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EVALUATION AND REPRESENTATION OF MACHINE TOOL DEFORMATIONS

This paper presents a novel test concept for the evaluation of the accuracy of NC machine tools. The evaluation of machine tools deformations is performed by help of a device similar to the double ball bar (DBB) with the difference that an adjustable load generated by the device can be applied between spindle nose and machine tool table. This load eliminates the play existing in machine tool joints, thus reproducing the testing conditions that exist during machining. Collected data are used to plot diagrams displaying characteristic aspects of machine tool performance and a number of key figures such as static stiffness may be determined. The data can also be used for trend analysis; to predict any accuracy deviations, and further to conduct preventive maintenance instead of emergency calls. The determined static behaviour could also be used to improve digital models for process simulations and compensation of errors that are caused by deflection.

1. INTRODUCTION

The major performance factors of any machining operation, productivity and accuracy, are determined by the static and dynamic stiffness of the machining system. One way of increasing the efficiency of a production system is to continuously improve, and develop new tests and evaluation methods of the machining system. This is especially important when the goal is to produce a specific part correctly for the first time, in the quickest and most cost effective way. In this regard, new or improved test methods help to gather information about system status and can be stored in digital machine tool models used for analysis and optimization [1]. New improved virtual machine tool models need experimental data for validation and optimization. Therefore, the main objective of this paper is to contribute to improving machining system deformation evaluation methods.

1.1. NEED FOR MACHINE TOOL TEST METHODS

The costs of unplanned disturbances are increased when lean and agile production is implemented on the shopfloors. It is becoming more and more important to detect emerging

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problems at an early stage. There is a need for new machine test methods to be able to perform regular diagnoses of sensitive equipment and to perform preventive maintenance in order to avoid unplanned disturbances. By using proper test methods, the performance of major interacting parts inside the machine tool, can be surveyed. Over the years machine tool testing has become increasingly important for machine tool builders and end users.

For the machine tool builders it provides a recognized mean for checking the machine against its design specification. For the machine tool user, capability testing offers both a mean of measuring production performance, and an evaluation aid for machine maintenance. The industry's requirements have been met to a certain degree by the wide availability of modern metrology equipment aimed specifically at machine tool testing. This has provided the means for accurate measurement of machine tool errors. Extensions of national and international standards to cover all aspects of machine accuracy and testing have increased the awareness and need for machine testing [2],[3]. Testing standards are essential if machine capability is to address the needs of both the machine tool builders and the end users. To meet these needs, the standards are, to a certain extent, a compromise. Economic considerations mean that machine non-productive time must be kept to a minimum, while quality considerations mean that the calibration should be detailed enough to provide meaningful results. To find the optimum between the two factors is a crucial issue when developing or improving test methods.

The relation between the time required performing the tests and the use of captured data is an important parameter when choosing test methods. In this context, mainly two categories of test methods during the lifecycle of a machine tool; named quick test (Q test) and complete test (C test), are relevant for accuracy inspection as shown in Fig. 1.

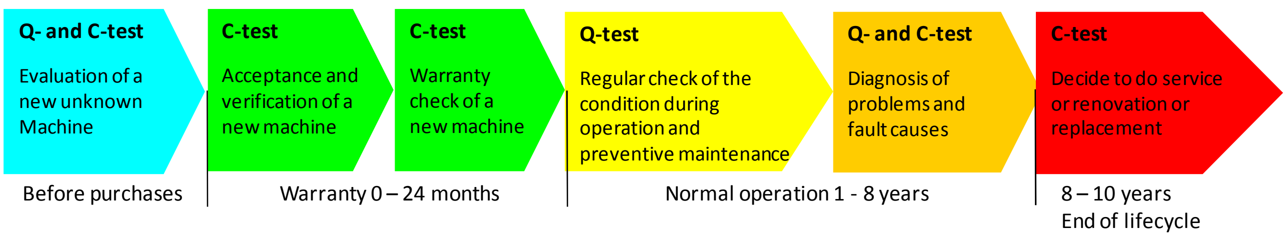

Fig. 1. Machine testing during the lifecycle of a machine tool

The Q test is a quick method (less than an hour) to monitor the overall performance and to give early warnings of dangerous trends in order to prevent unplanned expensive disturbances. This kind of test could be performed several times a year. Examples of test methods that can be included in a quick test are, double ball bar (DBB), vibration measurements of spindle unit, and checking spindle straightness.

The C test could, if necessary, take several days and has the special purpose of analysing the status in detail before a decision is taken to buy or accept new machines, to repair, renovate or replace used machines. This kind of test is normally done a few times during the lifecycle. The C tests are mainly done by specialists and are normally done in investment projects or when serious problems have come up. Condition tests according to type Q test for preventive maintenance are not common in industry. The main reasons are lack of practical tools and methods, lack of standardised routines at the company, and lack of knowledge. There are a lot of test methods available for machine tools [4]. Some can be used for Q tests but the majority of tests take too long to be performed and can therefore not be considered Q tests. However, a new test method, based on circular test [5], [6] is introduced in this paper. Detailed understanding of total geometric error in machining requires measurement of axes in simultaneous movement and applied load on the machine tool structure. These conditions are achieved in measurement using the loaded double ball bar system [7],[8].

2. LOADED DOUBLE BALL BAR (LDBB)

By combining the traditional DBB test and the capability to generate a load on the machine tool structure, valuable information can be obtained. A device that combines these two capabilities is called loaded double ball bar, abbreviated LDBB. The device can be used as an ordinary double ball bar system when no load is applied to the structure. The device is primarily of interest as a certification instrument for new machines, for testing machines after they have been moved or renovated, and as a tool for preventive maintenance.

The basic design of the LDBB (see Fig. 6) looks very similar to the traditional DBB system. The difference is that a pneumatic actuator is built inside the detecting probe. The detecting and loading instrument is attached between two steel balls, which are connected via special fasteners to the machine tool structure; one to the spindle and one to the machine table. When air pressurised is injected into the cylinder a resulting force is generated, which the machine tool structure deflects by a certain amount that depends on its static stiffness. The change in distance between the two balls is detected by a length gauge located inside the instrument. The measuring range is ± 1 mm and the system is designed to have an accuracy of ± 0.5 μm.

2.1. DEFLECTION IN TABLE AND TOOL JOINT

To accurately evaluate the machine tool's performance with the LDBB it is important to investigate the deformation of the device itself for different magnitudes and orientations of the applied load.. The resulting deflection between the ball and the attachment bar depends on both the force magnitude and the angle at which the force is applied.

To determine the maximal deflection in joints, a calibration fixture was developed. The maximum deflection of the attachment ε_{max}=14 μm occurred when the force was F_{max}=741 N (P_{max}=6 bar) and orthogonally applied to the ball. The results from the measurements showed that the deflections were described by either a $\sin^2(v)$ or $\cos^2(v)$ function, whereat v is the angle between the force direction and the horizontal axis trough the table and spindle ball.

Two major machine tool configurations are considered when calculating the deflection. The first configuration corresponds to a vertical machining centre and the second configuration corresponds to horizontal machining centre. Each measured value is sampled at the corresponding angle φ in a right shifted coordinate system, counted in a counter clock wise (CCW) direction. For X-Y plane the angle is positive from X to Y axis, in a Y-Z plane, positive from Y to Z axis and in a Z-X plane, positive from Z to X axis.

2.2. HORIZONTAL MACHINE TOOL DURING MEASUREMENT IN Y-Z PLANE

In this type of machine tool configuration the deflections occurs in both spindle and table joints. If we assumes that the table ball is centred in origo (0, 0) and the spindle ball is positioned in (y, z), then the unloaded (i.e. when no force is applied) length L of LDBB is

$$L = (y^2 + z^2)^{1/2} \tag{1}$$

When the force F is applied to the system, the length of the LDBB L' becomes, (see Fig. 2)

$$\begin{aligned} L' &= \left(((y + F \cdot k\cos(\varphi))^2 + (z + F \cdot k \cdot \sin(\varphi))^2\right)^{1/2} \\ L' &= (y^2 + F^2 \cdot k^2 \cdot \cos(\varphi) + 2 \cdot y \cdot F \cdot k \cdot \cos(\varphi) + z^2 + F^2 \cdot k^2 \cdot \sin^2(\varphi) + \\ &+ 2 \cdot z \cdot F \cdot k \cdot \sin(\varphi))^{1/2} \end{aligned} \tag{2}$$

where φ is the angle between the LDBB and axis of investigation. Eq. (1) in Eq. (2) and ($\sin^2 + \cos^2$) = 1 gives

$$L' = (L^2 + F^2 \cdot k^2 + 2 \cdot F \cdot k(y \cdot \cos(\varphi) + z \cdot \sin(\varphi)))^{1/2} \tag{3}$$

however

$$\begin{aligned} & y = L \cdot \cos(\varphi), z = L \cdot \sin(\varphi) \\ & \Rightarrow L' = (L^2 + F^2 \cdot k^2 + 2 \cdot F \cdot k(L \cdot \cos^2(\varphi) + L \cdot \sin^2(\varphi)))^{1/2} \end{aligned} \tag{4}$$

this gives

$$L' = (L^2 + F^2 \cdot k^2 + 2 \cdot F \cdot k \cdot L)^{1/2} \tag{5}$$

where

$$L' = L + F \cdot k \tag{6}$$

i.e. the compensation

$$L' - L = F \cdot k \tag{7}$$

Eq. (7) can be written as

$$L' - L = F \cdot k \cdot \sin^2(\varphi) + F \cdot k \cdot \cos^2(\varphi) \tag{8}$$

where $F \cdot k \cdot \sin^2(\varphi)$ and $F \cdot k \cdot \cos^2(\varphi)$ are the deflection in the table and spindle joint respectively.

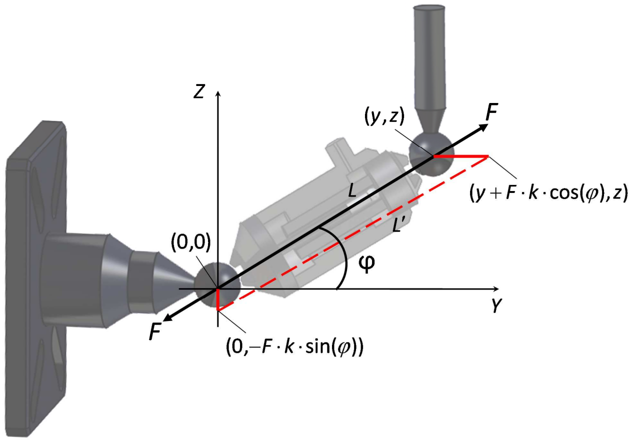

Fig. 2. Horizontal machine tool: deflection in spindle and table joint during measurement in Y-Z plane

2.3. VERTICAL MACHINE TOOL DURING MEASUREMENT IN Y-Z PLANE

If we assumes that the table ball is centred in origo (0, 0) and the spindle ball is positioned in (*y*, *z*), then the unloaded (when no force is applied) length *L* of LDBB is

$$L = (y^2 + z^2)^{1/2} \tag{9}$$

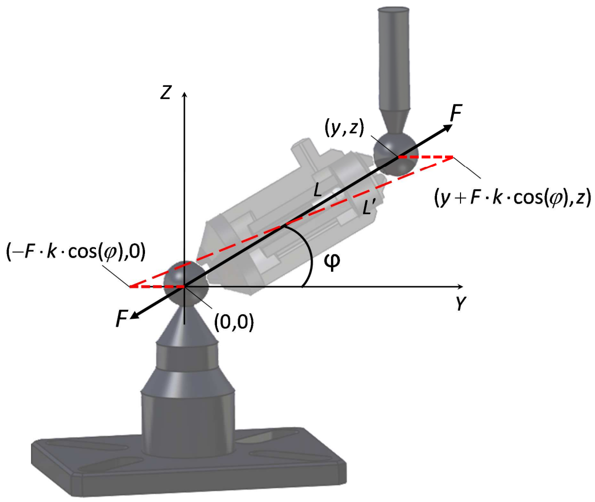

Fig. 3. Vertical machine tool: deflection in spindle and table joint during measurement in Y-Z plane.

When the force *F* are applied to the system the new length *L'* (Fig. 3) can be calculated accordingly Eq. (9)

$$\begin{aligned} L' &= ((y + F\cdot k\cdot\cos(\varphi) + F\cdot k\cdot\cos(\varphi))^2 + z^2)^{1/2} = \\ &= ((y + 2\cdot F\cdot k\cdot\cos(\varphi))^2 + z^2)^{1/2} = (y^2 + 4\cdot F^2\cdot k^2\cdot\cos^2(\varphi) + \\ &+ 4\cdot y\cdot F\cdot k\cdot\cos(\varphi) + z^2)^{1/2} \end{aligned} \tag{10}$$

$$L' = ((y + F \cdot k \cdot \cos(\varphi) + F \cdot k \cdot \cos(\varphi))^2 + z^2)^{1/2} =$$
$$= ((y + 2 \cdot F \cdot k \cdot \cos(\varphi))^2 + z^2)^{1/2} = (y^2 + 4 \cdot F^2 \cdot k^2 \cdot \cos^2(\varphi) +$$
$$+ 4 \cdot y \cdot F \cdot k \cdot \cos(\varphi) + z^2)^{1/2}$$

simplified

$$L' = (L^2 + 4 \cdot F^2 \cdot k^2 \cdot \cos^2(\varphi) + 4 \cdot y \cdot F \cdot k \cdot \cos(\varphi))^{1/2} \quad (11)$$

where $y = L \cdot \cos(\varphi)$ in Eq. (11) gives

$$L' = (L^2 + 4 \cdot L \cdot F \cdot k \cdot \cos^2(\varphi) + 4 \cdot F^2 \cdot k^2 \cdot \cos^2(\varphi))^{1/2} \quad (12a)$$

and

$$L' = (L^2 + 4 \cdot F \cdot k \cdot \cos^2(\varphi) \cdot (L + F \cdot k))^{1/2} \quad (12b)$$

The unloaded length *L* of the LDBB is 150 mm and the maximum deflection $F \cdot k = 14$ μm. This (*L*>>*FK*) gives the possibility to replace $F \cdot k$ with the smaller term $4 \cdot F^2 \cdot k^2 \cdot \cos^4(\varphi)$ in equation (12b)

$$L' = (L^2 + 4 \cdot L \cdot F \cdot k \cdot \cos^2(\varphi) + 4 \cdot F^2 \cdot k^2 \cdot \cos^2(\varphi))^{1/2} \quad (13)$$

which is

$$L' = ((L + 2 \cdot F \cdot k \cdot \cos^2(\varphi))^2)^{1/2} \quad (14)$$

$$L' = (L + 2 \cdot F \cdot k \cdot \cos^2(\varphi)) \quad (15)$$

The compensation for the deflection can be written as

$$L' - L = 2 \cdot F \cdot k \cdot \cos^2(\varphi) \quad (16)$$

The load is always assumed to act along the LDBB´s longitudinal axis as shown in Fig. 4 below.

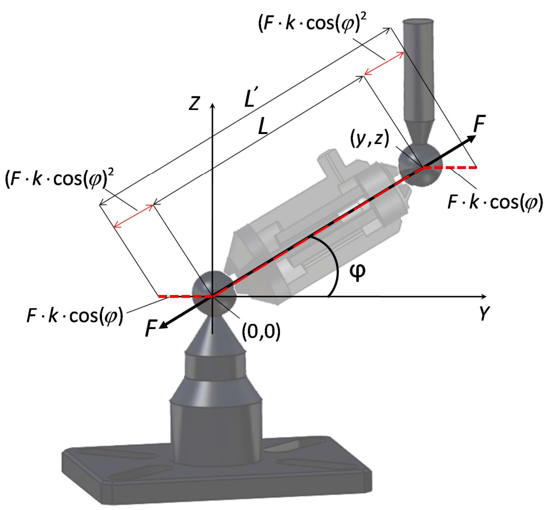

Fig. 4. Deflection in spindle and table ball

2.4. HORIZONTAL MACHINE TOOL DURING MEASUREMENT IN X-Y PLANE

Considering the table ball joint is centred in origo (0, 0) and the spindle joint ball is positioned in (*x*, *y*), then the unloaded (when no force is applied) length *L* of LDBB is

$$L=(x^2+y^2)^{1/2} \tag{17}$$

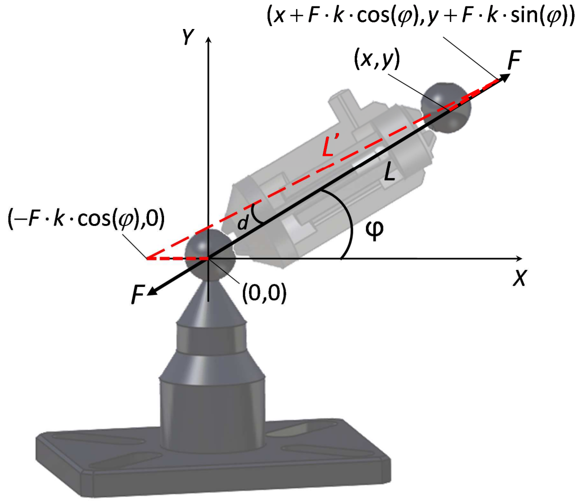

Fig. 5. Horizontal machine tool: deflection in spindle and table joint during measurement in Y-X plane.

The angle *d* between the unloaded length *L* of the LDBB and the loaded length *L'* (Fig. 5) obtained due to elastic deformation of the table ball is set to zero.

$$L'=((x+2\cdot F\cdot k\cdot\cos(\varphi))^2+(y+F\cdot k\cdot\sin(\varphi))^2)^{1/2} \tag{18}$$

$$\begin{aligned}L'=(&x^2+4\cdot F^2\cdot k^2\cdot\cos^2(\varphi)+4\cdot x\cdot F\cdot k\cdot\cos(\varphi)+\\&+y^2+F^2\cdot k^2\cdot\sin^2(\varphi)+2\cdot y\cdot F\cdot k\cdot\sin(\varphi))^{1/2}\end{aligned} \tag{19}$$

$$L'=(L^2+F^2\cdot k^2(4\cdot\cos^2(\varphi)+\sin^2(\varphi))+2\cdot F\cdot k\cdot(2\cdot x\cdot\cos(\varphi)+y\cdot\sin(\varphi)))^{1/2} \tag{20}$$

where $x=L\cdot\cos(\varphi)$ and $y=L\cdot\sin(\varphi)$ together with $\sin^2+\cos^2=1$ gives

$$\begin{aligned}L'&=(L^2+F^2\cdot k^2\cdot(1+3\cdot\cos^2(\varphi))+2\cdot F\cdot k\cdot(2\cdot L\cdot\cos^2(\varphi)+L\cdot\sin^2(\varphi)))^{1/2}=\\&=(L^2+F^2\cdot k^2\cdot(1+3\cdot\cos^2(\varphi))+2\cdot F\cdot k\cdot L(1+\cos^2(\varphi)))^{1/2}\end{aligned} \tag{21}$$

As the length of the unloaded LDBB *L*=150mm, is much bigger than the maximum deflection $F\cdot k=14$ μm gives the possibility to replace $F\cdot k$ with the smaller term $4\cdot F^2\cdot k^2\cdot\cos^4(\varphi)$ in Eq. (21)

$$\begin{aligned}L'&=(L^2+F^2\cdot k^2\cdot(1+2\cdot\cos^2(\varphi)+\cos^4(\varphi))+2\cdot F\cdot k\cdot L\cdot(1+\cos^2(\varphi)))^{1/2}=\\&=(L^2+F^2\cdot k^2\cdot(1+\cos^2(\varphi))^2+2\cdot F\cdot k\cdot L\cdot(1+\cos^2(\varphi)))^{1/2}\end{aligned} \tag{22}$$

i.e.

$$L'=((L+F\cdot k\cdot(1+\cos^2(\varphi)))^2)^{1/2} \tag{23}$$

Eq. (23) can be simplified by removing the square-root to obtain

$$L' = L + F \cdot k \cdot (1 + \cos^2(\varphi)) \tag{24}$$

The deflection is then calculated using Eq. (25)

$$L' - L = F \cdot k \cdot (1 + \cos^2(\varphi)) \tag{25}$$

3. IDENTIFYING LDBB:S MODAL PARAMETERS

Unlike many other types of mechanical systems, machine tool structures, due to their high accuracy requirements, are dimensioned with respect to static and dynamic deflection, and corresponding design criteria of stiffness must be applied. Therefore, a machine tools elastic structure is over-dimensioned in terms of strength. As a consequence of high rigidity of structural members of a machine tool, contact stiffness is one of the principal characteristics in machine tool building due to the presence of many moving or fixed linked joints. The emphasis on contact stiffness in the design of a machine tool structure makes the use of analytical computation methods difficult, since the real contact conditions depend on many internal and external factors. The values of the coefficient of contact compliance depend considerably upon initial pre-stress, dimensions, and accuracy of manufacturing of the joints. A computational model can be used for simulation and identification of basic characteristics such as modal parameters of the elastic structure: tool, tool holder and spindle. The results from simulations can be used as a tool for interpreting the results from experimental methods e.g. experimental modal analysis (EMA).

3.1. COMPUTATIONAL MODEL

To investigate the influence of LDBB on the machine tool structure, a computational model was developed. The purpose of the computational model was to identify the natural frequencies and mode shapes of the elastic structure, tool-tool holder-spindle and compare

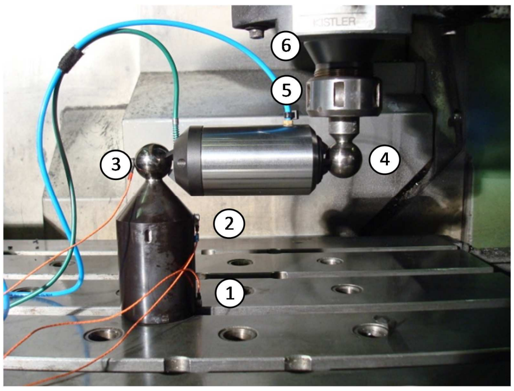

Fig. 6. EMA was performed by measuring the response in six positions (1 to 6) on LDBB, table joint and spindle joint

them to results from EMA. The model is a combination of elementary mass, spring and bar elements representing the spindle-spindle bearings, tool holder and the tool. The varying force applied between table and spindle is simulated through the variation of the spring stiffness k_{LDBB} representing the behaviour of LDBB.

The EMA set-up is illustrated in Fig. 6. The response was measured in six different positions on LDBB and spindle. The results from simulations and EMA are displayed below, and they show the frequency response function (FRF) in position 4.

In the absence of the LDBB the dynamic characteristic of the spindle is represented in Fig. 7. The third mode shape is the tool mode and, as expected, is the most flexible.

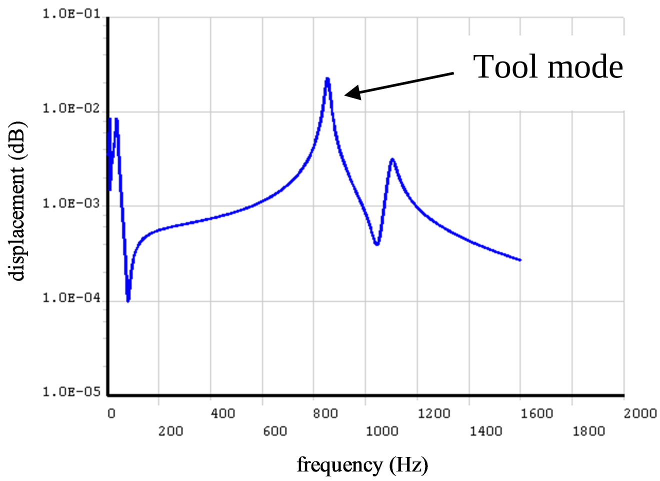

Fig. 7. Simulated FRF representing the first four natural frequencies in spindle-spindle bearings, tool holder and tool system when no load is applied on structure

By varying the spring stiffness representing the LDBB, the corresponding system's dynamic receptance is varying too (see Fig. 8). As expected, the third mode shape, representing the tool, changes significantly. The same behaviour was noticed in EMA of the real system (see Fig. 9).

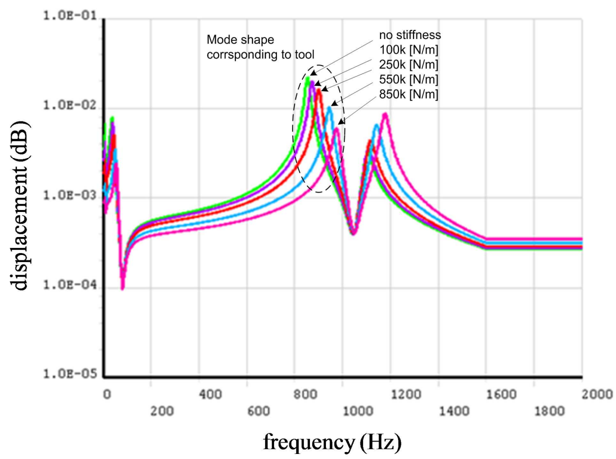

Fig. 8. Simulated FRF representing mode shapes corresponding to spring stiffness k_{LDBB}. The figure shows change in displacement as a function of stiffness increment

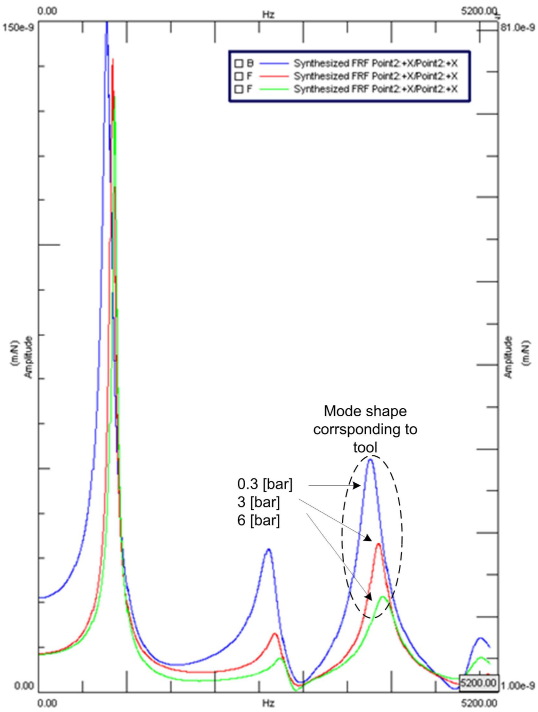

Fig. 9. FRF: EMA mode shapes corresponding to stiffness change in LDBB

Table 1. Mode shape change due to increased stiffness in tool

k_{LDBB} [N/m]	Natural frequency Standard tool stiffness [Hz]				Natural frequency Enhanced tool stiffness [Hz]			
	MS 1	**MS 2**	**MS 3**	**MS 4**	**MS 1**	**MS 2**	**MS 3**	**MS 4**
10k	8	37	855	1101	8	38	997	1724
100k	8.5	41	874	1107	8.5	41	1000	1736
350k	9	47	918	1124	9	49	1004	1767
850k	9	55	976	1178	9	60	1011	1828
Infinite	9	80	-	1047	9	128	1072	-

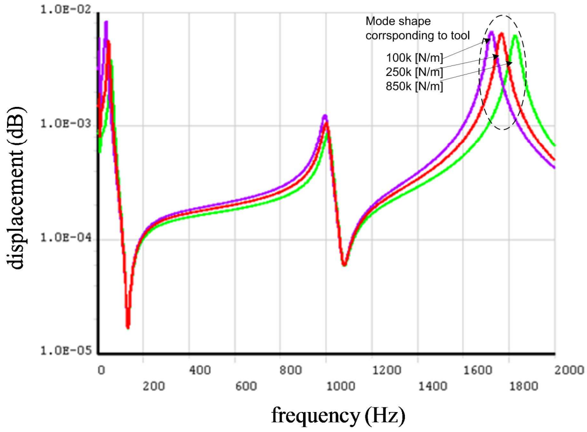

Fig. 10. Simulated mode shapes corresponding to tool shifted from approximately 800 Hz to about 1700 Hz

To investigate how the tool stiffness is affecting the mode shapes of the system, the spring stiffness corresponding to the tool was altered in the computational model. By increasing the stiffness, the natural frequency of the tool increased and as can be seen in Table 1 and Fig. 10, the modal frequency moves from approximately 800 Hz to approximately 1700 Hz.

4. MEASURING DEFORMATION IN X-Y PLANE

A series of experiments were carried out with the scope of showing that static stiffness could be determined by measuring the deflection in a machine tool with the LDBB system. Fig. 6 illustrates the experimental set-up for testing the static stiffness in X-Y plane in a vertical machining centre.

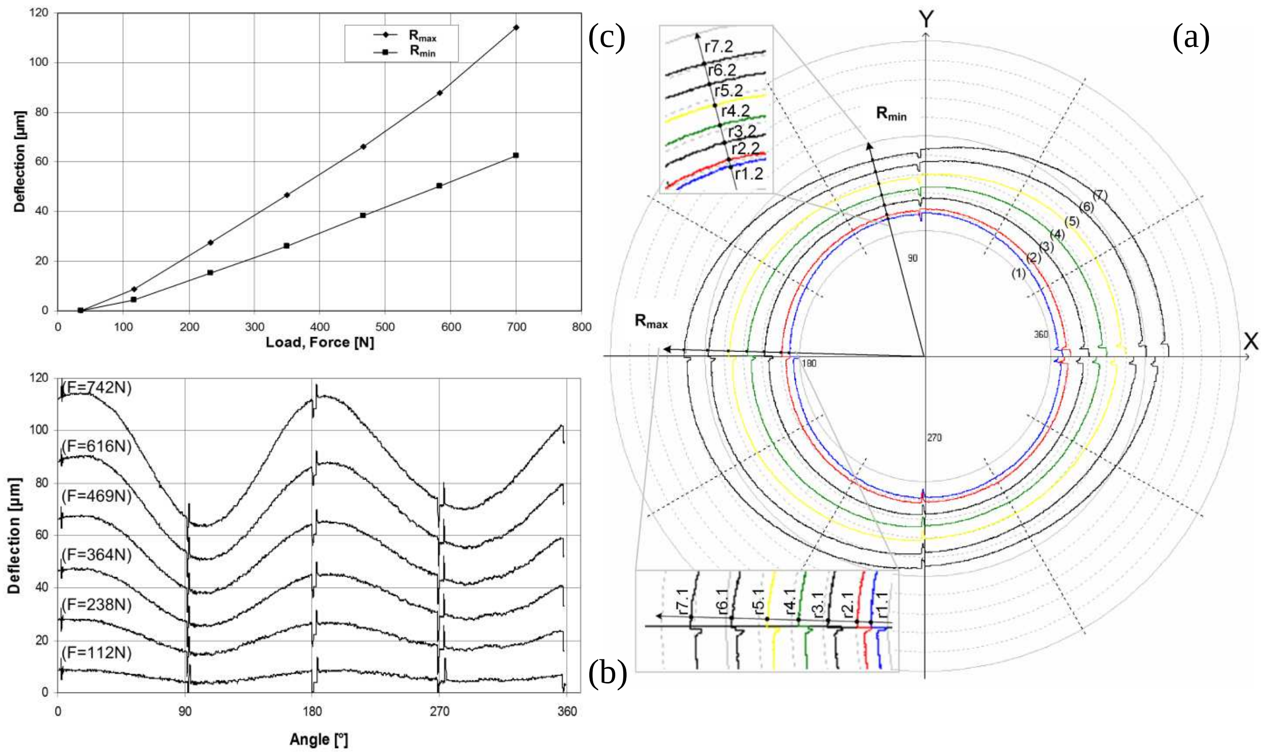

Fig. 11. LDBB measurement result plotted in polar (a) and Cartesian grid (b), (c) maximum deflection $\boldsymbol{R_{max}}$ and minimum deflection $\boldsymbol{R_{min}}$. Counterclockwise circular interpolation on 150 mm radius with feed rate of 2000 mm/min. Load P (1-7) = {36; 112; 238; 364; 490; 616; 742} N

A 3-axis milling machine tool, Mazak with a 5000 rpm spindle was used in the experiments. The tool joint was fastened in a standard ISO 50 taper in the machine spindle. To prevent the spindle from rotating due to external movement or the applied load, the spindle was locked by the servo. The table joint was fastened in the centre of the machine tool table. The circular interpolation feed in X-Y plane, with a radius of 150 mm and a counter clock wise sweep of 360 degrees, were chosen at 2000 mm/min and the load was altered in steps of 1 bar (1bar=112N) to maximum 742 N beginning with 36 N (0.4 bar). The minimum force required for holding the instrument in the right position between spindle and table joint was determined as 36 N.

For 7 different force magnitudes the deflection as function of direction in a 3-axis milling machine tool are given in Fig. 11.The inner circle, see Fig. 11a (1), is displaying the obtained motion trace with a load of 36 N, the second circle, see Fig. 11a (2), is illustrating the obtained motion trace with a load of 112 N, and continuing to the outer circle, see Fig. 11a (7), which is displaying the obtained load of 742 N.

By subtracting the motion trace obtained for 36 N, normalized deflection curves can be plotted, see Fig 11b. By this a correct comparison between the deflections of any two curves can be performed. By using data from the deflection diagram the static stiffness can be calculated. The relationship between deflection and applied force on the machine tool structure can be seen in Fig. 11c. As expected, the structure deflection is nonlinearly increasing with the force. This behaviour can be explained by the play in joints, contact characteristics and lost motion because of the applied load on the machine tool structure. Another explanation could also be the fact that the rigidity is lower than the preload added to the ball screws and, as a result, when the force is applied the structure is compressed and bent. Analysing values from the deflection diagram, linearity between values are apparently for higher force values. For low force values (about 50 to 150 N) the slope of the curve changes.

The static stiffness is calculated by using acquisitioned data from the deflection measurement and the force value for each run.

5. CONCLUSIONS

This paper describes a new test concept for the evaluation of the deformations of the machine tool, and a computational model to study the behavior of the testing device. The geometric error analysis by loading the structure with an adjustable static force provided by the LDBB equipment. Static error evaluation method is improved by using the LDBB system due to its ability to load or unload the structure.

The LDBB measuring method results in evaluating static stiffness of the machine tool in different directions. The machining system stiffness depends on all elastic elements in the closed structural loop machine tool – machining process.

ACKNOWLEDGEMENTS

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