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Response Prediction of Static Modal Testing on Milling Machine Tool

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Abstract. Milling is one of the most common manufacturing processes for automotive component, but its productivity is limited by chatter. This form of chatter is undesirable because it results in premature tool wear, poor surface finish on the machined component and the possibility of serious damage to the machine itself. Modal testing is a form of vibration testing which is able to determine the Frequency Response Function (FRF) of the mechanical test structures. In this paper, the main focus is to obtain natural frequency values for machine tool components in order to establish better conditions in the cutting process on the machine tool. For this purpose, a 3D model of the machine tool's part is made using design software and exported to analysis software. Later on, the Finite Element Method (FEM) modal analysis was used to obtain the natural frequencies. The model is evaluated and corrected through an experimental modal test. In the experiment, the machine tool vibration is excited by impact hammer and the response of excited vibration is recorded. In the end, the result of both FEM and experimental shows a good consistency in comparison.

Introduction

Milling is one of the most common manufacturing processes for manufacturing sectors. However, high speed machining problems notably tool chatter in function of both spindle speed and depth of cut. Thus, many researchers found that to detect or reduce chatter is by determine its dynamic characteristics such as natural frequency, damping ratio, mode shapes and frequency response functions (FRFs). FRF defined as a response; displacement velocity or acceleration type divided by excitation force. To obtain its dynamic characteristic, modal analysis and modal testing was done. Modal analysis is the process of determining the inherent dynamic characteristic of a system and modal testing is an experimental technique used to derive the modal model of a time-invariant vibratory system. Modal testing is to identify dynamic characteristic on a combination of the spindle, tool, and tool holder of a machine [1]. Impact hammer testing was started by determining the frequency response function (FRF) of the tool to identify the expected dominant chatter frequency for initial selection of the spindle speed and feed rate [2]. The basic steps are normal force was applied to excite the tool by using an impact hammer and the response is measured using an accelerometer or a displacement sensor, also, a siglab two-channel data acquisition system was connected to the hammer and accelerometer to determine FRF [2-7]. The measurement is repeated to get a more accurate result. Then, the measured data are converted from time-domain to the frequency domain using a Fast Fourier Transformation (FFT). In order to validate the experimental result, FEA was highly recommended. Therefore, through vibration testing combined with detailed calibrated finite element analysis (FEA) models have become powerful tools to identify and mitigate vibration issues. Nowadays, Finite Element Analysis Method (FEM) widely used for stability simulation and prediction [8-10]. [11-12] also agreed both the finite element simulations and experimental measurements reveal that the linear guide with different preload greatly affects the vibration behavior and milling stability agrees well with the cutting tests. Thus, this paper focused to determine eigenvectors and eigenvalues of modal testing on cutting tool.

Experimental Study

This testing was carried out in four general steps. A three dimensional model of end-mill cutting tool was created. The analysis of this model provided an estimate natural frequency and modal density of the structure. The properties of cutting tool were inserted into analysis process, which is made of Tungsten with several properties. In step two, trial impact excitation and measurement was conducted. The main objective was to determine the favourite excitation condition for measurement and to locate the optimal measurement. Step three of the testing was to conduct the full measurement. Altogether there were 20 measurement points. The responses were recorded by a tri-axial accelerometer and both excitation and response signals were recorded for analysis by Multi-Channel Data Acquisition System. The schematic diagram of the impact hammer test is shown in Fig. 1. Besides, Fig. 2 shows a quad view for all 20 measurement points selected for modal analysis, which needed to observed experimental mode shapes. The result obtained is shown in the next section with related discussion.

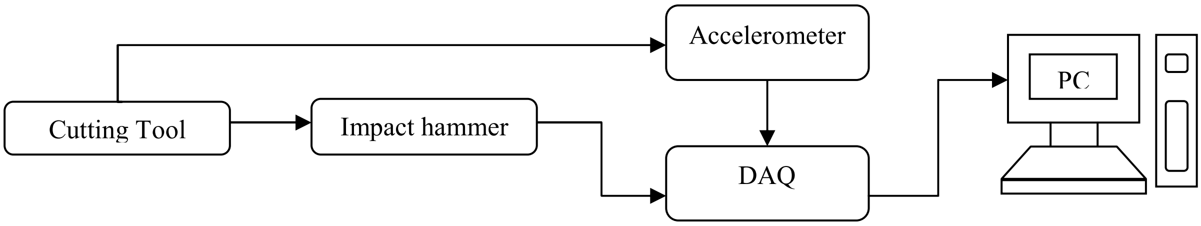


Figure 1: Schematic diagram of the impact hammer test

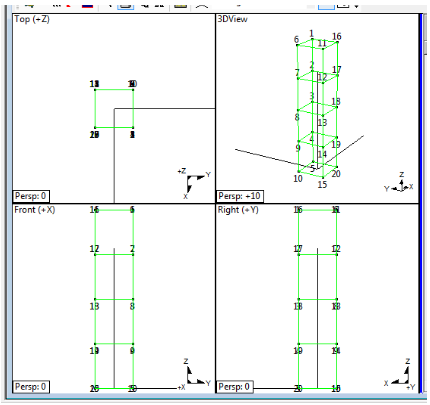


Figure 2: Quad view of measurement points for modal analysis

Results and Discussion

A natural frequency is a frequency at which a point likes to vibrate. A small change in the excitation can produce a significant change in vibration. The experimental modal analysis (EMA) process was conducted at the testing to let the tool model can be animated at any of the frequencies as it was vibrating. These animations give clear pictures on how the tool is vibrating or moving. Two types of analysis were performed; experimentally and FEA. Table 1 shows the experimental result of the impact hammer test. The natural frequencies and damping ratio values are listed below. These two values obtained from experimental measurements of frequency responses in these system and curve fitting procedure. The frequency range of impact testing are 700 – 1200 Hz. In real condition, for a milling machine that run in 40,000 to 60,000 RPM, the machine will excite frequency in the range 600 to 1000 Hz only. However, because of the milling machine structure is a complicated continuous structure, the response is expected to be distributed in wide frequency range. The extremely small damping values can be assumed from the noise.

From EMA, the first five modes are first lateral bending, first vertical bending, second lateral bending, second vertical bending, and first torsional deformation pattern respectively. All these mode shape are shows in Fig. 4 below. Besides, the maximum and minimum shift of mode also can be reviewed in the figure. The red colour represented as the maximum displacements while the blue colour is a minimum shift of the mode.

Table 1: Experimental Result

Mode	Natural Frequency [ωn]	Damping ratio [ζ]
1	751.1	1.818E-17
2	771.1	2.173E-17
3	912.6	2.065E-18
4	990.8	3.506E-18
5	1197.2	3.662E-19

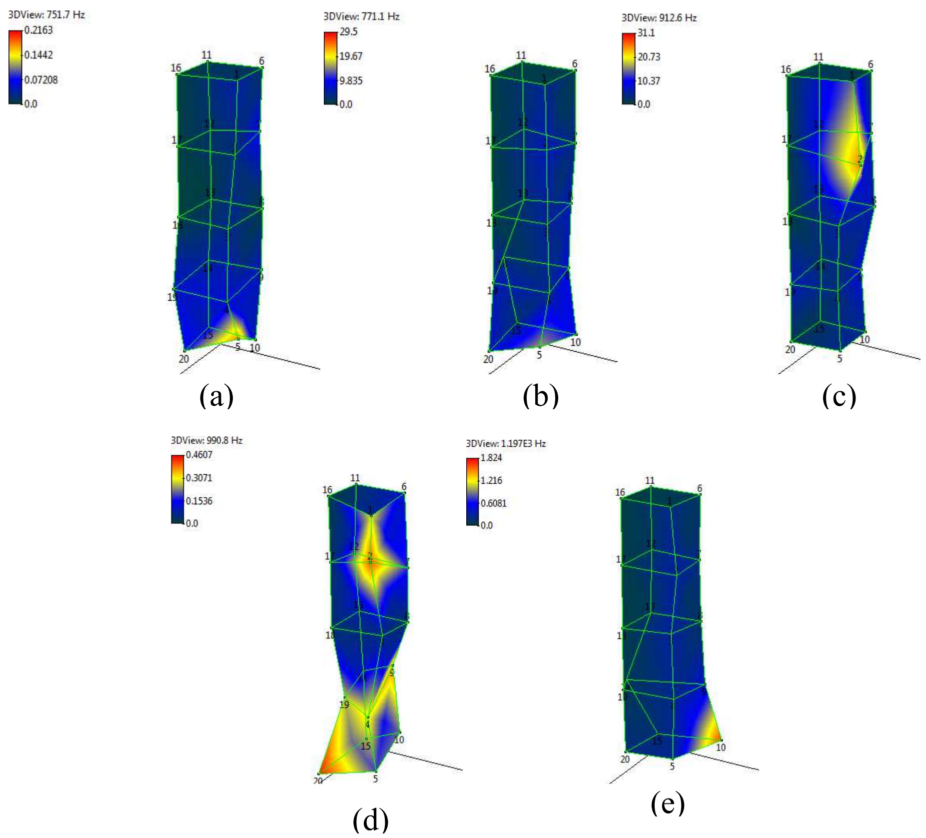
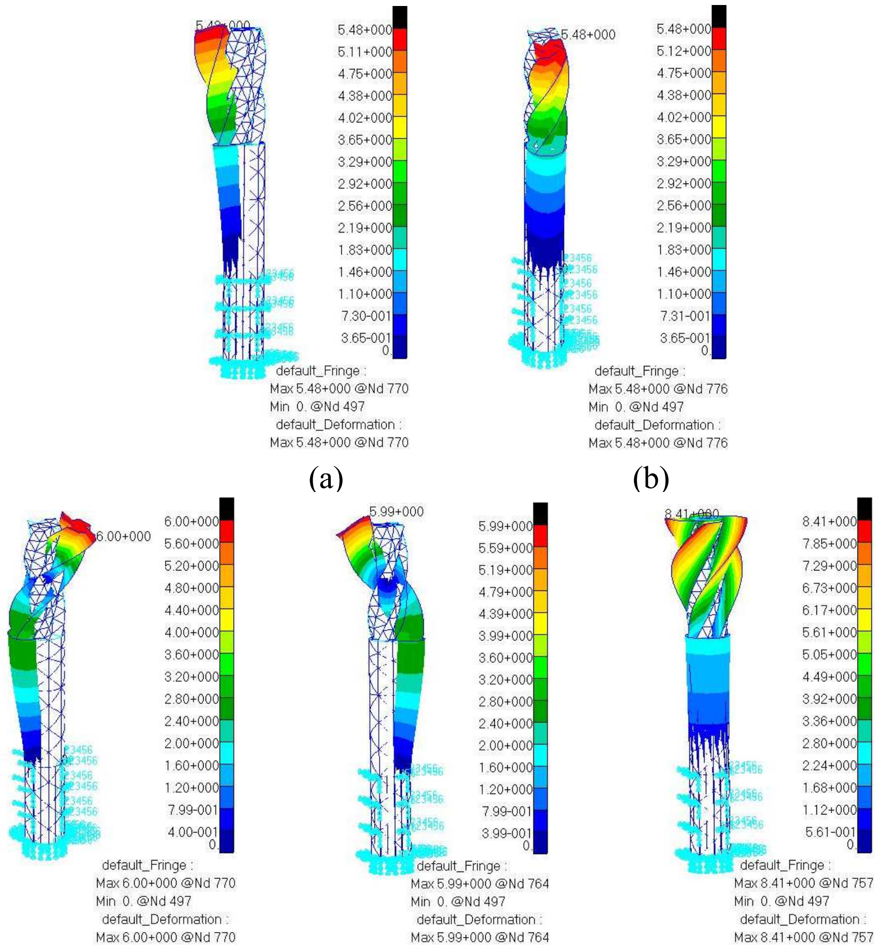


Figure 4: Cutting tool ODS animation at (a) first, (b) second, (c) third, (d) fourth, and (e) fifth modes

Next, a comparison of natural frequency values for both experimental and FE analysis were done. The model was created using MSC/NASTRAN finite element code. The entire model is constrained at the top surface of the solid. Both experimental and FEA for the first five natural frequencies and mode shapes are summarized in Table 2. The correlation between experimental and FE was good. From the obtained result of this study it showed the comparison between FEA and experimental is showing the closeness result and also have slight differences. The ranges are between 700Hz to 2000Hz for both. Furthermore, the first five mode shapes for FE analysis were shown in Fig. 4. The variability in frequency values is probably due to differences in the boundary conditions of the milling machine. Natural frequencies cannot be eliminated. However, its only may shift up or down in the frequency range. Some general methods to reduce vibration were reducing the exciting force or change the speed, mass, and the stiffness. Besides, a few factors that can lead to an accurate FEA include incorrect estimates of material properties, masses, stiffness, and boundary conditions.

Table 2: Correlation of experimental and FE analysis

Mode Number	Natural Frequencies of Cutting Tool [Hz]		Mode Shape
	Experimental	Finite Element Analysis	
1	751.1	763.8	First lateral bending
2	771.1	764.33	First vertical bending
3	912.6	1024.6	Second lateral bending
4	990.8	1024.8	Second vertical bending
5	1197.2	1909.5	First torsional



(a) (b)

(c) (d) (e)

Figure 4: Mode shape at (a) first , (b) second (c) third, (d) fourth, and (e) fifth mode of cutting tool

Conclusion

This paper presents an experimental study of modal analysis of a cutting tool. From the result, it was agreed both the finite element simulations and experimental measurements reveal that the linear guide of vibration behavior and milling stability agrees well with the cutting tests. Comparison of natural frequency also shows the closeness of the result and mode shape between experimental and FEA.

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