EXPERIMENTAL STUDY OF THE STATIC MODAL ANALYSIS ON MILLING MACHINE TOOL

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Abstract. Machine tool vibrations have great impact on machining process. 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 identify a procedure 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 structure 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

FRF defined as a response; displacement velocity or acceleration type divided by excitation force. In order to obtain FRFs value, modal and Operating Deflection Shape (ODS) analysis was done. Modal analysis used to characterize resonant vibration in machinery and structures while ODS analysis shows how a machine or structures is vibrating with a particular shape at each frequency. Each natural frequencies associates with a mode shape which provide dynamic behaviour of a structure. The natural frequencies and mode shapes depend on geometry, material properties and mass, support condition, and in-plane loads [1-2]. This agreed by previous researches [3-5]. By using the modal parameters to model the structure, they believed vibration problems caused by these resonances (modes) can be examined and understood. Later, [6-7] state since all bodies have mass and elasticity, they are capable of vibrating.

Milling is one of the most common manufacturing processes for manufacturing sectors. However, the high spindle speed associate with higher feed rates has led chatter vibrations to occur. In order to reduce chatter, many researches have done on chatter prediction. [8-9] with the aim of analysis of chatter phenomena, the tool's natural frequencies and the shape of their vibration modes were obtained from modal testing result. The introduction of the non-linear interaction between the tool and carries its part always gives interesting results which go from regular (periodic or quasi-periodic) vibrations to the possibilities of the chaotic ones or, always within the orthogonal framework of the cut, while utilizing in more the dry friction [10-11]. The 2D case is also examined while considering carries it rigid part but by taking into account the tool flexibility [12-13], the tool holder flexibility [14], or the rotor system [15].

A common approach is impact hammer modal testing. Impact testing was developed since the late 1970 when the ability to compute FRF measurement in a Fast Fourier Transform (FFT). Impact testing is an experimental modal analysis to determine dynamic characteristics of the structure such as natural frequency, damping ratio and mode shape [6, 16]. Impact hammer can be used to excite the force to the system while the accelerometer as transducer to measure the response [7, 17].

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 [18]. [19-20] used the finite element method to analyze the instability of machining process. They create a structural model of the machine tool system using the commercial FE code, without any experimental test. For this purpose, some researchers have concluded in his paper the finite element approach has been widely used to assess the static and dynamic behavior of machine tool structures because of the efficiency and reliability that it offers in the task of analysis. [15, 21] 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. Conventionally the natural frequencies and the damping ratios of a mechanical structure have been obtained from experimental measurements of frequency responses from the system and a subsequent graphical approximation or curve fitting procedure[22-23].

Experimental Study

Impact hammer excitation is the common method of measuring frequency response function. Figure 1 shows impact hammer excitation test set. An impact hammer was used to generate the excitation to measure cutting tool FRF. Then, the signal processing responses captured by a tri-axial accelerometer attached to the cutting tool. The tri-axial accelerometer was used to measure FRF response signal in each DOF (Degree of Freedom) that includes all 3 axis; X, Y, and Z axis. Lastly, the measured data were recorded and collected using the Multi-Channel Data Acquisition System and analyse using a PC-based data acquisition Analyzer. The DAS is to convert the analog time domain signal into digital frequency domain information compatible with digital computing and then to perform the required computations with these signals. A visual experimental finite element analysis was done to predict how the cutting tool is vibrating yet where excessive vibration levels occur for various points and direction. Lastly, a finite element modelling was done to validate the experimental modal analysis result collected earlier. Figure 2 shows the position of accelerometer and different knocking point. The accelerometer moved 32 points around the cutting tool. Impact hammer was applied vertically at the knocking point. The testing is made within 4 points selected at every angle of 90^o. The total of points at every angle is 8 points on the cutting tool.

Fig.1: Experiment set-up   Fig.2: Knocking method and points

In order to make a finite element model, a 3D geometric model of cutting tool using drawing software has been developed and then converted to igs. format for further analysis. The cutting tool was meshed with solid typed elements, with a total 1269 elements and 2414 nodes. Yet, boundary conditions on supporting are applied on the earth connection of machine. Furthermore, for this analysis, the materials used for the cutting tool were Tungsten with an elastic modulus E = 4.096e+011 Pa, shear modulus G = 1.6e+011 Pa, Poisson's ratio μ = 0.28, and density ρ = 19300 kg/m^3. The result obtained is shown in the next section with related discussion.

Result and Discussion

This section presents the results from both experimental and finite element analysis. The study was carried out using analysis software for the finite element analysis and experimental analysis using impact hammer testing. There will be discussion about dynamic properties and behaviour yet comparative study between experimental and finite element analysis. It has been observed that the natural frequencies obtained from the experiment agree with the finite element analysis results. The table shows the comparison of natural frequencies obtained from the experiment and finite element analysis, where it shows a quite satisfactory correlation.

Table 1: Comparisons of natural frequencies

Mode Number	Natural Frequencies of Cutting Tool (Hz)	
	Experimental	Finite Element Analysis
1	751.5	703.93
2	868.8	704.11
3	1379	2928.7
4	1591	2931.4
5	1768	5233.4

As stated earlier, the testing is made within 4 points selected at every angle of 90^o. The total of points at every angle is 8 points on the cutting tool. The result from both the experimental study and finite element analysis shows there are good satisfactory in terms of increase the natural frequency by time. However, they are slightly difference of result obtained from both analyses respectively. The frequency range obtained from experimental study is between 700Hz to 2000Hz. These frequencies are a bit low compared to finite element studies where the frequencies range obtained are between 700Hz to 6000Hz.

The difference of both experimental and finite element analysis might cause by its boundary conditions specification. This is because it is not easy to simulate the realistic boundary condition for a cutting tool that attach to a large machinery system as milling machine. Furthermore, this experimental study is conducted in a static and fix condition, thus the effect of damping which also affect test rig. A little vibration on the machine and the noise from environment since the machine is located at wide area also affect the result.

Figure 3 shows the first two natural frequencies and mode shapes of the cutting tool obtained through both experimental and finite element analysis. In real condition, for a milling machine that run in 40,000 to 60,000 rpm, the machine will excite frequency in range 600 to 1000 Hz. Thus, only the first and second mode for both analysis were valid and acceptable. For finite element analysis, there is first and second vertical bending mode for cutting tool at mode 1 and mode 2 respectively. On the other hand for experimental study, the result shows at mode 1 and 2, there is also first and second vertical bending mode for cutting tool. The red region represented as the maximum displacements occur in the mode and the blue region is a minimum shift.

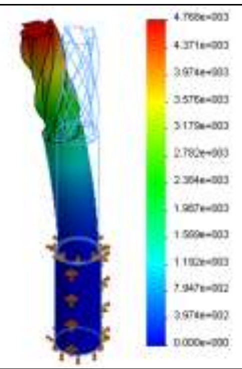
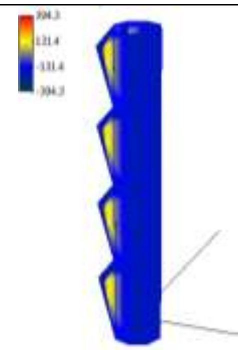
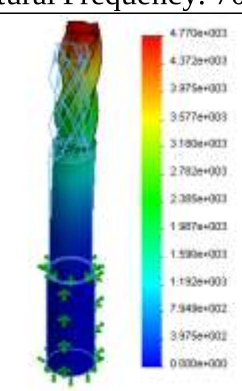
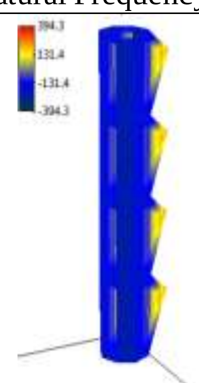
Finite Element Analysis	Experimental Analysis
	
First Natural Frequency: 703.93 Hz	First Natural Frequency: 751.5 Hz
	
Second Natural Frequency: 704.11 Hz	Second Natural Frequency: 868.8 Hz

Fig.3: First two natural frequencies and mode shapes of cutting tool

Generally, the higher is the frequency, the larger is the difference between finite element analysis and experimental values. The differences should have the tendency that the finite element analysis values of frequencies are higher than the measured ones, because usually damping is not included in the finite element analysis whereas experimental frequencies are always damped and thus of lower values. Furthermore, the experimental analysis is completely different situation from finite element analysis where the density of the mesh highly influences the precision of the solution.

Besides that, grounded or fixed support is theoretically such a type of support where some points on the body are completely fixed by connecting to the ground. It is quite complicated, because ideal fixation is impossible in real. This type of support causes difficulties when comparing experimental with the finite element analysis, because the differences in both models could be caused namely by different boundary conditions. Thus, the computed mode shapes could differ as well.

Moreover, this is also related to the stiffness of the contacting surfaces. The stiffer the materials, the shorter will be the duration of the pulse and the higher will be the frequency range covered by the impact. For a hammer's tip, it can be said that a tip as soft as possible has to be used in order to supply input energy only to the frequency range of interest.

Different situation occurs when two mode shapes look very similar, but their frequencies are quite apart from each other. In this case, the mode shapes differ very likely in something that was not measured. The geometrical model used for modal test is usually quite simple and it could easily happen that it would not capture all the details of the movement. Thus, two modes could appear as being the same even if they are not. In this case, it is not a measurement or approximation error, but improvement on geometrical model to have a finer model.

Besides, if two or more mode shapes look similar, it again might be an approximation error. It might happen when the software identifies false modes thus more modes are required in the frequency bands than really exist.

Conclusion

This paper presents an experimental study of modal analysis of a cutting tool. It has been concluded from the results that the natural frequencies obtained from the experimental modal analysis and analysis software shows a good relation in comparison. However, they are some errors due to boundary condition, drawing design, stiffness, contacting surface, etc... Thus, improvements will be highly recommended for further experiment test and modal test.

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