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Computational and experimental analysis of machine tool vibrations in micro-milling

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Abstract. In machining processes, it is necessary to study the vibration phenomena which take place in cutting zone between the cutting tool and the workpiece in order to ascertain the factors that affect them. The subject of this paper is to identify the influence of the cutting parameters and the dynamic characteristics of the machine tool spindle and the cutting tool on the vibrations by means of FEM analysis. A FEM modal analysis of the machine tool spindle in combination with cutting force measurements are used to build up a transient FEM model in time domain in order to study the vibrations induced by the cutting process. The results of the transient FEM model will serve for further analysis to find out the optimum cutting parameters in micro-milling.

1 Introduction

During the cutting process, it is crucial to know the vibration behaviour of the “Machine Tool- Cutting Tool- Workpiece” system in order to ascertain the factors that affect it [1]. The subject of this paper is to develop a numerical model using the Finite Element Method (FEM) to simulate the vibration behaviour of the system. To succeed that, it is necessary to model the system in such a way taking into account the particular stiffness of the system components which take an effect in the machine tool dynamics. The current work aims at the development of a FEM simulation model to

- assess the natural frequencies and eigenmodes of the “Machine Tool Spindle - Cutting Tool” system
- calculate the cutting tool deformation, results from the cutting forces during the micro-milling process

A FEM modal analysis in combination with experimentally measured cutting forces results are taken in order to develop a transient FEM model in time domain to describe the vibration phenomena in milling. The results of the transient FEM model will serve for further analysis to find out numerically the optimum cutting parameters in micro-milling.

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2 Experimental determination of cutting forces

The experiments to measure the cutting forces during the milling process were conducted in the CNC machining center DECKEL MAHO MH600C. The measuring equipment includes a dynamometer (KISTLER 9257B), a charge amplifier (KISTLER 5233A) and an Analog/Digital converter (NATIONAL INTRUMENTS NI PCI-MIO-16E) connected to a computer. The dynamometer is capable to measure the cutting forces in three axes simultaneously. In Figure 1 are presented the cutting force's components. The analog force signals are amplified and consequently digitized and recorded.

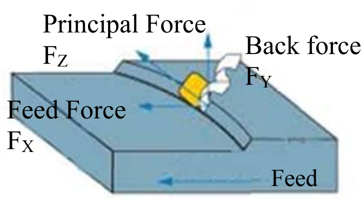

Fig. 1. Cutting force's components during milling process.

The cutting parameters of the conducted experiments are shown in Table 1. The material of the specimens used to machining was aluminium alloy 7075 T651.

Table 1. Cutting parameters

Symbol	Parameter (Units)		Value
S	Spindle Speed	(rpm)	5500
Vc	Cutting Speed	(m/min)	34.5
f	Feed Speed	(mm/min)	220
f_x	Feed per cut	(mm/cut)	0.01
a_e	Radial depth of cut	(mm)	0.5
a_{xz}	Axial depth of cut	(mm)	0.2/0.4/0.6
d	Cutter diameter	(mm)	2

The data of the force components are recorded within a time frame of 0.04 sec with a sampling resolution of 4e-05 sec. In Figure 2 a typical force component measurement is shown. It can be assumed that during the cutting process the main cutting force component is developed in ZZ direction and the feed force component in XX direction. On the other hand, the force component in YY direction is negligible.

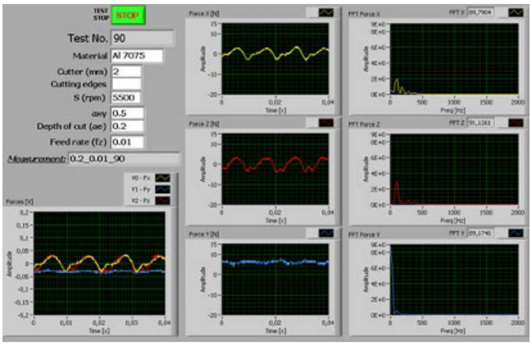

Fig. 2. Cutting force measurement during milling process.

3 Experimental determination of the machine spindle dynamic characteristics

In order to determine the natural frequencies and the damping factor of the "Machine Tool-Cutting Tool" system, there were conducted specific measurements of the vibration response of the cutting tool mounted on the machine spindle with the aid of the cutting tool holder [2]. The vibration behavior of the assembly in cutting position is mainly affected by the machine tool spindle and the cutting tool. Based on excitation-response measurements of the machine spindle - cutting tool assembly at various critical positions it was verified that a subsystem is substantially isolated when mounted in rolling elements (bearings). For this reason, it is necessary to determine just only the dynamic characteristics of the Spindle-Tool holder- Cutting tool compound.

The experimental modal analysis was conducted in the following manner [3]. An impact excitation produced by a hammer hit is applied on the cutting tool edge and the response (acceleration) is measured. The analog signals (impact force and response) are undergoing further processing and the vibration characteristics (natural frequencies and damping factor) are determined. The analog signals taken with the aid of a piezoelectric accelerometer, after being amplified, were digitized and recorded for further processing and analysis. The results of the experiments are shown in Table 2 and 3 for the XX and ZZ direction accordingly. After the experimental measurement of the cutting forces and the determination of the dynamic characteristics of the vibratory system, it is possible to setup the 3D simulation model of the machine spindle in order to develop the transient model in time domain, because of the time-dependent self-excited vibrations induced by the cutting process.

Table 2. Dynamic characteristics on XX direction

Frequency w_q (Hz)	Damping ratio j_q	Stiffness k_q (N/m)	Mass m_q(kg)
4817	**0.098**	**172866**	**0.0076**

Table 3. Dynamic characteristics on ZZ direction

Frequency w_q (Hz)	Damping ratio j_q	Stiffness k_q (N/m)	Mass m_q(kg)
4650	0.064	227941	0.01

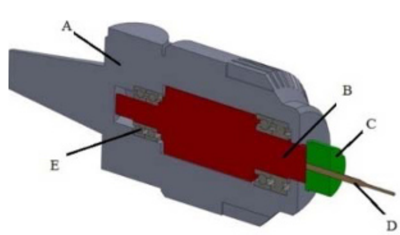

Fig. 3. 3D modelling of the spindle system (A: High speed spindle's shell, B: Machine tool high speed spindle, C: Tool holder, D: Cutting tool, E: Bearings).

4 High speed spindle modelling

In order to develop the 3D simulation model of the "Machine - Cutting Tool" assembly (Figure 3), it is necessary to design, as accurately as possible, the geometry of each part of the system. To facilitate the modeling work, specific experiments were conducted. It should be mentioned that while there were not available the mechanical drawings and therefore many of the geometry details of the vibratory system were missing, special attention was paid in proper distribution of the mass of the various components, in order to develop a consistent equivalent model. However, the drawing of the high-speed spindle assembly allowed us to extract some useful information about the main dimensions of the parts geometry.

The cutting tool in the 3D graphical representation in Fig. 3 has the same geometry as the cutting tool used in the experiments, in order to be possible to compare the simulation results with the experimental ones. In particular, an end-mill tool was used with a diameter of 3 mm and a shaft diameter of 4 mm. In order to simplify the FEM model, special consideration was paid on the fact that the bearings due to their stiffness dynamically separate the shaft vibrations from the rest of the machine tool. Therefore, it was not necessary to include the whole machine tool spindle as well as the bearings into the FEM model. As a result of that in the 3D-model, which was built for the FEM analysis, the shaft surfaces where the bearings are located were also defined as pivot joints and are indicated with light grey color in Fig. 4.

Fig. 4. Equivalent 3D-model used for the FEM Analysis.

5 FEM modal analysis

The Finite Element Method (FEM) simulation of the machine tool spindle was performed with the aid of the ANSYS WorkBench software. It concerns the modal analysis to find out the natural frequencies and eigenmodes of the spindle. This numerical simulation was based on the machine tool spindle equivalent model presented in Figure 4, as well as on the appropriate model characteristics, such as material properties, boundary conditions and contact conditions between the parts of the spindle assembly. In order to simulate the dynamic behavior of the spindle model, it is necessary to define the boundary conditions of the problem. In particular, the bearing positions described in section 4, were considered as cylindrical joints in order to allow the free rotation of the shaft and its axial movement, preventing in this way the development of virtual forces and stresses. In Fig. 5 it is shown the meshing into finite elements of the 3D model on the left and the boundary conditions in FEM modal analysis in order to proceed with the FEM Analysis on the right.

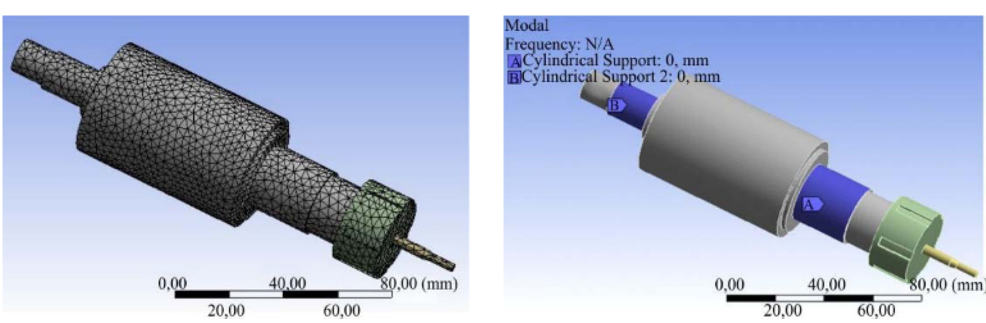

Fig. 5. Meshing of the spindle model and boundary conditions in FEM modal analysis.

With the aid of the FEM modal analysis it was possible to calculate the first two natural frequencies of the spindle and the relevant eigenmodes. The first natural frequency was calculated at 4794,5 Hz and the first eigenmode in XX direction is shown in Fig. 6 (left). The second eigenmode in ZZ direction corresponding to the second natural frequency calculated at 4837,8 Hz is shown in Fig. 6 (right).

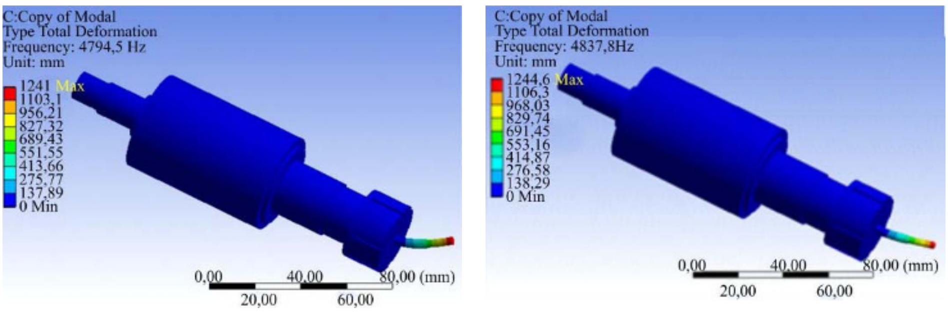

Fig. 6. Graphical representation of the eigenmode corresponding to the first natural frequency of the machine tool spindle (left) and the eigenmode for the second natural frequency of the machine tool spindle (right)

The values of the natural frequencies (4794.5 Hz and 4837.8 Hz) is substantially the first main natural frequency of the assembly. The deviation between the two eigenmodes is due to the small geometrical deviation of the device in two directions XX and ZZ, mainly because of the cutting tool since the elements of the tool holder and the spindle are rotationally symmetrical. It can be assumed that the spindle natural frequencies calculated with the aid of the FEM simulation model are very closed to the natural frequencies, which were determined experimentally, so that the accuracy of the FEM simulation model can be validated. After the approval of the FEM simulation model with the experimentally performed modal analysis of the machine tool spindle it was possible to go forward and to develop the FEM transient model in time domain. This is useful to numerically evaluate the time-dependent self-excited vibrations induced by the cutting process.

6 FEM transient analysis

Transient analysis is used to predict the response of structures where time depend excitation is implemented [4,5]. In order to describe the excitation, it is necessary to know the mathematical description of it. In situations, where no mathematical function exists for the implemented excitation, an empirical model from experimental measurements is required. The subsequent analysis of the data in time domain is used to obtain a frequency response model of the vibratory system.

Thus, in this paper, in order to develop a consistent transient FEM model a simulation model validated with FEM modal analysis was firstly developed. The self-excited vibration phenomena which take place during the milling process were introduced in the model as an implemented force at the cutting tool edge. In this case, the implemented force represents the phenomena occurring in an up-milling process. The values of the force components were determined experimentally for specific cutting conditions (feed per cut 0.01 mm/cut and cutting depth 0.2 mm) and introduced in the transient analysis as numerical data. The FEM analysis results are derived for a time step equal to 4e-05 sec, where 1000 steps of force history for each experiment were applied. In Figure 7 the deformation course of the cutting tool edge estimated by means of the FEM transient analysis is presented. By comparing this result with the experimentally determined deformation a good correlation can be established. More specifically, according to the conducted damped forced vibration experiments the defined cutting tool stiffness amounted to 172866 N/m for 4 N cutting force (see Figure 2 and Table 2) and the tool deformation was calculated at about 2,3e-05 m, which is in a good agreement with the FEM calculated deformation of about 2,0e-05 m, at the specific time point 0.011s of the deformation course.

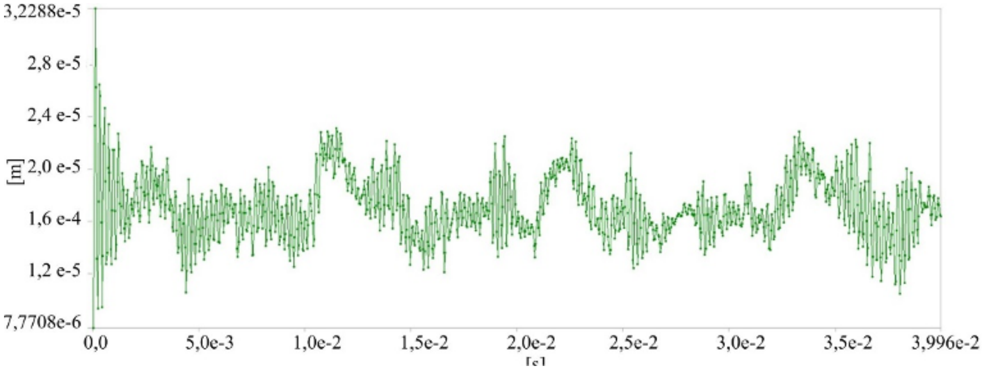

Fig. 7. Total deformation course of the cutting edge resulting from the FEM transient analysis.

7 Conclusions

In milling processes it is necessary to study the vibration phenomena which take place in cutting area between the cutting tool and the workpiece in order to ascertain the factors that affect them. In this paper, the influence of the cutting process parameters on the machine tool spindle vibration by means of FEM analysis is investigated.

Firstly, by means of a wide spectrum of end-milling experiments the cutting forces that occur during the cutting process under various cutting conditions were determined. Moreover, there were also specific experiments conducted in order to determine the machine tool dynamic characteristics of the machine tool spindle. A simulation model of the machine tool spindle was developed and it was validated by FEM modal analysis.

Furthermore, the experimentally determined cutting forces were used in combination with the cutting tool and the machine tool spindle stiffness, in order to develop the transient FEM model in time domain. The results of the transient FEM model are validated with experimental results. This FEM model will serve in future for further analysis to find out the optimum cutting parameters in micro-milling.

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