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Using Finite Element Analysis on Dynamic Characteristics in a Micro Stepping Mill

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***Abstract*—**For smaller mechatronic device, especially for micro Electronic system, a micro machining is a must. However, most investigations on vibration of a mill have been limited to the traditional type mill. In this article, vibration and dynamic characteristics of a micro mill were investigated in this study. The trend towards higher precision manufacturing technology requires producing miniaturized components. To improve micro-milled product quality, obtain a higher production rate and avoid milling breakage, the dynamic characteristics of micro milling must be studied. A stepped pre-twisted mill is used to simulate the micro mill. The finite element analysis is employed in this work. The flute length and diameter effects of the micro mill are considered. It is clear that the effects of micro mill shape parameters on vibration in a micro mill are significant.

***Keywords*—**micro system, micro mill, vibration.

I. Introduction

THE milling is frequently employed in manufacturing to produce many goods. A precisely milling leads to a high quality product and its accuracy is based upon the milling process. During this process, cutting location errors, reaming and mill fracture occur. The trend towards higher precious manufacturing technology requires more micro machining, such as micro milling. To improve quality, produce a higher production rate and avoiding micro mill breakage, the cutting force and dynamic characteristics of a micro milling must be studied. In this work, the effects of rotation speed, feed velocity and cutting depth on vibration were considered and the cutting critical force was also investigated. Recently, some investigations as [1-3] turned attention to these micro milling problems. However, most studies are focused on the cutting chip, force operation or prediction. Few investigations examined the micro mill dynamic characteristics, even though the dynamic properties may change the machining performance significantly. This study considers the micro mill dynamic characteristics.

Most traditional end milling analysis focused on the cutting force and chip deformation, such as [4, 5]. Few studies focused the dynamic mill properties as in [6], which examined the complex geometry of cutting bits. Some investigations, such as [7] reported that the helical flute structure may affect the dynamic characteristics of a mill. The helical flute structure and complex cutting bits are often found in a mill. Some studies [8, 9] reported on the vibrations in a pre-twisted beam, modeled as a drill or end mill. The effects of the pre-twisted angle and rotation speed on vibrations in the beam were presented. The effects of complex geometry or the cutting chip on dynamic mill bit properties were also examined. Even a small variation in the geometry or symmetry could produce a very strong influence on the cutting and dynamic properties of a cutting system, such as [10]. Such models can provide useful information for mill bit design

In nearly all cases, micro machining is widely used to cut miniaturized components in the electronic, aerospace and biomedical industries. The micro machining problem has recently attracted many researchers [11, 12]. However, few investigations examined the dynamic properties or vibration of complex stepped structures in micro end mills. Complex stepped micro mill sections with helical flute structure are considered in this article. A stepped pre-twisted mill was used to simulate the micro mill structure. Using the finite element analysis to solve the micro mill natural frequency problem is considered.

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II. Finite Element Analysis

Figure 1 and 2 show photographic and enlarged views of a micro end mill. This micro mill was simulated as a stepped pre-twisted mill. This mill is a cantilever stepped pre-twisted beam with a constant rotation speed of Ω as shown in Fig. 3. The total mill length is L. Notations L_1 and D were employed to denote the length and diameter of the mill shank. A pre-twisted beam was used to simulate the micro mill body. t and b were used to denote the thickness and breadth of the mill body.

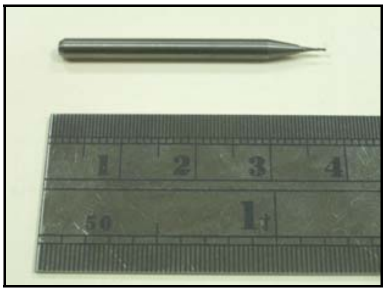

Fig. 1 A photograph of the micro mill

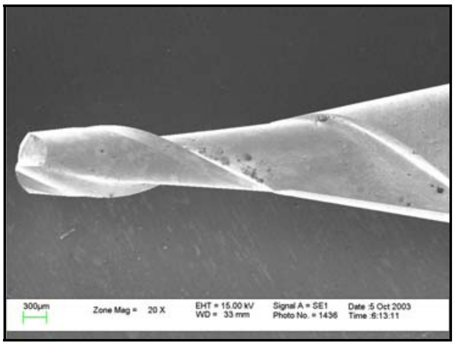

Fig. 2 An enlarged view of the micro mill

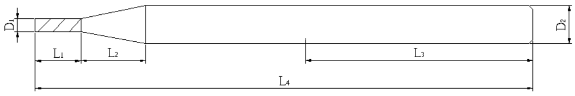

Fig. 3 The schematic diagram of a micro mill

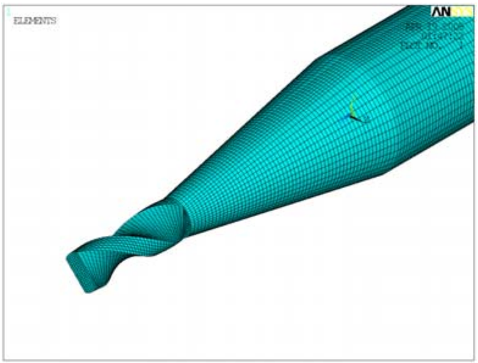

Fig. 4 A FEA model of the micro mill

The complex geometry of a twist drill or mill is difficult to model by mathematic simulation, so the finite element method is employed to analysis these complex geometry system. The finite element analysis is widely used to investigate the complex system [13, 14]. Recently, investigations as [15] employ finite element analysis (FEA) to compare the different type cutting edges. Besides, cutting force by using finite element analysis for this complex system also attracts some investigation [16]. For a micro mill, not only a twist cutting flute but also the stepped sections must be considered to investigate. Therefore, the finite element analysis is also employed to study. The most common cause of drill failure is breakage. Mill breakage usually occurs because of excessive milling force in the drilling process. No study has been conducted on dynamic milling process properties yet. The cutting force and vibration in a micro mill are focused to investigate by using FEA.

An investigation of the dynamic properties in a micro mill by using finite element analysis is considered. A photo of the micro mill is displayed in Fig. 1. The complex geometry of micro mill is too small to found. To make the complex geometry flute body clarity, an electron microscope is employed to amplify the view of flute body. Figure 2 shows the enlarge view of micro mill flute body. From Figs. 1 and 2, the micro helical flute body and stepped sections body is observed. For performing the finite element analysis on the twisted tapped micro mill model, meshes were created by using the ANSYS software. This software is widely used to analyze the dynamic properties of complex system, so it is also used to investigate the vibration in a micro milling process. In this ANSYS, element meshing of the micro mill model is performed with the Solid45 element type using a three-dimensional meshing. A FEA model of the micro mill is displayed in Fig. 4. The finite element models are assigned material properties. These properties are: Young's modulus is 207Gpa; density is 7870 kg/m^3 and Poisson Ratio is 0.3. In this analysis, the dynamic properties as natural frequencies and mode shape of a micro mill can be found.

III. Vibration Analysis

The vibration and dynamic characteristics of a micro mill were investigated in this study. Some geometrical parameters of the micro mill are displayed in Table 1. The most common cause of mill failure is breakage. Few investigations examined the dynamic properties of the micro mill structure. The purpose of this article was to present the dynamic properties of a micro mill. Table 2 shows the difference in the lowest natural frequency using theoretical and finite element analysis. Little difference was found between the theoretical and finite element analysis. Hence, this result of finite element analysis of a micro mill is accepted. First, the critical load with different milling diameter effect in a micro mill is illustrated in Fig. 5. The cutting load effect on natural frequency of a micro mill is also shown in this figure. Natural frequencies are almost independent on the cutting load is clear. However, the natural frequencies are dropped suddenly as the cutting load approaches the critical load. The critical load will be found as the natural frequency is equal to zero for a micro mill, and the critical load is 196N for a micro mill with 0.5mm diameter in this work. This figure also displays that the critical load will be increased as the diameter of a micro mill increases. Figure 6 illustrates the critical load with different cutting flute length effect in a micro mill. Stiffness of a micro mill may be changed by the cutting flute length. It is found the shorter flute length is stronger than the longer one. For the natural frequency of a micro mill, the natural frequency will be decreased as the cutting flute length is increased. The same phenomenon is observed that the critical load will be decreased as the cutting flute length is increased. The effects of tapered shank length on critical load are illustrated in Fig. 7. Results indicate that the critical load is decreased as the tapered shank length is increased, and so is the natural frequency.

TABLE I
GEOMETRY PARAMETERS OF THE MICRO MILL

Mill type (diameter)	β (rad/mm)	D_1 (mm)	D_2 (mm)	L_1 (mm)	L_2 (mm)	L_3 (mm)	L_4 (mm)
0.8mm	1.5	0.8	3.0	9.6	15.8	20	38.2
1.0mm	1.5	1.0	3.0	9.6	15.2	20	38.2

TABLE II
THE DIFFERENCE BETWEEN THE THEORETICAL AND FINITE ELEMENT ANALYSIS RESULTS.

Mill type (diameter)	Finite Element Analysis (Hz)	Theoretical Analysis (Hz)	Difference (%)
0.8mm	83577.3	87525.3	3.87%
1.0mm	82225.4	84281.6	2.4%

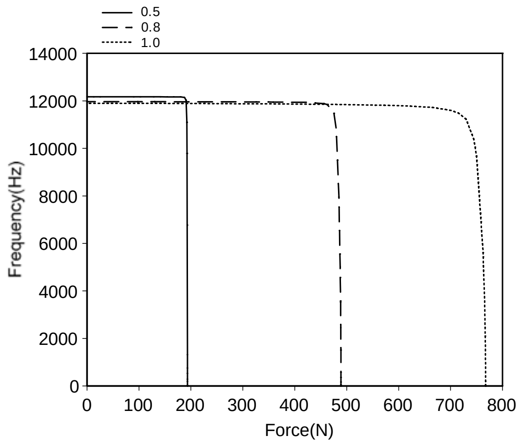

Fig. 5 Effects of different cutting flute diameter on critical load of a micro mill

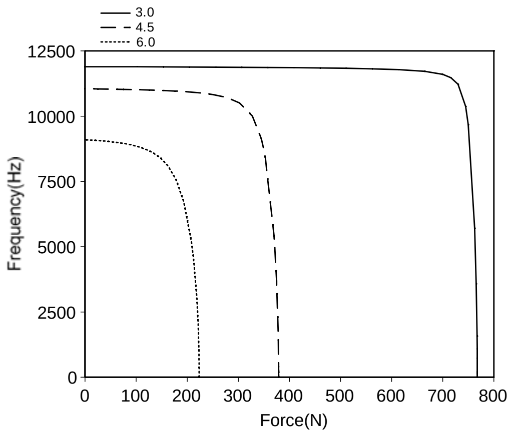

Fig. 6 Effects of different cutting flute length on critical load of a micro mill

For a high precision micro machining, the vibration amplitude of cutting tool may change the cutting quality, even for a little residual vibration. The residual vibration effect is considered in this article. Figure 8 shows the residual vibration amplitude in a micro mill with different diameter. Generally, a larger diameter of a micro mill may have stronger stiffness, so the excited vibration is lower. By another word, the residual vibration will be decreased as the diameter of a micro mill is increased. The residual vibration amplitude in a micro mill with different cutting flute length is shown in Fig. 9. As the Fig. 6, the natural frequency will be depressed as the cutting flute length is increased. It is found that the mill stiffness is dependent on the flute length. In this Fig. 9, however, the result also displays that the residual vibration amplitude is depressed if the cutting flute length is decreased. The tapered shank length of a micro mill effect is also considered. Fig. 10 shows the residual vibration amplitude in a micro mill with different tapered shank length. Results indicate that the residual vibration amplitude will be depressed if the tapered shank length is decreased.

In actual engineering, the lower mode natural frequencies affect the dynamic characteristics of system more than the higher mode. Hence, only the lower four modes are displayed in this article. The large displacement occurs only on the micro mill helical flute. This phenomenon agrees with the micro mill in actual milling process. The dynamic characteristic of a micro stepped mill is different from the traditional mill. Figure 11 illustrates the frequency response in a micro mill with different mill diameter. At lower mode, the 1st natural frequencies are almost identical even though they have different diameter. However, at higher mode, the natural frequency may shift a higher domain frequency as the micro mill has a smaller diameter flute. The frequency response in a micro mill with different mill diameter is shown in Fig. 12. The longer cutting flute length of a micro mill with weaker stiffness in unavoidable. Hence, in this figure, the natural frequencies including the lower and higher mode are depressed if the cutting flute length is increased. To proceed farther into the tapered shank length effect on the frequency response, the variations in frequency response with different tapered shank lengths is shown in Fig. 13. Results indicate the natural frequency peaks shifted the lower frequency domain if the tapered shank length is increased

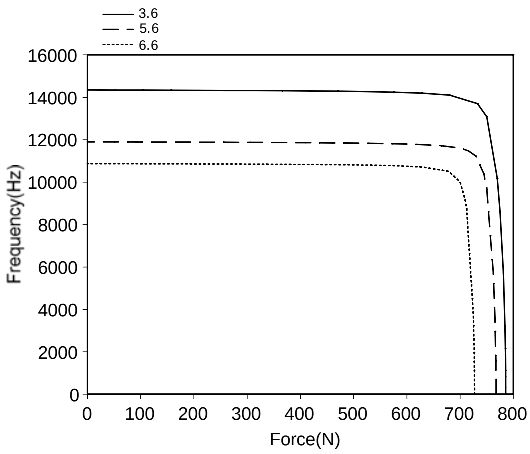

Fig. 7 Effects of different tapered shank length on critical load of a micro mil

IV. CONCLUSIONS

The vibration and critical load of a stepped micro end mill were investigated. The major conclusions drawn from the analysis and numerical results obtained in this study are summarized as follows:

1. A study of the vibration and critical of the micro mill is necessary to improve micro milling performance and capabilities, especially for ultra-high-speed micro milling. It was found that the critical load is increased as the flute diameter of a mill is increased.
2. The lowest natural frequency of a micro mill decreases as the flute length is increased.
3. Results indicate that the flute length, diameter and taper length drastically change the vibration and critical of a micro mill.

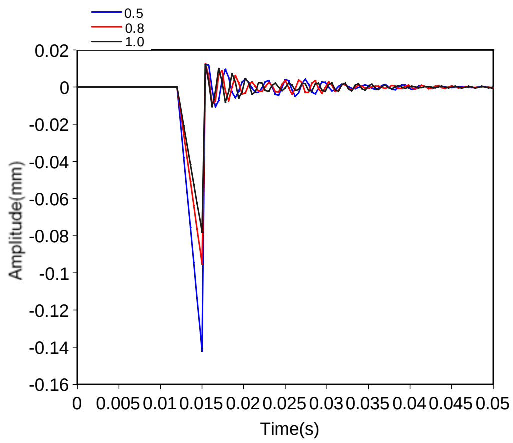

Fig. 8 Variation on residual vibration of a micro mill with the different cutting flute diameter

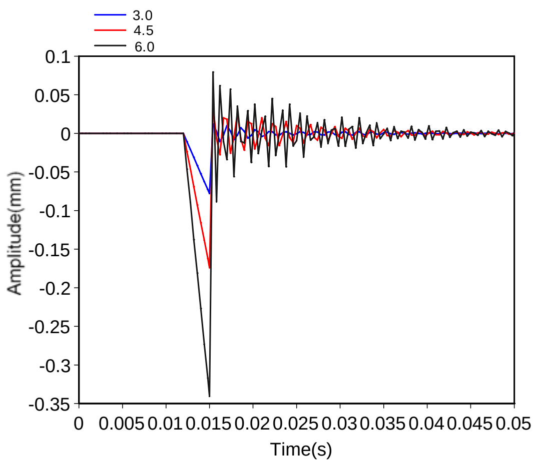

Fig. 9 Variation on residual vibration of a micro mill with the different cutting flute length

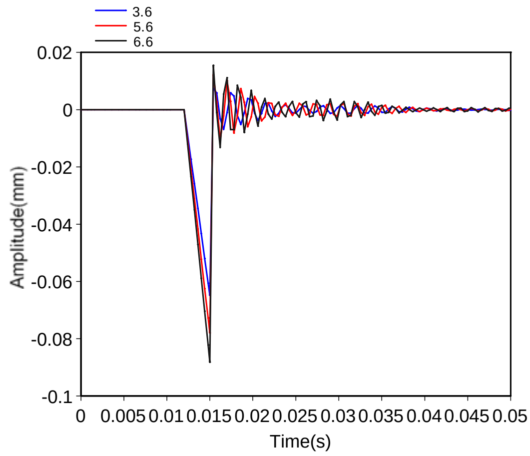

Fig. 10 Variation on residual vibration of a micro mill with the different tapered shank length

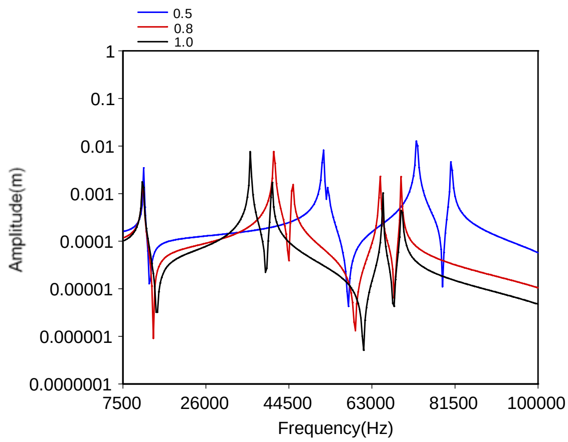

Fig. 11 Frequency responses of a micro mill with the different cutting flute diameter

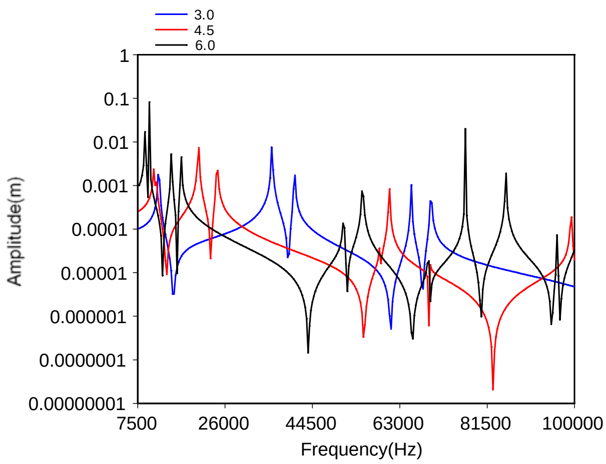

Fig. 12 Frequency responses of a micro mill with the different cutting flute length

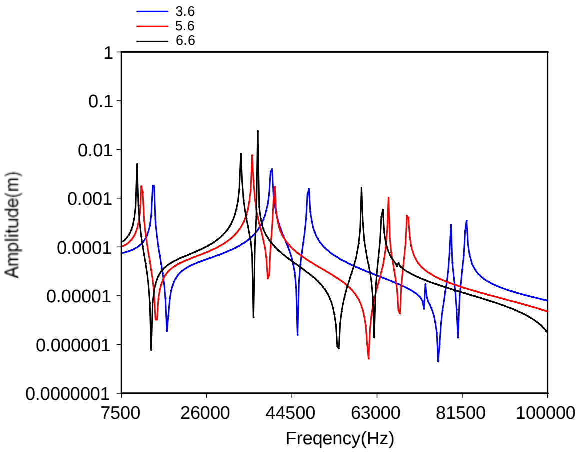

Fig. 13 Frequency responses of a micro mill with the different tapered shank length

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