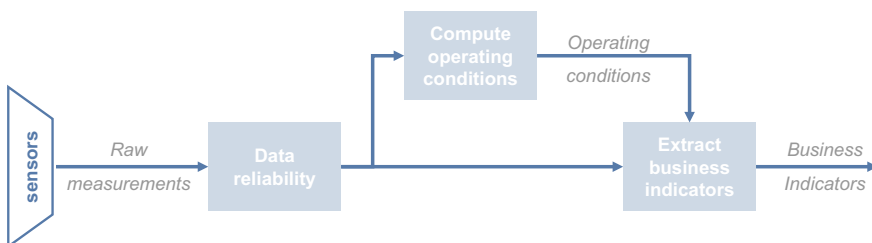


Fig. 8.1 From raw sensors' measurements to indicator extraction

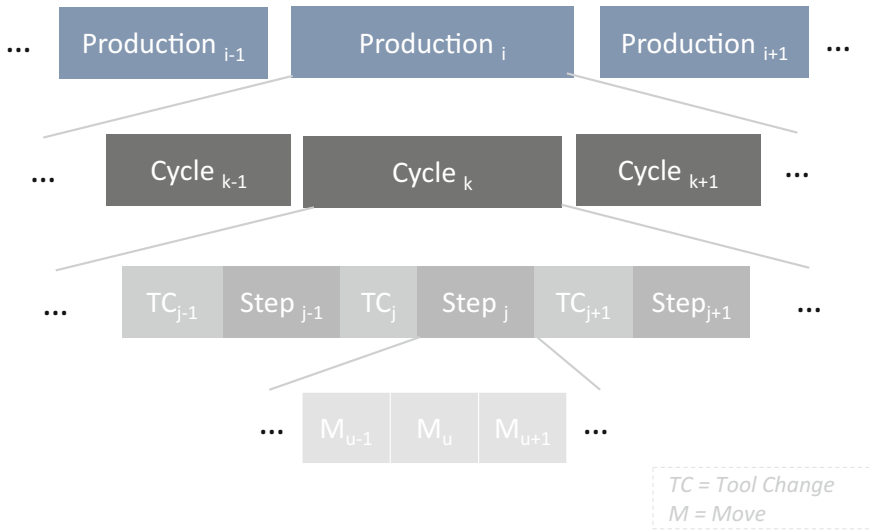


Fig. 8.2 Machine operating conditions

At the top level, the production phase characterizes uninterrupted sequences of machining cycles where the machine tool can produce from one to multiple workpieces of, possibly, different types. A machining cycle is the production of one workpiece. It is composed of successive steps, i.e. an operation such as drilling, boring, finishing with a specific tool and tool changes. For a specific workpiece type, the number of steps and the length of cycles remains constant if the program parameters remain unchanged. Within each step, several moves are performed, such as linear or circular motion, fast or slow, machining or not. Each move can be associated to a single G-Code line of the machining program. Such decomposition allows the observation of specific behaviour and to monitor weak signals. The example in Fig. 8.3 illustrates condition monitoring necessity. In this example, the spindle torque reproduces the effects of a tool change (in blue).

The different operating conditions can be collected directly from the machine numerical command. If it is not the case, they should be inferred from the raw sensors measurements such as axis positions. It is suitable to prioritize the first solution as it contains more reliable information describing the machine state. Algorithms based on raw sensors measurement depend on the relevance, the sampling rate and the synchronicity of the crossed data.

The machine tool efforts are different from one condition to another; to study the behaviour of the machine or a specific sub-system, it is recommended to observe sensor measurement independently from one condition to another. Moreover, the behaviour analysis is possible by extracting indicators from the dataset of sensors' measurements collected in each specific condition as explained in the next section.

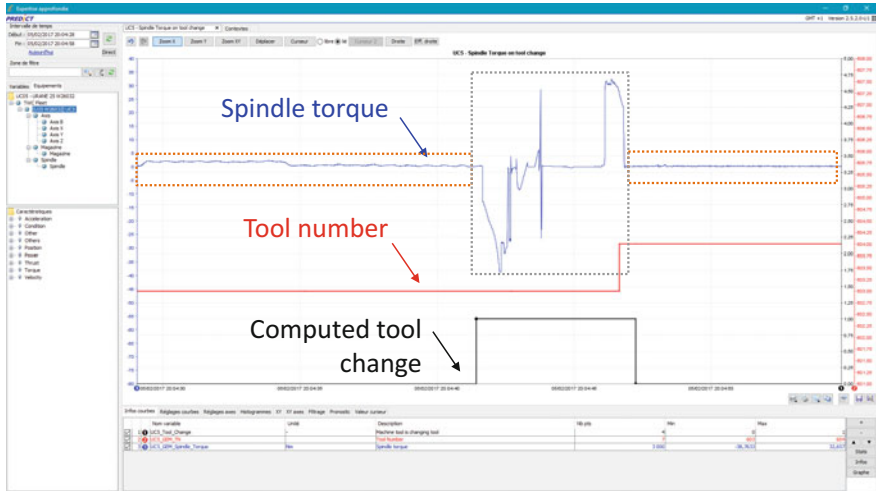


Fig. 8.3 Example of tool change detection for step decomposition

8.2.3 Indicator Processing

Rather than using the overall dataset to understand the behaviour, indicators based on descriptive statistics are computed to summarize the dataset. The indicators commonly used to describe a data collection distribution are (Fig. 8.4).

- The central tendency or centre of the distribution given by the mean and the median.
- The dispersion given by the percentiles, extreme values and standard deviation. A percentile is a value below which a given percentage of the data collection falls. The most frequently used percentiles are:
 - The median or 50th percentile.
 - The lower and upper box, respectively, the 25th and 75th percentile.
 - The lower and upper whisker, respectively, the 5th and 95th percentile.

8.2.4 Example of Indicators

In this section, two examples of indicator extraction are presented. The first one is focused on tool behaviour, based on spindle torque observed in a specific machining step. The second one aims at monitoring axis dynamic behaviour.

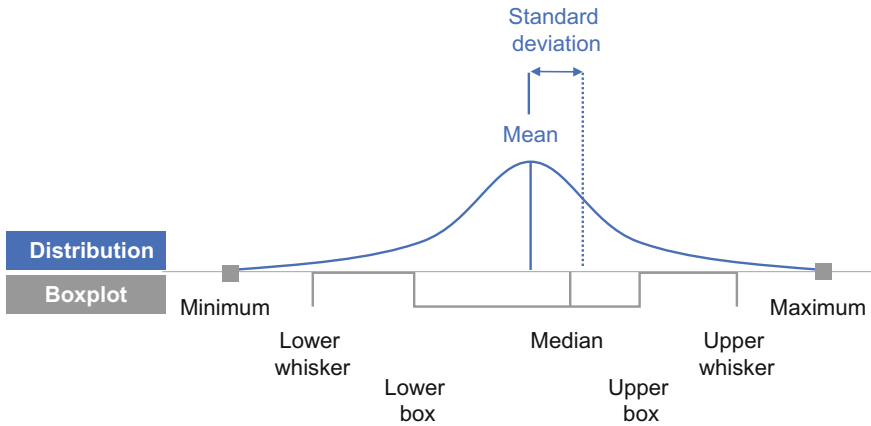


Fig. 8.4 Descriptive statistics: representation of distribution and box plot data



Fig. 8.5 Example of machining step decomposition. In blue, Z-axis position; in red, the tool changes; and in green, axis moving conditions

8.2.4.1 Spindle Torque When Machining at a Specific Step—Tool Behaviour

To observe a tool behaviour, one should focus on a specific step and extract indicators from spindle torque sensors when machining. A specific step is depicted in Fig. 8.5, where the red curves correspond to the tool change phases and the cyan curve shows phases where Z-axis is moving. The blue curve represents the Z-axis position.

As shown by the Z-axis position, this step consists of successive drilling operations. In Fig. 8.6, the spindle torque associated to this step is represented by the

This example shows the evolution of tool behaviour, characterized by spindle torque upper box, for a machine programmed to produce two types of workpieces, part 1 and part 2. Each data on the graph represent the spindle torque upper box. Thanks to this indicator, it can be observed:

- Tool changes: ruptures are visible each time the tool is replaced.
- Tool wearing: for each new tool, the indicator's value is around 3 Nm and increases with use.

8.2.4.2 Axis Thrust When Axis Is Moving Linear—Axis Dynamic Behaviour

An axis linear move is composed of three phases: acceleration, linear displacement and deceleration. These steps are visible observing the axis position as illustrated in Fig. 8.8. The monitoring of axis thrust, illustrated by the black curve, during acceleration and deceleration phases gives an overview of the dynamic efforts required by an axis to move.

Hence, the following indicators may be extracted:

- Lower whisker characterizes *X*-axis thrust required to accelerate.
- Upper whisker characterizes *X*-axis thrust required to decelerate.
- Mean gives an indicator of axis balance.

In Fig. 8.9, the evolution of *X*-axis dynamic behaviour is represented, characterized by the mean thrust. A specific move for each processed part type has been defined. The exact same conditions could not be found between the two parts types'

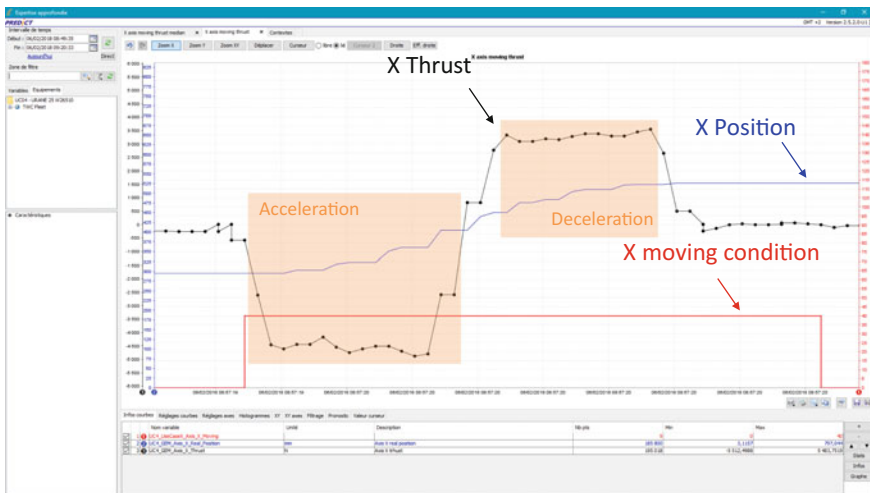


Fig. 8.8 *X*-axis moving thrust behaviour



Fig. 8.9 X-axis moving mean thrust

operations, leading to different values for the same indicator depending on the part being operated. For each move, the indicator analysis gives the same observation: with the use of the machine, X-axis thrust centre drifts until a certain point and then resets to the initial value. The breaking point is in fact due to a maintenance operation, leading to the conclusion that the value decrease was due to the axis degradation.

8.3 Machine Tool Characterization Tests

The analysis of indicators obtained from raw measurements during conventional machining operation is sometimes difficult, especially when trying to determine the condition of the machine tool. Perturbations, like the machining process itself, can hide the real performance of the machine tool. In addition, it is sometimes difficult to get repetitive movements from which comparable indicators can be obtained, especially in small batch sectors like aerospace.

In this line, a characterization procedure for machine tools has been defined, validated and implemented in Twin-Control project. The objective is to provide the opportunity to the end-user to perform a very simple and fast characterization of the machine tool, under controlled conditions. This way, a periodic checking is possible, leading to a better track of machine tool condition over time.

Next, the different proposed tests are presented.

8.3.1 *Diagonal Positioning Error Measurement*

The aim of this test is to determine the volumetric performance of a machine tool through a fast and reduced procedure. To achieve a volumetric performance indicator, diagonal positioning measurement is done in two diagonals of the machine tool. This way, it can be known if machine continues under specifications or not. The measuring procedure is based on an indirect method; it means that not just positioning error of each of the three linear axes is achieved, but perpendicular error between each pair of axes too.

This measuring procedure is suitable for three axes machine tools without moving table (bed type, column type, gantry type) or rotary axis. Moreover, the considered range is between 400 and 20,000 mm for the largest axis length of a machine tool.

As a reference, four measurements per year are suggested, one every three months. However, depending on the results of the volumetric performance indicator, architecture of the machine and workshop ambient conditions, the frequency of the tests could be varied and adapted on each case.

Diagonal positioning measurement in medium-large machine tools requires from an interferometry laser-based measuring system with the capacity to do the tracking of a mirror/retroreflector placed on the machine tool spindle. Either laser tracer or laser tracker measures the relative movement/displacement of a retroreflector from the initial point, based on their interferometry laser-based system. Both measuring devices can track a retroreflector placed on the machine tool's spindle, allowing the measurement of machine tools movement in a fast and easy way, without special set-ups or fixing tools. This is the main advantage compared with common laser interferometry, which requires a tricky set-up process for this kind of measuring procedures where several axes of the machine tool are interpolated to create a special diagonal.

The measuring procedure is based in the ISO 230-6 [2] and consists of measuring two opposite diagonals carried out by the machine, such as B1-E1 and G1-D1 in Fig. 8.10. A diagonal positioning machine cycle needs to be programmed with stops at, at least, four equidistant points per metre. If the measuring range is short, the number of points should be higher. Indeed, not only the spatial position of the machine is measured, but also the distance between predefined (objective) points.

ETALON AG provides the most suitable software to manage this measure, Track-check [3]. If it is connected to the machine tool and measuring device, it automatically detects machine stops to perform a measurement. When the measurement has been successfully completed, the software calculates the mean bi-directional positional deviation which is graphically represented. A report summarizing the results is also provided.

This test provides a quick view of the geometric condition of the machine tool, but its aim is not to provide quantitative data. If the results show deviation with respect to reference values, a complete volumetric measurement should be performed to map the geometric errors of the machine tool and to be able to compensate them.

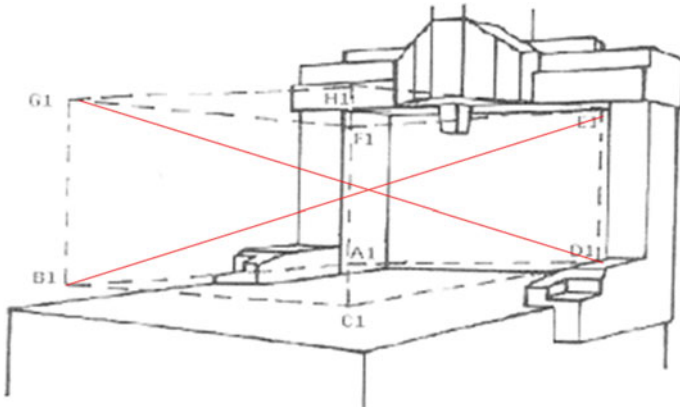


Fig. 8.10 Two opposite diagonal measurements [2]

(a)



(b)

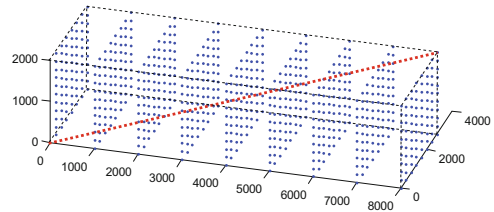


Fig. 8.11 Validation of diagonal error measurement test: **a** laser tracker installed in GEPRO 502 machine; **b** example showing the measurement points needed for the complete volumetric characterization (blue) and the diagonal measurement (red)

This procedure has been validated in different machines. Next, the results obtained in one of the use cases from the aerospace validation scenario, GEPRO 502 machine (Fig. 8.11a), are presented. As indicator, maximum value of the mean bi-directional positional deviation (ξ) is obtained from the measured diagonal, according to [1], for each measured point. In all cases, results obtained in a complete volumetric error characterization, with a test time of around 10 h, are compared against an error measurement in a machine diagonal, with a duration of around 30 min (Fig. 8.11b).

Figure 8.12 shows the results obtained for the GEPRO 502 machine with the complete volumetric characterization and the diagonal measurement. A direct correlation between both measurements exists since the machine tool’s maximum volumetric positioning error is between 250 and 300 μm for both cases. When validating diagonal measurement against the volumetric mapping of each machine, it can be concluded that positioning error correlates properly between results, but perpendicularity does not. It seems that the model that converts diagonals into positioning and perpendicularity errors does not fit to the model of the volumetric error modelling. Anyway, for

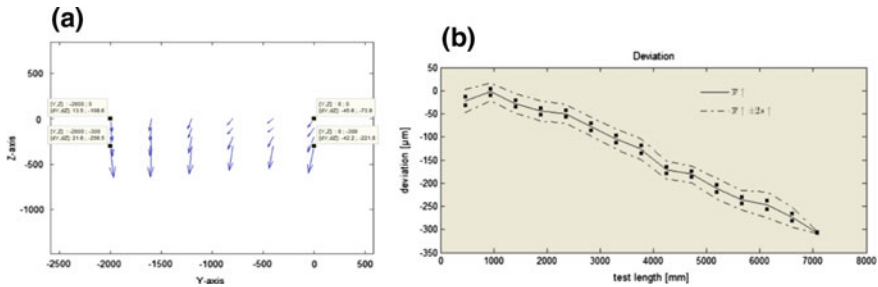


Fig. 8.12 Error measurements obtained in the GEPRO 502 machine: **a** complete volumetric characterization—YZ-plane; **b** space diagonal

a qualitative detection of machine geometric performance's deviation, the proposed test is valid.

8.3.2 *Artefact Measurement Using Touch Probe*

The main objective is to carry out a fast and reliable “health check” of the machine geometric performance, verifying whether the relative position/orientation between the machine tool coordinate system and the working volume is within the expected tolerances, using an artefact as a reference for the measurements.

The procedure consists of measuring the centre or position of several features (e.g. spheres) of an artefact located in the working volume with the touch probe and the corresponding software that allows doing the measurement. The proposed measuring process is automatic (using a CNC macro) and suitable to have the chance to export the results from the CNC.

A KONDIS MAXIM machine tool, located at IK4-TEKNIKER (Fig. 8.13a), has been used to validate this test. This machine has a moving table where the artefact is mounted and fixed during the measurements (Fig. 8.13b). In addition, the KONDIS machine provides the possibility to use a Renishaw touch probe with external software (Power Inspect) [4].

As cited above, a calibrated artefact located and fixed on the machine tool volume is measured to analyse the geometrical stability of the machine tool. The artefact is comprised of four spheres, and these geometries are measured each time to assess their position according to machine tool coordinate system and thermal environmental conditions. During the measurements, temperature is monitored to establish a relationship between the dimensional measurements and thermal ones.

For the validation, the measurements have been repeated over a certain period (24 h) to study the effect of thermal variations. After the tests, data are processed to correlate the geometrical instability with the thermal environmental condition variation. The result depicted in Fig. 8.14 shows the deviation of the position of the

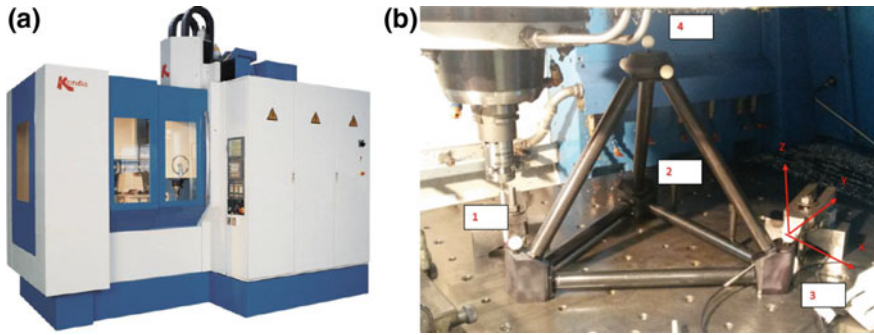


Fig. 8.13 a KONDIA MAXIM machine tool; b artefact mounted in the machine

four spheres of the artefact during part of the validation process. It can be observed that the positions of the sphere centres measured by the machine and the touch probe are not stable according to temperature variations. The measurements registered for 9 h clearly prove that the coordinate system of the machine tool and therefore its kinematics are not constant against thermal influences.

For an increase in T^a of approximately $5\text{ }^\circ\text{C}$ (comparing to the starting state), the maximum drift of the machine is established in Z -direction (inverse to gravity direction) and is around $60\text{ }\mu\text{m}$. Moreover, as all the centres present the same behaviour, a lack of stability of the artefact is discarded. The drift in X - and Y -directions is lower than in Z -direction for this kind of machine tool.

With these results, it can be concluded that the indicator, maximum deviation in X - Y - Z of any of the spheres for a certain temperature will be enough to determine the thermal stability of the machine. If the obtained indicator is above the determined threshold, to be characterized before, the machine will need to be examined in deep.

8.3.3 *Dynamic Stiffness Measurement of Tool/Part*

The objective of this test is to control the dynamics stiffness of the machine tool. A hammer test is proposed to evaluate the dynamic performance of the machine tool [5].

On the one hand, the force sensor at the hammer serves to provide a measurement of the amplitude and frequency content of the energy stimulus that is applied to a test object. On the other hand, accelerometers are used to measure the machine's structural response due to the hammer force. A single triaxial accelerometers located at the spindle will be used. A multichannel Fast Fourier Transform (FFT) analyser is needed to carry out the signal acquisition, sensor conditioning and FFT processing.

If possible, both excitation and measurement will be carried at the machine tool spindle. Different resonant frequencies must be identified and characterized with the following indicators: frequency, dynamic compliance, damping ratio and direction of excitation.

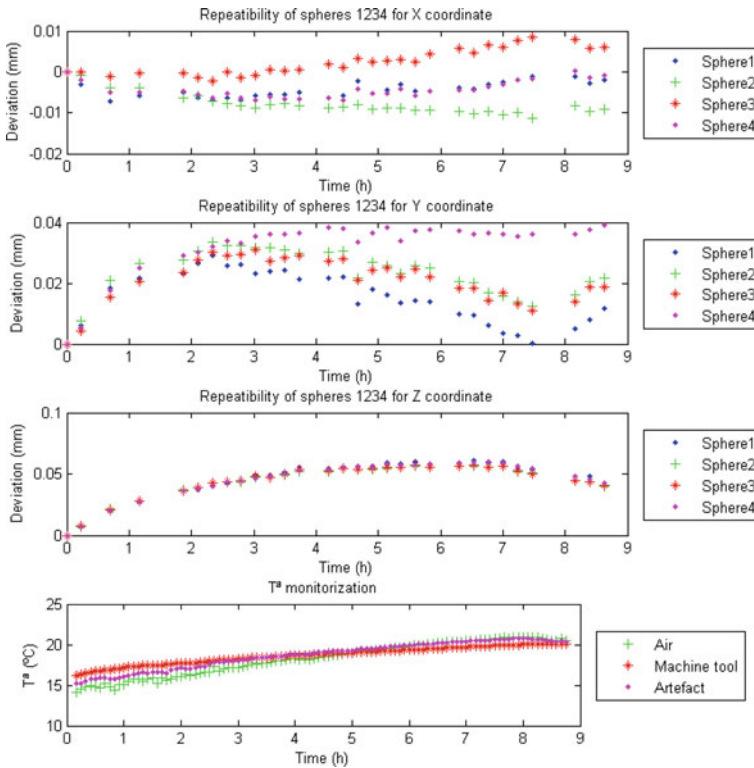


Fig. 8.14 Results of sphere positioning variation and temperature variation

A complete modal analysis has been carried out on the GORATU D-Dynamic machine located in IK4-TEKNIKER. Modal analysis consists of the experimental identification of vibration mode frequencies and the correspondent mode shapes. To do that, the machine is hit by a hammer and the vibrations are measured by accelerometers located in all the structure of the machine as depicted in Fig. 8.15.

Figure 8.16 presents the frequency response of the different points of the machine in X -direction when the disturbance, i.e. hammer force, is also done in X -direction. Two main resonance frequencies are identified, at 82 and 124 Hz. When using a single accelerometer at the tool tip, which is the aim of the proposed test, the frequencies will be accurately identified, since the obtained curve is part of the bunch of curves presented in the previous part. However, the measurement of a single point will not be enough to represent vibration mode shapes, but this is not the aim of the proposed periodic measurement.

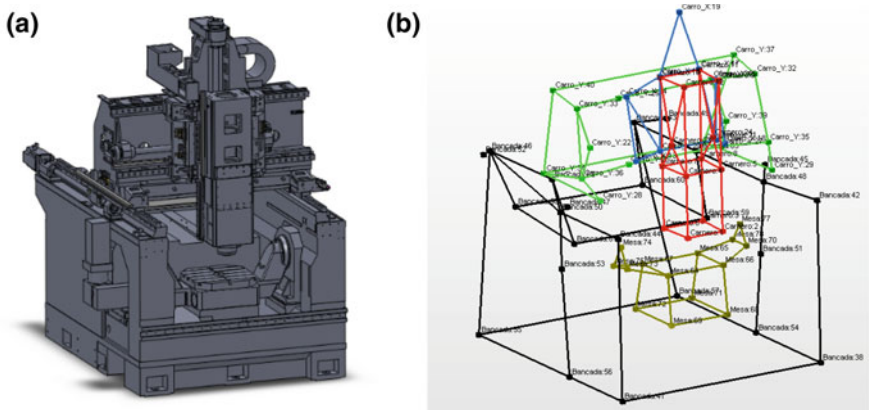


Fig. 8.15 Validation of dynamic stiffness characterization in the GORATU G-Dynamic: **a** diagram showing structural components; **b** points where accelerometers were located

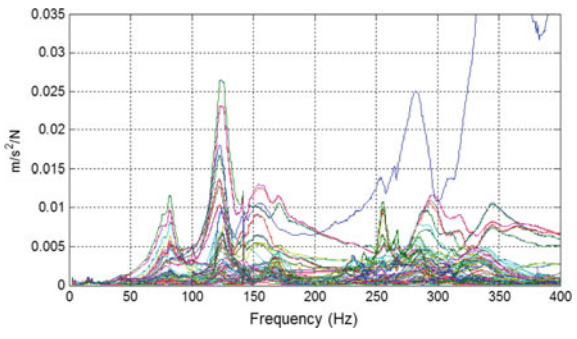


Fig. 8.16 Frequency response diagram showing vibrations of the different points of the GORATU machine in X-axis when excited in X-axis

8.3.4 Feed Drive and Spindle Auto-Characterization

In this case, a very fast characterization of the dynamic response of the feed drives and spindles of the machine tool is proposed. The idea is to execute very simple movements under controlled conditions while monitoring internal variables of the machine tool. The proposed sequence of movements is:

1. Back and forth displacement of each linear axis.
2. Circular interpolation of each pair of axes.
3. Spindle rotation at constant speed.

Each movement is a simplification of a more complicated test. For example, circular interpolation and the monitoring of internal position sensors is a simplification of the ball-bar test [6], which is commonly applied for machine tool geometric evaluation. Ball-bar test requires a specific hardware to track the position of the spindle

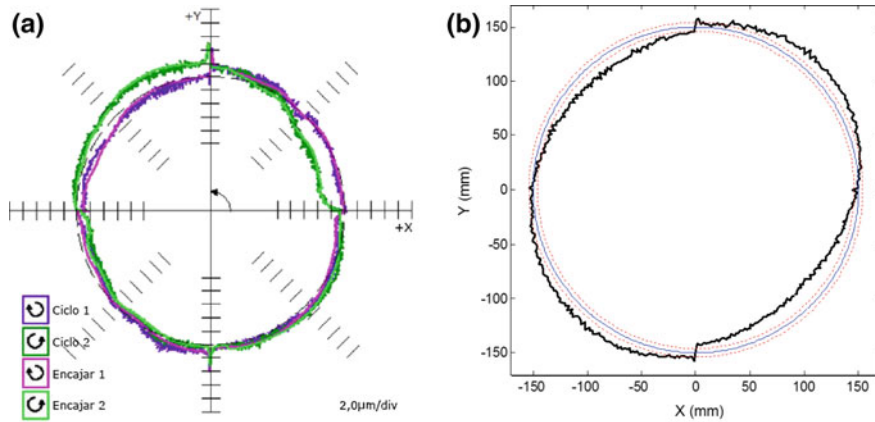


Fig. 8.17 Validation of the circular interpolation test from the feed drive auto-characterization procedure. Results obtained in a circular interpolation of the X- and Y-axes of the GORATU G-Dynamic machine: **a** results from the report available after the ball-bar test; **b** results obtained by using internal sensors for measurement

Table 8.2 Comparison of the indicators obtained in the circularity tests

	Ball-bar (μm)	CNC (linear scales) (μm)
Reversal peaks	2.5	2
Backlash	0.5	4
Circularity	8.3	10

during a circular interpolation. In Fig. 8.17, a report generated by a ball-bar device during a circular interpolation is compared with the results obtained in the same test by using linear scale position.

Table 8.2 summarizes the most important indicators obtained with both approaches to analyse circular interpolation performance. Although the simplified approach does not provide a quantitative estimation of the desired indicators, it provides an approximate idea and can be used for a qualitative analysis. The internal control variable measurement approach is not aimed to replace the ball-bar test to determine interpolation performance of the machine tool, but to provide the chance to quickly evaluate changes in the performance of a machine tool without installing the required hardware.

The complete sequence of movements is programmed in ISO code and is fed to the machine. By making use of monitoring capabilities implemented in Twin-Control project [7], data are continuously acquired during the test. The monitored data are uploaded to the fleet server, where it is processed to obtain relevant indicators like friction, backlash, inversion peaks and maximum power in feed drives, and power consumption in spindles. If an accelerometer is installed in the spindle, vibration analysis can be performed, providing relevant indicators to estimate its condition [8].

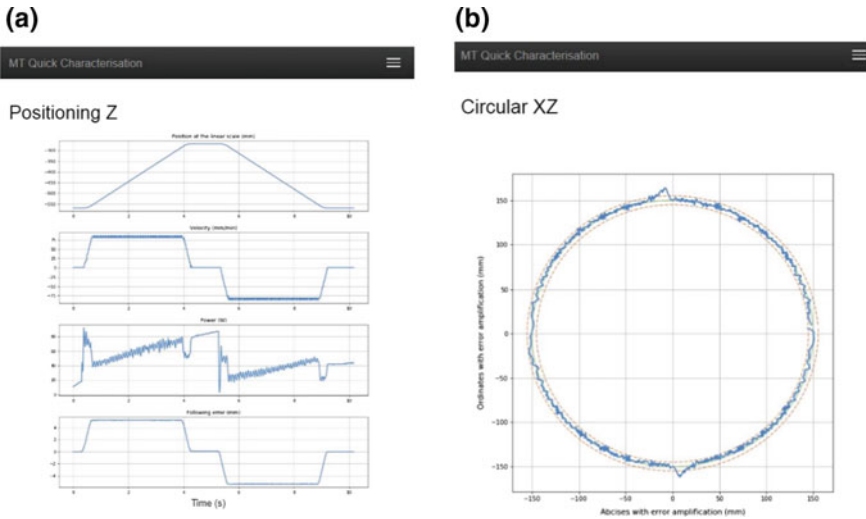


Fig. 8.18 Sample of the machine tool characterization test report generated on KASEM[®] after the auto-characterization: **a** linear translation of the Z-axis; **b** Circular interpolation of X- and Z-axes

The results of the tests are available in the cloud platform, KASEM[®], just after tests execution. Indicators are managed together with the rest of indicators coming from the normal operating condition of the machine and, in case a deviation from nominal conditions of the machine tool is detected, a warning is generated. Apart from that, after each test execution a report is generated where the obtained indicators are summarized, and the user can analyse in detail the performance of each test as shown in Fig. 8.18.

The proposed test is totally automated and does not require special skills to machine tool operator nor special equipment. Test duration can vary depending on machine size, number of axis and dynamics, but it is always below 5 min.

Although the proposed procedure is not aimed for a quantitative characterization of the machine, it is very well suited for a qualitative analysis of machine tool condition. In addition, the short duration and its simplicity make it suitable for a periodic execution, leading to a better control of machine condition during its life cycle.

8.4 Conclusions

The behaviour of a machine tool is observable by computing contextualized information from sensors measurements. Two indicator extraction methodologies were described in this section. The first one exploits the in-production sensors' measurements to extract statistical features from specific machine operating conditions, and

the second one exploits the results of specific tests, called characterization tests, performed by the machine.

Both methodologies are based on known machine context exploitation. To have a full overview of the machining process and capacities, it is recommended to analyse indicators from both methodologies:

- The raw sensors' measurements indicator extraction offers high volume of data and is performed in parallel of the production. Nevertheless, the machine capabilities observed depends on the program performed such as indicators that illustrate only a part of the machine capabilities.
- The characterization test approach allows to observe the overall machine tool capacities as entire axis moves are performed under controlled conditions. Nevertheless, it requires to perform a specific program interrupting the production for about five minutes.

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