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STATIC AND DYNAMIC PROPERTIES EXAMINATION OF R1000 MILLING MACHINE PROTOTYPE

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Summary

This article presents results of experimental investigations of static and dynamic properties of machine tool R1000 prototype. Investigations were conducted for two different machine tools, each at different stage of exploitation. Dynamic properties were estimated on the basis of experimental modal analysis results. Comparative analysis of both models was conducted. This research was complemented by estimation of static stiffness of the machine tools, based on displacement measurements.

Keywords: modal analysis, dynamics of machine tool, static stiffness of machine tool

Właściwości statyczne i dynamiczne prototypu frezarki R1000

Streszczenie

W pracy przedstawiono analizę wyników badań doświadczalnych prowadzonych celem określenia właściwości statycznych i dynamicznych prototypu frezarki R1000. Badania wykonano dla dwóch obrabiarek na różnym etapie ich eksploatacji. Właściwości dynamiczne obrabiarki określono na podstawie eksperymentalnej analizy modalnej. Dokonano analizy porównawczej modeli modalnych zbudowanych dla obu obrabiarek. Badania uzupełniono estymacją sztywności statycznej, na podstawie wyników pomiarów przemieszczeń.

Słowa kluczowe: analiza modalna, dynamika obrabiarek, sztywność statyczna obrabiarki

1. Introduction

Modern machine tools have to fulfill high requirements regarding quality, repeatability and productivity of machining process. From the other hand, there is a tendency to reduce energy consumption and noise level of machining process [1, 2]. This leads to evolutionary changes in machine tool structure rather than revolutionary and can be divided into two categories. First one consists in the application of new sensor systems or control algorithms, implemented in machine tools, which can be used for thermal error compensation, tool path optimization process or compensation of volumetric error [3]. Second group of machine tools

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modernization employs changes of MDS (mass – damping – stiffness) model structure or it's parameters e.g. a usage of a different headstock, application of some changes in guideway systems [4]. A very common situation is when a machine tool is assembled with components delivered by various suppliers, and these elements varies dynamic properties of a final product. In such a situation, the experimental tests are needed in order to estimate static and dynamic properties. Additionally, gathered data can be used in identification process of FEM (Finite Element Method) models.

In this article, results of such experiments are presented. Modal models of two different machine tools, each at different stage of exploitation were obtained, on the basis of experimental modal analysis results. This research was complemented by estimation of static stiffness of machine tool, based on displacement measurements.

2. Experimental modal analysis

Investigations on both static and dynamic properties of machine tools are present in scientific literature since decades. But still, there is no standard for such investigations. Methodology proposed by authors [5, 6] is still not universal. There is no proposal how to take the control system (presence of linear drives for instance) or non-stationarity (for significant changes of relative position of machine tool bodies) into consideration. Consideration of various relative position of machine tool bodies during experimental tests was proposed [7], but those are not applicative in industrial environment.

The experimental modal analysis of two R1000 milling machines was conducted. First one, was used under normal operational conditions, and the second one was completely new prototype (Fig. 1). The technical differences between both were very slight and connected with control algorithm of the rotational table. The objectives of these investigations were: estimation of dynamic properties of machine tool, comparison of modal models obtained for two specimens of the same type of machine tool, gathering input data needed for FEM model identification process (Table 1).

Modal tests were preceded by: analysis of optimal sensor placement, analysis of different excitation methods applicability, Maxwell rule verification, frequency range setting due to acceptable coherence function value, power spectral density analysis. Then main experiment was conducted twice (for both machine tools), by means of impact test. The excitation was executed in two points along three orthogonal directions. Dynamic response of a structure was measured in 63 points using triaxial sensors that resulted in 1134 FRFs (frequency response function). These functions were used in modal analysis estimation process, using Polymax algorithm. Orientation and relative placement of machine tool bodies for both machines were the same. Sensitivity of acceleration sensors was about 10 mV/(m/s^2), resolution of spectrum was 1 Hz, H1 type of FRF estimator was used after linear averaging of 12 realizations. Scadas III hardware under control of LMS Siemens Test Lab software was used during signal acquisition and modal model parameters estimation process as well.

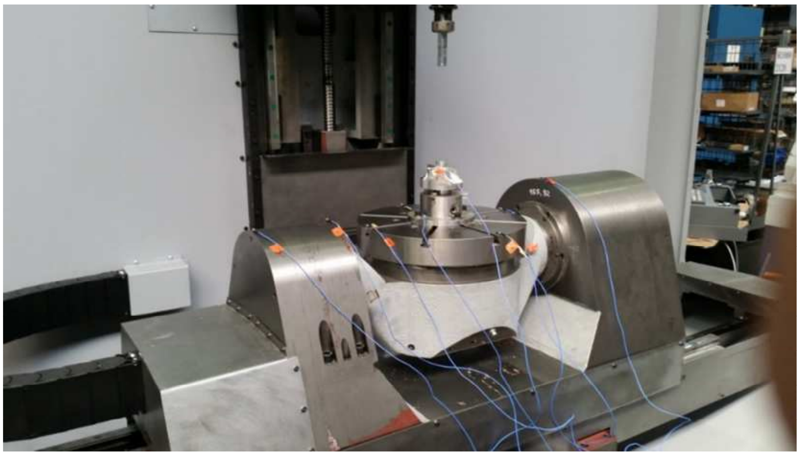

Fig. 1. Tested structure of milling machine R1000

Modal model estimation process relies on analysis of stability diagram. It is a good practice to verify the level of displacement amplitudes at each resonance frequency due to its significance. Results of such analysis leads to conclusion, that few frequencies with significant values of amplitude can be pointed (Fig. 2). Still, amplitude of FRF is below 0.2 μm/N at resonance frequency, which gives an information about good dynamic properties of machine tool. This assumption will be verified in the next stage of examination.

Table 1. The comparison of modal models of two R1000 milling machine specimens

Mode	**Frequency, Hz**	**Modal damping, %**	**Frequency, Hz**	**Modal damping, %**
	Exploited machine		**Prototype**	
1	40.083	5.64	32.910	2.42
2	50.367	3.72	43.058	1.76
3	61.621	6.91	61.022	1.64
4	126.885	4.12	124.418	2.96
5	165.323	3.37	152.578	1.86
6	171.771	3.23	173.609	2.28
7	206.459	5.21	225.345	2.07
8	262.439	4.20	294.950	1.64
9	288.365	3.12	349.962	1.78
10	380.096	5.86	372.911	1.58
11	462.729	2.44	462.745	2.15

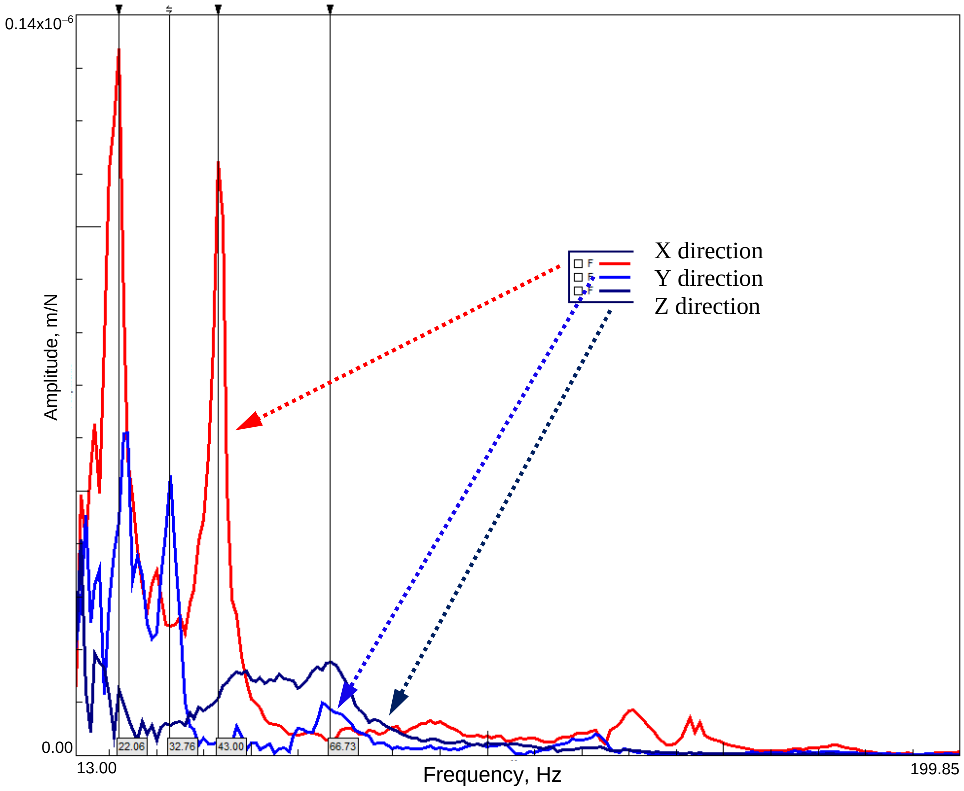

Fig. 2. Selected FRFs after double integration

In the next step, modal model parameters were estimated using Polymax algorithm with default values of tolerance on frequency (1%), vector (2%) and damping (5%) and maximum order of model equal 100. The same procedure was conducted for both sets of FRF's each for both machine tools. Parameters of modal models are listed in table 1. Both models were compared using MAC (Modal Assurance Criterion) (Fig. 3). Result are not satisfying and it will be discussed in Conclusion section.

Next step of modal analysis is animation of mode shapes in order of pointing important modes in terms of relative displacement of tool and workpiece at significant amplitude level. Just one mode shape, with the highest MAC value, in form of animation frames is presented below (Fig. 4).

As a result of these investigations, modal models for both R1000 milling machines were obtained. Information about resonance frequencies and mode shapes is very useful in designing process, and can be used in searching for a "weak element" with respect to dynamic properties. But the most important conclusion is, that dynamic properties are changing significantly during

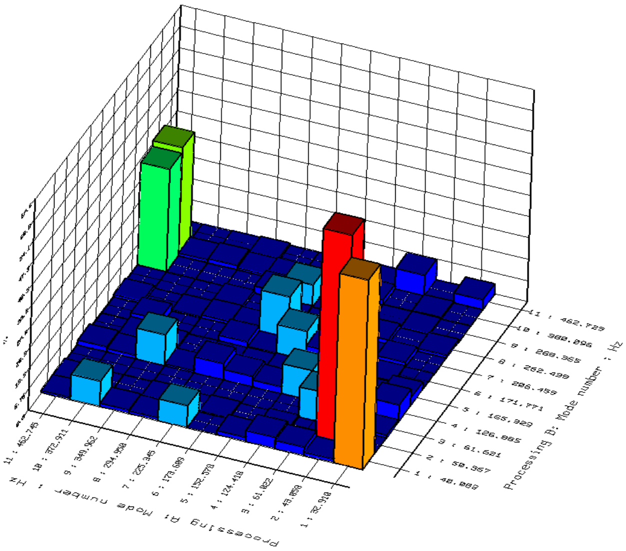

Fig. 3. Comparison of modal models using MAC

exploitation of machine tools. Both modal models are almost incomparable, except 2 modes. It is really difficult to observe a repeatability of modal models, built for real machines, being under normal exploitation. In case of machining problems, loss of stability, increasing of vibrations amplitude or decreasing of surface quality – full modal experiment is suggested for precise recognition of a problem reason.

3. Estimation of machine tool static properties (stiffness)

As a complement of modal analysis, examination of static properties was conducted. Measurement of machine tool static stiffness is treated as a measuring of effect (displacement) acting force, which can be considered as a static. Quasi static force was generator by actuator mounted between tool and workpiece (Fig. 5). This is a unique solution designed in Institute of Manufacturing Engineering, and allows to generate force up to 1 kN with controlled frequency in range 0.1-20 Hz. Relative displacements of machine tool bodies were measured using capacitive displacement sensors CPL190 with: range up to 250 μm, sensitivity 80 mV/μm, linearity error less than 0.05%, error band less than 0.06%. Sensors were connected to Elite Series CPL190 conditioning system of Lion Precision. Measurement results were corrected due to the nonlinearity calibration curve, resulting in extended uncertainty (k = 2) less than 160 nm at 15 kHz sampling frequency.

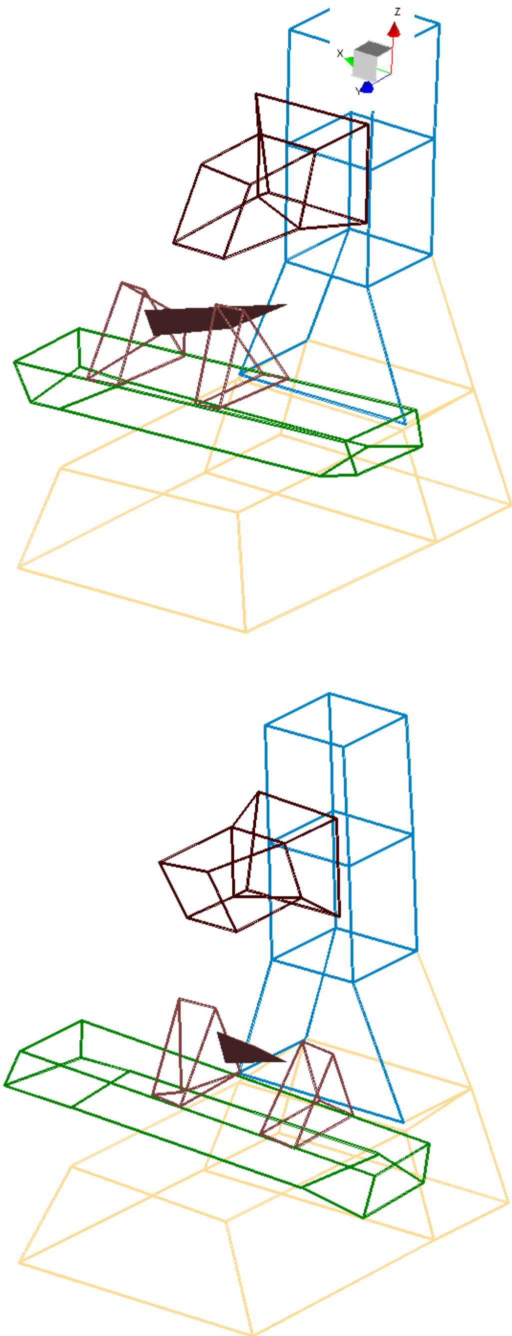

Fig. 4. Frames of mode shape animation, at frequency 43.058 Hz
and modal damping 1.76 %

Program of investigations consists of: setting up thermal state of machine tool, generation of sinusoidal force signal with frequency of 0.5 Hz and measuring the relative displacement.

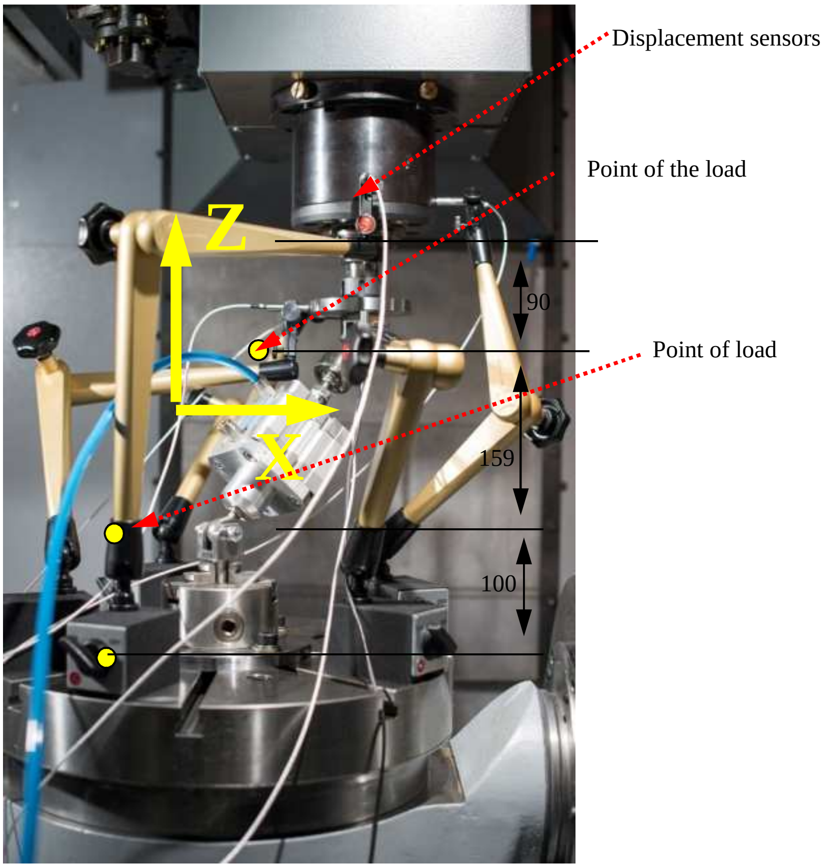

Fig. 5. Experimental setup (static stiffness estimation)

Static stiffness coefficients K_x, K_y, K_z are defined as follows:

$$K_x = \frac{F_x}{\delta_x}, \quad K_y = \frac{F_y}{\delta_y}, \quad K_z = \frac{F_z}{\delta_z} \tag{1}$$

where: δ is a displacement as a result of acting force F on direction x, y, z respectively.

Displacements were transformed to the point where force was acting. Force was projected on certain directions related with milling machine geometry. Resulting static characteristics are presented in Fig. 6.

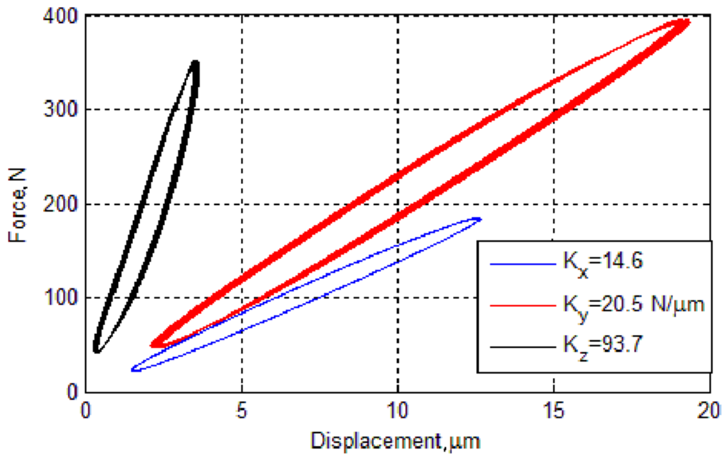

Fig. 6. Results of stiffness estimation procedure

Static stiffness of milling machine R 1000 prototype are acceptable, and comparable with parameters of similar constructions of machine tools. Additional tests should be conducted, including control algorithm optimization. The highest stiffness is in Z direction, and it agrees with dynamic examinations results.

4. Conclusions

In the article, results of static and dynamic properties examination were presented. Modal model was built for two R1000 milling machines, static stiffness was calculated only for the prototype (new machine). Both static and dynamic examinations results are comparable, but there are very important conclusions: first, exploitation of machine tool impacts significantly its dynamic properties. Probably, long exploitation leads to a "stabilization" of these properties, but difference between new machine and the one which was used under operational conditions, are incomparable. This is attributed to a changing (increasing) damping of used machine tools. It leads to another conclusion, that every single machine is unique. If there is a need of identification of FEM model or stability prediction, separate experiments must be provided.

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