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Characterisation of dynamic behaviour of vertical machining centre components: experimental and simulation approaches

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Abstract: The paper presents a systematic procedure and details of the use of experimental and analytical modal analysis technique for structural dynamic evaluation processes of a vertical machining centre. The main results deal with assessment of the mode shape of the different components of the vertical machining centre. The simplified experimental modal analysis of different components of milling machine was carried out. This model of the different machine tool's structure is made by design software and analysed by finite element simulation using ABAQUS software to extract the different theoretical mode shape of the components. The model is evaluated and corrected with experimental results by modal testing of the machine components in which the natural frequencies and the shape of vibration modes are analysed. The analysis resulted in determination of the direction of the maximal compliance of a particular machine component.

Keywords: experimental modal analysis; EMA; vibration; vertical machining centre; mode shape.

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1 Introduction

The dynamic behaviour of a structure is characterised by its natural frequencies, damping and mode shapes. These parameters are called the modal parameters. By using the modal parameters to model the structure, vibration problems caused by these resonances (modes) can be examined and understood (Inman, 2007; Huang, 1991; de Silva, 2005; Maia and Montalvao e Silva, 1997). In addition, the model can subsequently be used to come up with possible solutions to individual problems. Vibration occurring on machine tools has been a serious problem for engineers for more than one century. Undesired relative vibrations between the tool and the workpiece jeopardise the quality of the machine surfaces during cutting. Modal analysis is a process whereby a structure may be defined in terms of its natural characteristics which are the frequency, damping and mode shapes – its dynamic properties. Since all bodies have both mass and elasticity, they are capable of vibration. Therefore, most engineering structures and machines experience some form of oscillatory motion. To better understand any structural vibration problem, the resonances of a structure need to be identified and quantified. A common way of doing this is to define the structure's modal parameters. Static and dynamic deformations of machine tool, tool holder and cutting tool play an important role in tolerance integrity and stability in a machining process affecting part quality and productivity.

Experimental modal analysis (EMA) has rapidly developed as an area of science in last few years and has become as efficient as the finite element method. It is an experimental approach for solving technical problems is a means to estimate or evaluate modal properties of a mechanical structure. Modal analysis is vital to understanding and optimising the inherent dynamic behaviour of structures, leading to lighter, stronger and safer structure with better performance. In modal analysis, a mathematical model of a structure's dynamic behaviour is obtained. The mathematical model consists of a set of mode shapes each with an associated natural frequency and modal damping. These modal parameters provide a complete description of the structure's dynamic behaviour. Baker and Rouch (2002) used finite element method to analysis the instability of machining process. They created a structural model of machine tool system using the commercial FE code, ANSYS, without any experimental tests. In this model the bed of machine tool, spindle and tool holder, as steel blocks, are modelled. The integrity of these models not only is not confirmed by experimental results. In another research with the aim of analysis of chatter phenomena, the tool's natural frequencies and the shape of their vibration modes were obtained by modal testing results. In this case, the variations of acoustic emission signal during chatter are analysed, so that it can be used for chatter detection in machining duration (Lee and Kim, 1995).

Many researchers (Altintas, 2000; Budak and Altintas, 1994; Tlusty and Polacek, 1963) tried to analysis the static and dynamic analysis of the structure involved in machining system by resting using stiffness measurements and modal analysis. Talantov et al. (1980) and Amin (1983, 1982) have observed that chatter arising during turning is a result of resonance caused by mutual interaction of the vibrations due to serrated elements of the chip and the natural vibrations of the system components, e.g., the spindle and the tool holder. The chatter phenomena were indicated by the some of the researchers as a resonance effect where system components played a vital role. The numerical method and the experimental method are two kinds of ways for the dynamic characteristics analysis of structure. The reliability of the simple numerical method usually cannot be guaranteed and the experimental method only gives a result under a given experimental condition. So the way, so-called pre-experimental analytical method combining the numerical method and experimental method, is widely used (Lammens, 1995; Bai and Guo, 2001).

So, it is important to extract the accurate mode shape of the dominating components of machine structure to identify the chatter formation causes. The paper is focused at dynamic properties of a vertical milling machine, namely at the resonance frequencies and vibration shapes of a vertical machining centre components. All this properties are identified by measurements. The machine tool vibration was excited by impulse force and a response of excited vibration was recorded. The measurement points for vibration were selected at the different location of spindle, tool and collect.

2 Simplified modal analysis of milling machine

Aiming to investigate the vibration phenomena occurring occasionally at the different components of milling machine an experimental and analytical modal analyses were performed. The study focused on extracting the mode shape of the dominating components of the milling machine in order to ensure resonance phenomena as a cause of chatter. In a first step the significant eigenfrequencies with corresponding mode shapes were obtained by means of an EMA. Subsequently, the dynamic behaviour of the machine components was simulated using an ABAQUS FE model. The comparison of the eigenfrequencies based on FE calculations with their experimental counterparts proved in general quite satisfactory correlation.

2.1 *Experimental modal analysis*

2.1.1 *Measurement hardware*

A vibration measurement generally requires several hardware components. The basic hardware elements required consist of a source of excitation, called an exciter (impulse hammer), for providing a known or controlled input force to the structure, a transducer to convert the mechanical motion of the structure into a electrical signal, a signal conditioning amplifier and an analysis system in which modal analysis program resides.

The schematic diagram of hardware used performing in a vibration test is shown in Figure 1. The different equipments that have been used are listed below: pulse front-end (data acquisition); impact hammer; USB dongle; accelerometers; impact hammer cable; accelerometer cables; pulse front-end power supply; TCP/IP cross cable; bee's wax.

Figure 1 EMA test set-up (see online version for colours)

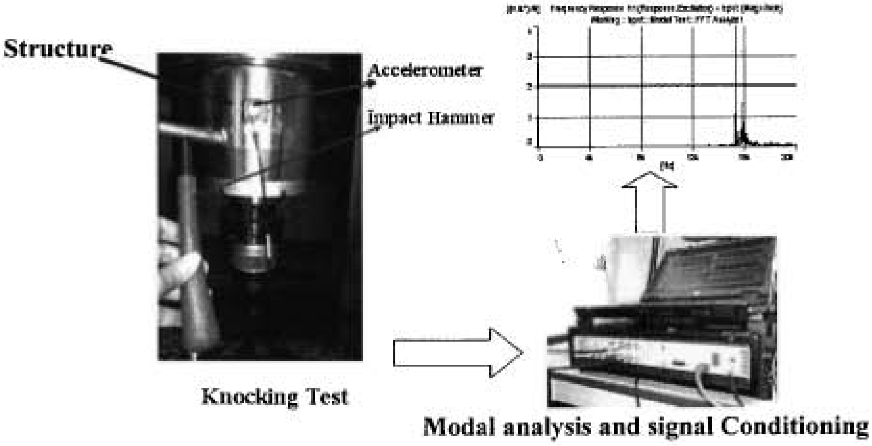
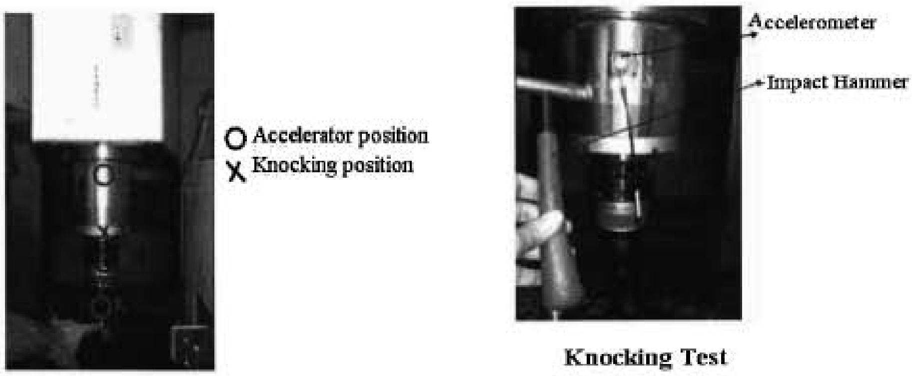


Figure 2 Position of accelerometer and knocking point at different components of milling machine (see online version for colours)



2.1.2 Test procedures

The different milling machine components were identified which play a dominating role for the chatter generation. The natural frequency of the different components was measured using modal analysis under static and dynamic conditions and consequently the different mode shapes were identified.

Initially, excited frequencies were monitored during the operational mode under no load condition. It is easy to record a response in vibration during machining but almost impossible to measure the mentioned dynamic force. Therefore, the force measurement was replaced by measurement of impulse response to the impact force excited by a hammer, whose tip was fitted by a force sensor. As the goal of these measurements was to evaluate frequency transfer function, the responses at various machine points with respect to a reference point were recorded and analysed. The reference point was selected at the different location shown in Figure 2.

2.1.2.1 Knocking test

The natural frequencies of the different components were extracted form the recorded FFT diagram. One accelerometer was connected to the component, the natural frequency data from the FFT graph was recorded by knocking the different components using the impact hammer.

2.1.2.2 Operational test

The dominating frequencies were identified considering high values based on the natural frequencies obtain from the knocking test during no-load operating condition. Accelerometers are connected to the components and data was recorded in auto spectrum graph. The time excitation, the coherence response excitation and time response excitation were also recorded to investigate the quality of the signal as shown in Figure 3.

EMA is based on determining the modal parameters by testing, unlike analytical modal analysis, where the modal parameters are derived from finite element models (FEMs). There are two ways of doing EMA: classical modal analysis and operational modal analysis. In classical modal analysis, frequency response functions (or impulse response functions) are calculated from measured input forces and output responses of a structure shown in Figures 3–4.

Much of the analysis in modal testing is performed in the frequency domain inside the analyser. The analyser task is to convert analogue time domain signal into digital frequency domain information compatible with digital computing and then to perform the required computations with these signals. Figures 3–4 indicates the frequency domain information by fast Fourier transform for the domination components of vertical machining centre like tool-holder and collect and spindle casing. As it is very difficult to extract the inner spindle mode shape so operational modal analysis was done for inner spindle.

Figure 3 EMA responses of tool holder (see online version for colours)

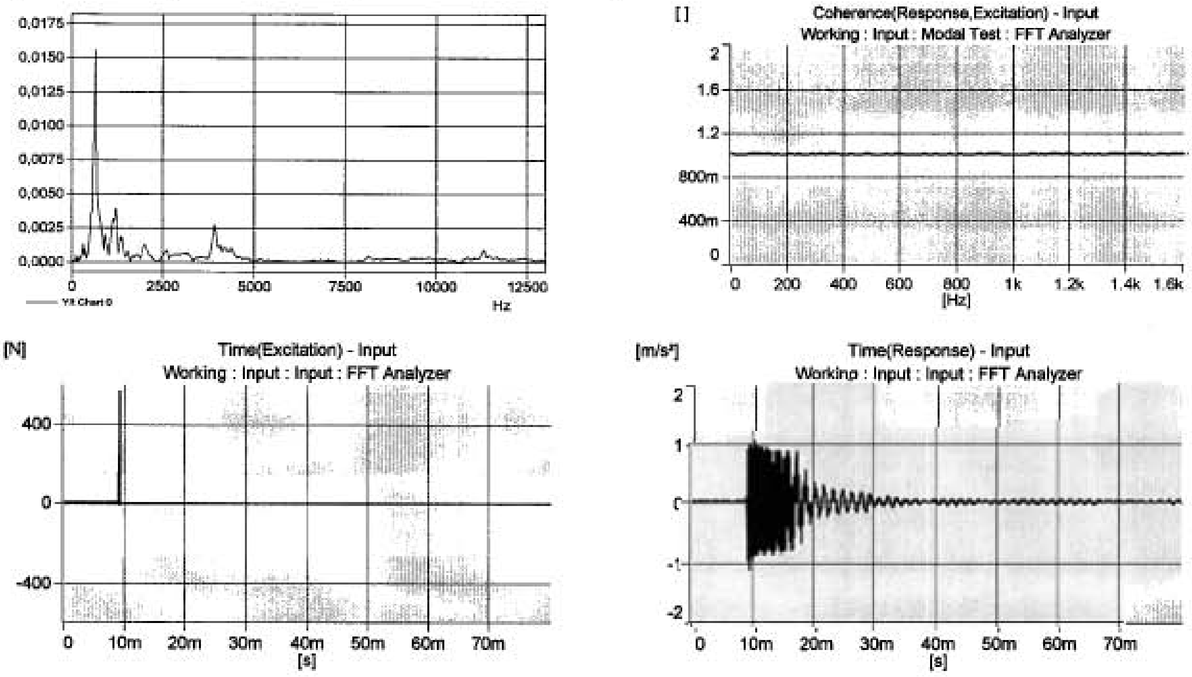
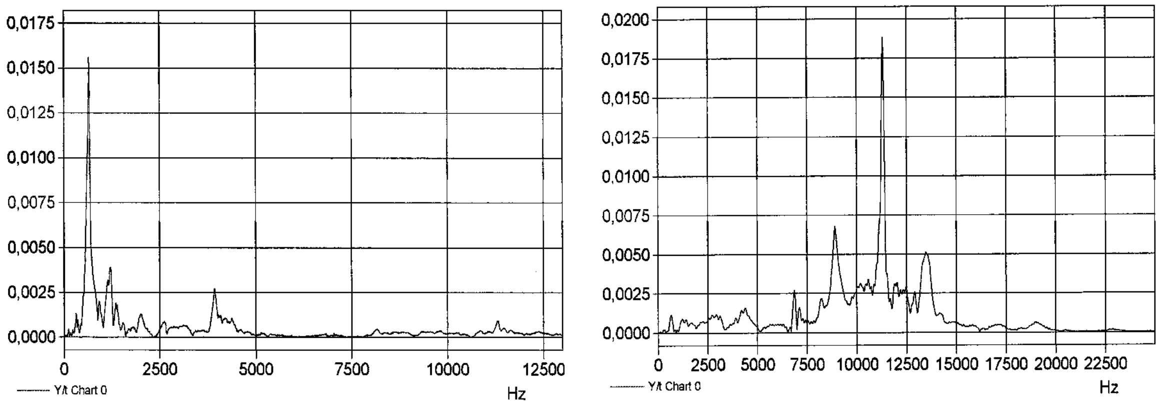


Figure 4 EMA power spectrum responses (FFT), (a) collect (b) spindle casing of vertical machining centre (see online version for colours)



(a)

(b)

Figure 5 Operational modal analysis of inner spindle with no load and load condition, (a) inner spindle operational deflection shape with no load (b) inner spindle operational deflection shape with load (see online version for colours)

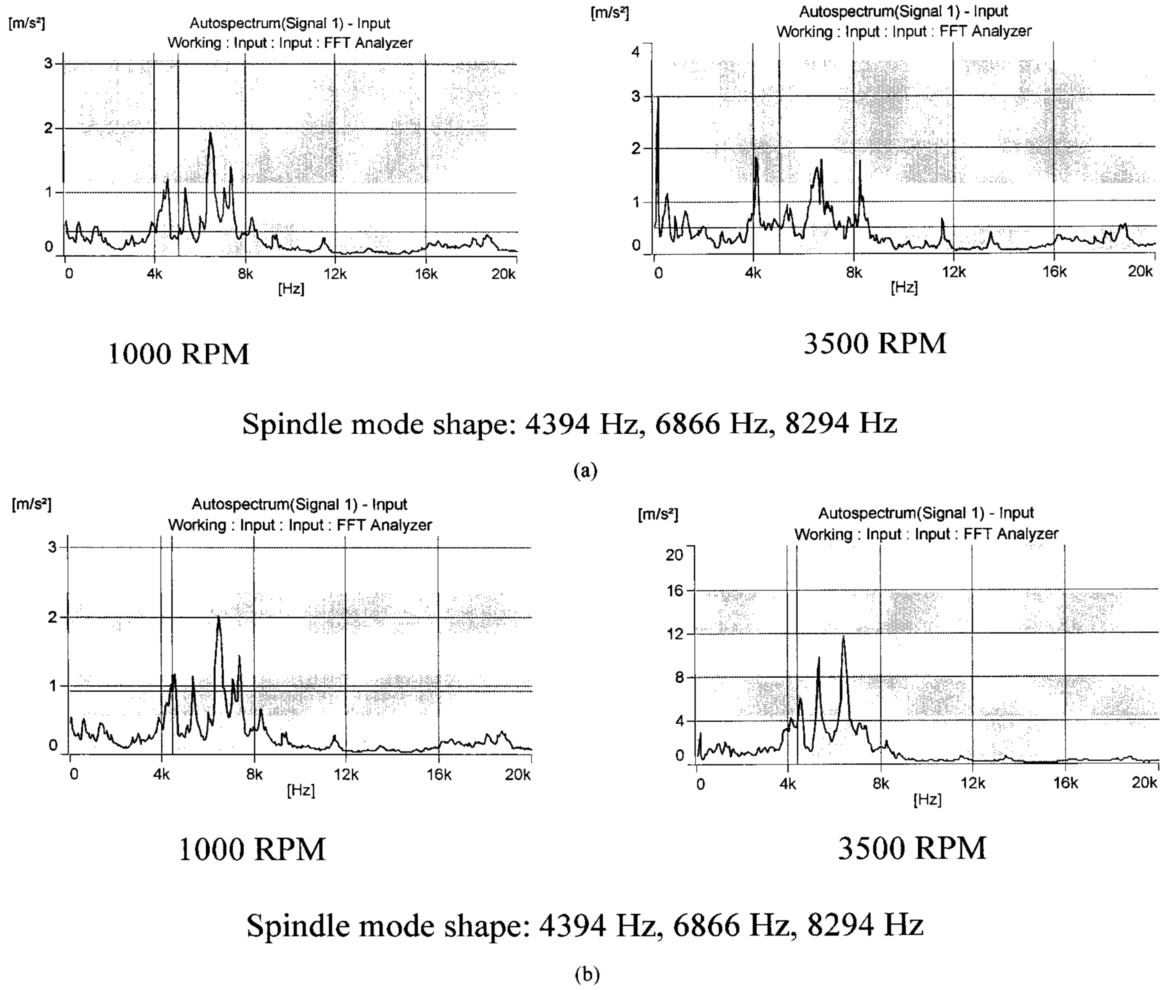


Figure 6 CATIA model of the different components of vertical machining centre (see online version for colours)

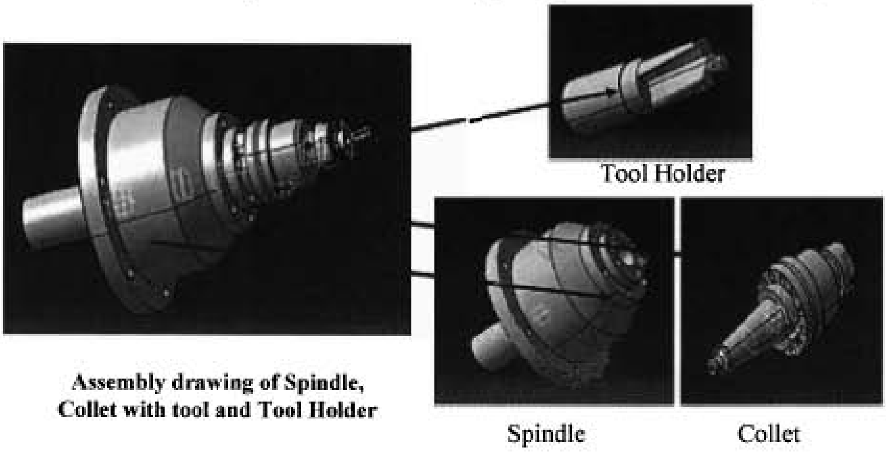
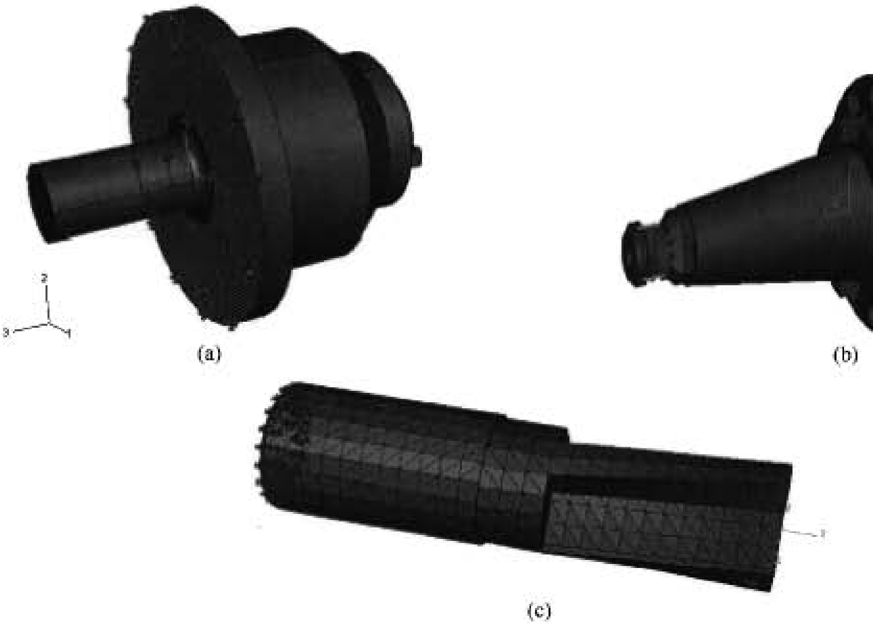


Figure 7 The free body diagram of milling components, (a) spindle assembly (b) Collet assembly (c) tool holder assembly (see online version for colours)


(a)
(b)
(c)

2.2 *Operational modal analysis*

Operational modal analysis is based on measuring only the output of a structure and using the ambient and operating forces as unmeasured input. It is used instead of classical mobility-based modal analysis for accurate modal identification under actual operating conditions and in situations where it is difficult or impossible to control an artificial excitation of the structure.

In the milling machine structure, the inner spindle is surrounded by the outer spindle as a result it is not possible to extract the mode shape using knocking test. Operational modal analysis was carried out to find out the mode shape of the inner spindle using load and no load conditions as shown in Figure 5.

3 Procedures: FE modelling

In order to obtain an equivalent model which agrees with the practicable machining state, a FEA model is set up first to get the theoretic natural frequency and mode shape. At the same time, the actual natural frequency and mode shape are obtained by means of EMA. When the theoretic results of FEA close to the actual results of EMA, the FEA model is proved to be reasonable; otherwise, the FEA model is amended until the theoretic results of FEA agree with the actual results of EMA very well. Then the parameters of the FEA model can be obtained. The combined amendment procedure and the solid model of the different parts of the vertical machining centre are presented in Figure 6.

In order to make an FEM, a three-dimensional geometrical model of machine's structure with CATIA software has been developed and then converted to igs format for further analysis by ANSYS software. This model provides natural values and response frequency extraction. The observation of vibration modes of machine tool components are three-dimensional shapes which provides better capability to analysis of vibration model. The model is applied on vertical machining centre. The different components of the machine were measured and designed by CATIA software. The designed models were three dimensional models.

After modelling the selection, the necessary input data as material properties such as modulus of elasticity, Poisson ratio and density is applied. The elements used in the FEM model for mesh generation is quadratic tetrahedral element. The element distribution is uniform to exceed boundary and it is so that in the parts with relatively small dimensions like spindle, tool holder, collect, etc., the element dimensions are finer and controlled. Afterwards, boundary conditions on supporting are applied on the earth connection of machine tool and finally modal analysis has been done to obtain natural frequencies. In continuation, fine screening of the FEM is accomplished to match the natural frequencies results from EMA.

3.1 FE modal analysis

Modal analysis has been done on the three different components of vertical machining centre using FEM to determine the natural frequency of machine tool structure elements and to discrete them from each other. These models are as follows:

- Model no. 1: complete model of spindle both outer and inner.
- Model no. 2: complete model of collect with chuck case.
- Model no. 3: complete model of tool holder.

The element used in this analysis is quadratic tetrahedral element. As the boundary conditions the nodes' displacements x, y and z of the surface of milling components, is constrained according to the actual contact state. Centrifugal force is considered in analyses, three steps are taken namely load, load centrifugal force to get the pre-stress and then have modal analysis. In ANSYS, the loading of centrifugal force is obtained by defining the angular velocity of model. The free body diagram of milling components are shown in Figure 7.

4 Results and discussion

A comparison of calculated modes with their measured counterparts is very helpful in general to verify the quality of an FE model for dynamic simulation purposes and to detect any possible improvements. The modal analysed natural frequencies of these models via ABAQUS software of different components at different mode shape are shown in Figures 5–7. The results of analysis of the calculated and experimental mode shape are mentioned in result analysis section.

4.1 Model no. 1: complete model of spindle both outer and inner of eigenfrequency analysis

Finite element analysis of the inner and outer spindle is performed using ABAQUS. The calculated distortions of the each element are shown in Figure 8 at different mode shapes. The elements used in the FEM model for mesh generation is quadratic tetrahedral element. It has been observed form the calculated results that there are five prominent mode shape of the spindle. In most of the mode shape, the distortion in the inner spindle is significant than the outer spindle.

4.2 Model no 2: complete model of collect for eigenfrequency analysis

Finite element analysis of the collect is again performed using ABAQUS. The calculated distortions of the each element are shown in the following Figure 9 at different mode shape.

4.3 Model no. 3: the model of tool holder and selected eigenmodes of the components

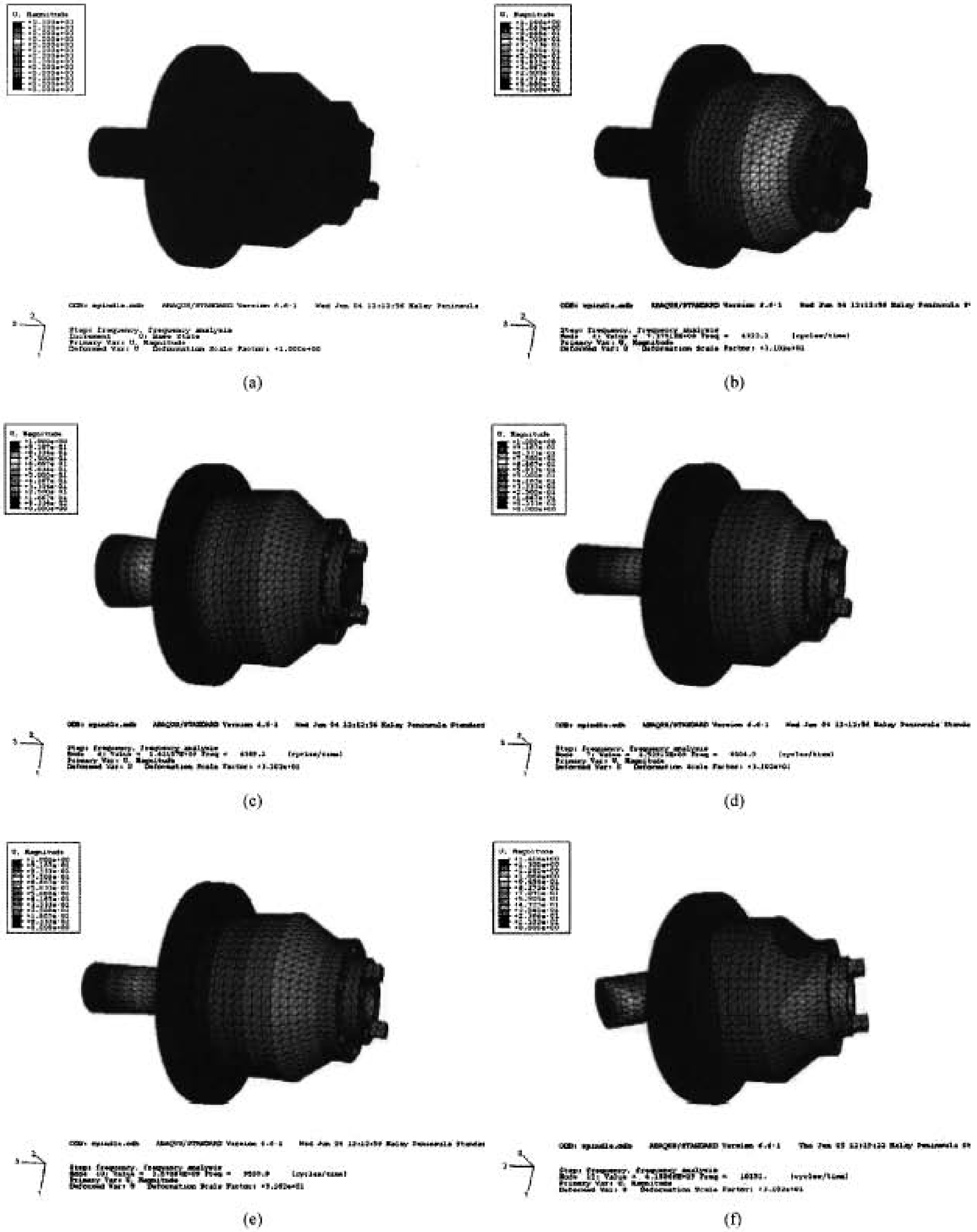
Finite element analysis of the tool holder was performed using ABAQUS. The calculated distortions of the each element are shown in Figure 10 at different mode shape.

4.4 Correlation EMA/FEA

In order to verify natural frequency and mode shape of the results of FEA, hammering tests are performed in EMA since the reliability of dynamic characteristic analysis usually cannot be guaranteed only using a numerical method. FEA is carried out to get the theoretical natural frequency and mode shape of the model, and EMA is carried out synchronously to obtain the natural frequency and mode shape of the practical conjunction of milling components. When the results of FEA and EMA are coincident well, the FEA model is verified. When the result of FEA deviates from the result of EMA greatly, the models parameters will be adjusted according to the result of EMA until the results meet the requirement of the given error limit.

The natural frequencies obtained from modal analysis of system testing results and FEM are shown in Tables 1–3.Table 1 shows natural frequencies obtained from the modal analysis of FEMs and modal testing results of spindle both inner and outer and the amount percent of their errors in the different cases.

Figure 8 Selected eigenmodes of the spindle by FE analysis, (a) base state (b) mode: 4,322 Hz (c) mode: 6,389 Hz (d) mode: 8,004 Hz (e) mode: 9,520 Hz (f) mode: 10,291 Hz (see online version for colours)



(a) (b)

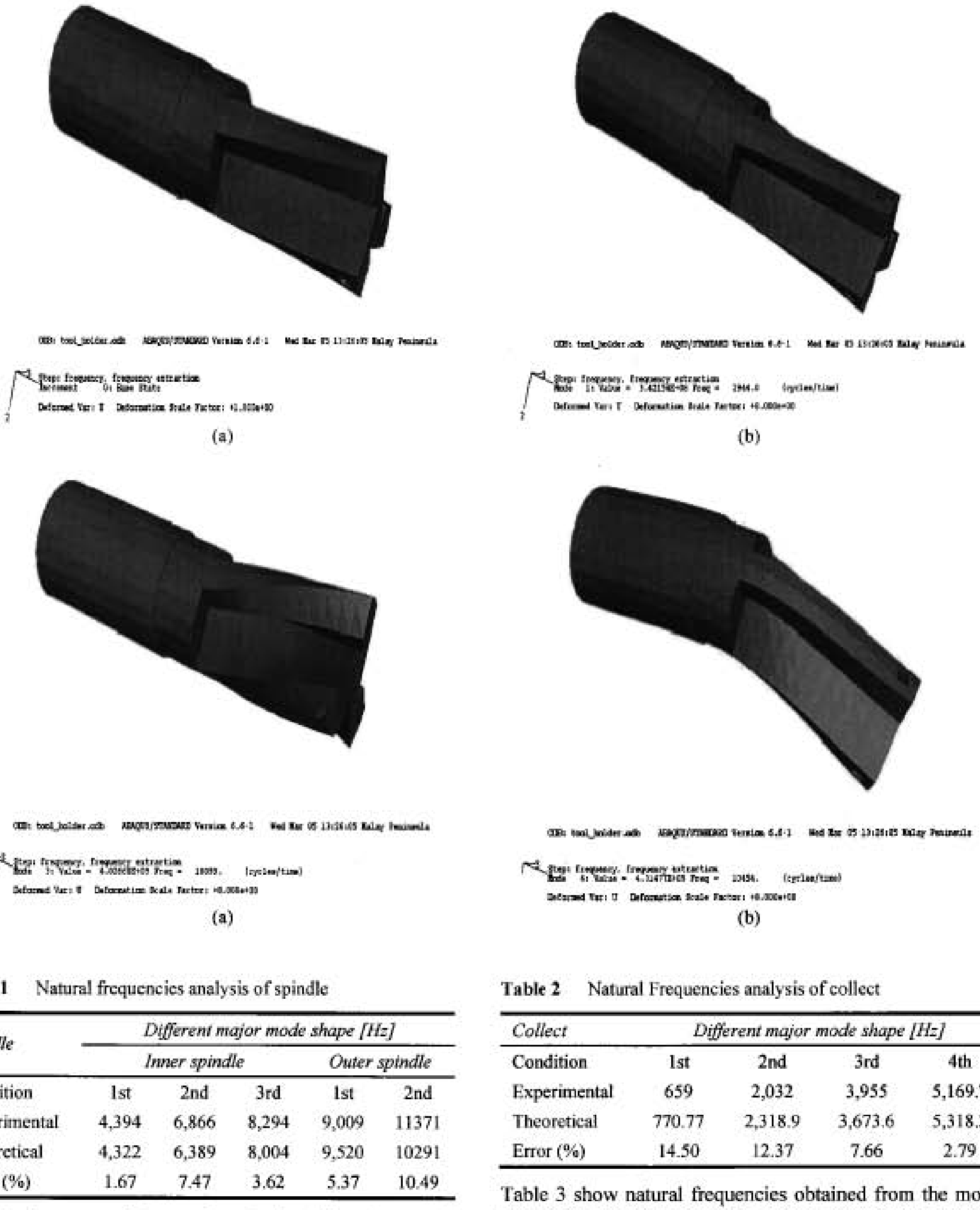
(c) (d)

(e) (f)

Figure 9 Selected eigenmodes of the collect by FE analysis, (a) base state (b) mode: 770.77 Hz (c) mode: 2,318.9 Hz (d) mode: 3,673.6 Hz (e) mode: 5,318.2 Hz (see online version for colours)

(a) (b) (c) (d) (e)

Figure 10 Selected eigenmodes of the tool holder by FE analysis, (a) base state (b) mode: 2,944 Hz (c) mode: 10,099 Hz (d) mode: 10,454 Hz (see online version for colours)



(a) (b)

(a) (b)

Table 1 Natural frequencies analysis of spindle

Spindle	*Different major mode shape [Hz]*				
	Inner spindle			*Outer spindle*	
Condition	1st	2nd	3rd	1st	2nd
Experimental	4,394	6,866	8,294	9,009	11371
Theoretical	4,322	6,389	8,004	9,520	10291
Error (%)	1.67	7.47	3.62	5.37	10.49

Table 2 show natural frequencies obtained from the modal analysis of FEMs and modal testing results of collect and the amount percent of their errors in the different cases.

Table 2 Natural Frequencies analysis of collect

Collect	*Different major mode shape [Hz]*			
Condition	1st	2nd	3rd	4th
Experimental	659	2,032	3,955	5,169.7
Theoretical	770.77	2,318.9	3,673.6	5,318.2
Error (%)	14.50	12.37	7.66	2.79

Table 3 show natural frequencies obtained from the modal analysis of FEMs and modal testing results of tool holder and the amount percent of their errors in the different cases.

The First and second vibration mode of outer spindle is almost similar to the second and third vibration mode of tool holder respectively. The vibration frequency region of spindle model is much higher than the vibration frequencies of collect model. The percentage error level for all the components are with in the accepted ranges.

Table 3 Natural frequencies analysis of tool holder

Tool holder	*Different major mode shape[Hz]*		
Condition	1st	2nd	3rd
Experimental	2,081	8,892	11,352
Theoretical	2,944	10,099	10,454
Error (%)	29.31	11.95	8.59

5 Conclusions

In this paper a FEM is used to analysis the mode frequencies and shapes of different machining components and hence compare the results with the experimental one. This model is produced in CATIA software based on the real dimensions of vertical machining centre (model: MCFV 1060LR) machine and analysis was done by ABAQUS software. According to the model analysis, the natural frequencies and vibration modes shape of the model in spindle, collect, tool holder cases, were determined and the evaluated.

The comparison between natural frequencies of finite element modelling and model testing shows the closeness of the results. From the results, it has been observed that the suitable frequency ranges for end milling will be up to 12,000 Hz. This research work will help to find out the natural frequencies of the components and hence predicting the chatter formation zone as resonance phenomena.

In order to establish a dynamic characteristics analysis of the milling components, the combination of FEA with EMA is proved to be a highly effective method by the milling experiment. A reasonable FEA model can give a good reference to select and optimise the milling parameters in a practical high-speed milling process.

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