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Research Article

Dynamic analysis of an integrated Micro-End mill spindle

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ABSTRACT

In recent years, demand for exact three-dimensional (3D) microscale features has been from various sectors, including the production of medical devices, military/defense, aerospace, electronics and consumer goods. Renewable chatting is an unpredictable phenomena during the micro-machining phase that results in low quality, tool wear and injury. Because of its high rotational speed, micro-cutting operations often undergo chatter behaviour. Different factors, including variations in the rigidity of the loads, gyroscopic impact should be considered for the spindle dynamic. Dynamics greatly affect the stability of the cutting process and the composition of the tool also influences the dynamics of the tool. Dynamics of the tooltip are influenced by the part of the tool because of its mode-interactions. A model of micro spindle device for machining stability is currently considered in this work. The Timoshenko beam principle is used as part of a short and thick beam style systems on each part of the micro-tool to understand shear deformation and rotary inertia. A comprehensive, complex model of the revolving micro end mill is developed with the extended Hamilton principle. The method of micro-milling is modelled on a two degree system of independence, which considers the modal dynasty of the tool-holder-spindle installation and the micro-milling power. The cuts are modelled as a function of the uncut instantaneous chip thickness, largely influenced by the radius of the tool edge and tooth feeds.

Keywords: thick beam; micro-machining; Timoshenko beam; uncut instantaneous chip thickness; tool edge.

INTRODUCTION

Miniaturizing devices is now needed in the field of optics, electronics, pharmaceuticals, biotechnology, communications and avionics to produce mechanical components that have produced properties in the range of a few to a few hundred microns. Micro-scale fuel cells, liquid micromechanical reactors with micro-scale pumps, valves and mixing machines, fibres, microscales, micro-scale jets, micro-scale jets, micromolds, deep X-ray lithography masks and several others are specific applications. A technique that uses end-mills, usually with diameters ranging from 100 and 500 mm, and with edging radii varying from 1 to 10 mm is one of the mechanical processes for micro-milling. Different phenomena dominate the microfining procedure, relative to those usually found in traditional frills, because the method of final milling sizes are reduced from conventional (100mm/tooth feed rate, 1mm depth of cut) to micro-end

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frying sizes (1m/tooth feed rate, 100mm depth of cut). Due to the extent of the operations, despite the cinematic nature, the basic distinction between micro-milling and traditional milling comes. In Micro-milling however, the feed per tooth ratio is much higher than standard friction, which also contributes to a mistake in the prediction of cutting powers. In contrast to the traditional milling, the performance of the tool edge, also in microns, significantly affects the precision of micro-finishing.

To prevent premature wear, breakage and smooth surface finish on the miniature pieces, the geometry of the tool, speed of cuttings, load of chips and depth of the cut must be properly choosen. The prediction of cutting power, tension, temperature & vibration depends on the properties of the material, geometry of the tools and cutting conditions. In order to forecast process activity before expensive physical experiments, the cutting mechanisms and dynamics of micro-filling must be modelled. Many authors documented complex simulation approaches to the micro-end mill.

For the micro end mould dynamics, Filiz and Ozdoganlar[2] introduced an analysis model, including configuration defects, the axial force, the geometry of the divided machine and the real cross-section of the fluted section. Mustapha and Zhong[2] found the transverse reaction of a Micro End Mill as a hybrid analytical model. The model has been discussed and spread in structural components to take care of the machining system's stiffness and damping coefficients. Zaman et al.[3] suggested a new approach to the determination of a theorespatial chip range by taking into account the geometry in the direction of the cutting edge and compared this to the tangent cutting force by taking a three-dimensional cutting force model. Rahnama et al. [4] studied the dynamics of micro-frying by examining the influence of process dynamics, extending traditional stability theory of chatter by integrating process damping, which is a property of the amount of disturbance from instrument to workpiece. The reception coupling approach for mathematically pairing of substructural dynamics using non-contact sensors was used to identify the tool tip dynamics. Shi et al.[5] also studied the gyroscopic and mode-interaction effects of regenerative talk on microendynamics and stability. The transmission activity of the micro-end mill during cutting processes was identified by using piezoelectric components. In the micro-end milling of both individual and multiphase workpiece materials, Vogler et al.[6] investigated the surface generation mechanism. A model of surface generation is then built based on the minimum chip thickness definition to estimate surface ruggedness for the middle line of the slate floor.

In order to measure the chip thickness of microend-milling, Bao et Tansel have proposed a new theoretical model [7] by looking at the trajectory of the tip as the instrument continually turns and passes. It is possible to calculate the cutting forces using computational techniques without simulating the whole tool rotation. The theoretical model for the prediction of micro-friction cutting forces was proposed by Bissacco et al [8], taking into consideration a cutting edge radius effect, the instrument run out, and an angle of inclination of chip flow deviation.

The calculation of cutting force in microfrying by using the maximum vibration amplitude was investigated by Huang et al.[9] and comparison was made with earlier studies. Mascardelli[10] examins the use of mathematical coupling of spindles/micro machines with various geometries of receptance coupe technique and arbitrary micros. The Response Frequency (FRF) feature was tested experimentally through the use of laser movement and capacity sensors by hammer testing. Indirectly, joint rotational dynamics were calculated by the testing of FRFs in the gauge instruments. Chat conditions are forecast and checked by means of micro-frying experiments from the FRFs. The three-dimensional (3D) model vibration-assisted vibration (2D) cutting force was proposed by Ding et al.[11]. Ding et al. The cutting forces are calculated with the proposed models and both have fair agreement with the test, and the dynamics leads to a strong agreement with the experimental data without taking into account the dynamics. The mechanical modelling of micromiller forces was examined by Malekian et al.[12], taking into account the effects of ploughing, elastic recovery, depression and dynamics. The elastic recovery rate of the workpiece has been identified experimentally by a conical indenter. The elastic deformation is checked for the Aluminum 6061 sample after the scratch tests and the trimming force model. The predictions of micromilling forces were investigated by Jin and Altintas[13] using the cutting force coefficients assessed from simulations with the finite element. Included in the model were strain hardening, strain rate and temperature effects. For the nonlinear functions of the radius of the tool edge and uncut chip width, which are the reproduction of mechanical patterns, the projected cutting forces were used. Cutting forces predictions were correlated with experimental measurements using the proposed SE and previously published slipline field models. Huang et al.[14] considered a dynamic micro-stage mill model with time-sensitive cuts that is essential for an understanding of the dynamic characteristic of a micro-finishing mill. It considered the impact on dynamic characteristics of rotation speed, cutting depth and limit stiffness. Hsieh et al. [15] developed the spindle accelerometer, data acquisition and signal transformation module and back propagation of the neural network, a microtool condition monitoring device. They examined the vibrational signals obtained from the spindle housing in the micro-milling and discussed the extraction function and classification nature of the device proposed. The predictions of cutters and chat stability in micro-milling operations based on the material's component flow stress and structural dynamics for the micro-end mill were proposed by Jin and Altintas[16]. In the frequency domain, the Chatter stability lobes have been predicted by using the cutting force and process damping coefficients defined by the building model of the material and directly measured FRF in the micro mill. For the prediction of cutting power, Kang et al. [17] suggest an empirical mechanistic model of MM. Microtool's cutout range is simulated and its validity is tested by a newly developed micro-end milling tool dynamometer. Park et al. (18) improved the classical reception technique by proposing an identification approach that included translational and rotational independence for the end-mount spindle-tool-holder joint dynamics. The Spindle Holder's dynamic rotational response is analytically replaced by the direct and cross FRF measurements taken in the reaction coupling expressions at the free end of the assembly and the joints of the blank cylinder.

In the current work, a finite element analysis is provided in the coupling spindle-tool model for a microend milling process. The micro end-mounting system's vibration response is examined. Centered auf Timoshenko beam theory, the governing equations are formed and the microscope is idealised as a stepped distributed dynamic device. Also modelled as a solid geometry this spindle structure is analysed using a 3-D finite element mesh. The dynamic characteristics of the coupled spindle-tool unit will be validated by modal and harmonically based analyses. A theoretical model for the prediction of cutting force in a microfinishing system takes the cutting-edge radius-size effect into account.

MATHEMATICAL MODELING

The general model (rotationally from 10 000 to 60,000 rpm) of the microfinder spindle mechanism as seen in Fig. 1. The spindle shaft has a hollow ring cross section and a conical part on the front to fit the tool holder. A taper section together with the spinder shaft and a uniform section outside the spindle shaft can be used to approx. the tool holder including the collector. The internal radius of the tool holder (including the collector) is supposed to be the same as the radius of the shank of the microend tool. The shank has a diameter of 4 mm with a surface of 16 mm and a 0.6 mm tool diameter as shown in Fig. 2.

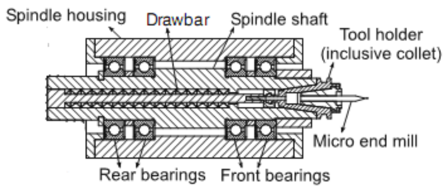

Fig. 1: Schematic of micro end-mill spindle unit

A rotating shaft with eight degrees of freedom for each node is used to model the rotating micro end spindle with gyroscopic terms based on Nelson's timoshenko beam theory[19]. Apply the theory of Hamilton to the element translational and rotatable mass matrices, the rigidity matrix and the gyroscopic matrix. The matrix equation obtained by the FE method is as follows:

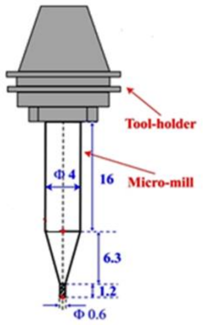

Fig. 2: Equivalent analysis model

$$[\mathrm{M}]\{\ddot{\mathrm{q}}\}+[\mathrm{C}]\{\dot{\mathrm{q}}\}+\left([\mathrm{K}]-\Omega^2[\mathrm{M_c}]\right)\{\mathrm{q}\}=\mathrm{F} \qquad (1)$$

Where the system element matrices are given by [19]:

$$[M] = [M_T] + [M_R] \qquad (2)$$

$$[M_T] = [M_0] + \phi[M_1] + \phi^2[M_2] \qquad (3)$$

$$[M_R] = [N_0] + \phi[N_1] + \phi^2[N_2] \qquad (4)$$

$$[K] = [K_0] + \phi[K_1] \qquad (5)$$

$$[C] = -\Omega[G] + \alpha[M] + \beta[K] \qquad (6)$$

$$\phi = \frac{12EI}{k_s AGl^2} \qquad (7)$$

The micro end spindle FRF consisting of real and imaginary parts can be given expressed as:

$$[H(j\omega)]=[Re(\omega)]+j[Im(\omega)]=[-[M]\omega^2+j\omega[C]+([K]-\Omega^2[M_c])]^{-}1 \qquad (8)$$

Here Re and Im are the actual and imaginary part of the spindle tool tip transmission mechanism, respectively.

The natural frequencies and mode forms of the Micro-Mill by ANSYS 13 are predicted using the finite-element method. The shank end is applied with a perfect cantilever restriction. A 3-dimensional strong micro-end mill model is developed and the spindle framework is meshed with a solid of 187 components. The carbide for the microfining device used is 14300 kg/m3 and 580 GPa as material, density and elastic modulus. A cylinder with a diameter of 90 percent of the nominal value of the tip diameter is estimated in the cutting flutes.

3. CUTTING FORCE MODEL IN MICRO END-MILLING:

For mechanical research and dynamics of cutting processes, the study of cutting forces plays an important part. If cuts are unsuitable, the tools are easily fractured and waste money and time. Furthermore, tool wear or cracks is not easily detected by the user. The cutting force analysis therefore plays an important role in determining the characteristics of cutting procedures, such as tool wear and surface texture, the establishment of cutting plans and conditions for cutting. Due to its important position in the Surface Quality of machined parts, force analysis is important. By considering the direction of the tool tip, the current strength model measures the immediate chip thickness as the tool rotates continuously and moves forward. For the anslysis of the cutting force in the slip-line slip model micromilling the forming model and friction parameters between the tool and the piece material are used. The accuracy of the forecast depends greatly on the correctness of the material model. In addition to the analysis of the microcutting method, the slip-line field approaches are faster than the finite element processes computationally. After identifying one edge radius values for the tool chip friction parameters, the cutting forces for another tool edge radii can be predicted. The slip-line scope model however is focused on the legislation on plastic flow and cannot cope with fracture and non-homogenous materials. The orthogonal micro-cutting simulated cutting forces are used to convey cutting power coefficients as a non-linear feature of the radius of the rim and the uncut chip thickness that imitate mechanical model. By changing cuts force coefficients that are important variables for the force prediction, since the chip varies, the frying forces are then predicted. The coefficients are calculated by the numeric simulation of the FE model capturing basic characteristics of micro-frying, including the radius-and-plug effects of the tool tip, and by using the Johnson Cook constituent material model, taking the material work properties into account. By slip-line field model, the projected tangential and natural cutting force components are:

$$F_t = K_t(h)hw$$

$$F_n = K_n(h)hw \tag{9}$$

Where h is the uncut chip thickness, w is the cutting distance, which gives the amount of the differential cut depth equal to that value. Then, by a non-linear curve, which matches the simulated forces, the initial cuts force coefficients with the variance of uncut chip thickness (h) may be found.

$$K_t(h) = \alpha_t.h^{pt} + \beta_t.h^{qt} \qquad K_n(h) = \alpha_n.h^{pn} + \beta_n.h^{qn} \tag{10}$$

The empirical consistencies (α, β, p and q) are related to the radius of the border and the thickness of the chip. When the tool edge width is equal to the uncut chip thickness, the nonlinearity increases. For cutting speeds between 19 m/min and 45 m/min, cutting forces have very few effects. The coefficients are therefore considered in the present model to be independent of the cutting speed.

Table.1Estimated constants for the brass cutting forces

	α	**β**	**p**	**q**
K_t	252.9	-0.3833	0.08159	-1.39
K_n	1.597	-1.16	-0.01627	-1.581

All the elemental forces contributed by N flutes I along the axial depth of cut are assessed to integrate the total mowing power (a).

$$F_x(\phi) = \sum_{i=1}^{N_t} \int_0^a dF_x\left[\phi + (i-1)\frac{2\pi}{N}\right]d\phi \qquad (11)$$

$$F_y(\phi) = \sum_{i=1}^{N_t} \int_0^a dF_y\left[\phi + (i-1)\frac{2\pi}{N}\right]d\phi$$

4. RESULTS AND DISCUSSIONS

Table 1 shows parameters for the spindle model finite element. All the elements are regarded as carbide. Tables consider the densities and shear modulus for the problem.

Table 2: Parameters for finite element model of the micro end-mill spindle [18].

Parameter	Elements of the spindle					
	1	2	3	4	5	6
Length (mm)	1.2	2.1	2.1	2.1	16	20
Outer dia.(mm)	0.6	0.8	1.2	2.5	4	8
Inner dia. (mm)	0	0	0	0	0	0
E (Gpa)	580	580	580	580	580	580
Density (Kg/m^3)	14,300	14,300	14,300	14,300	14,300	14,300

The software for the analysis of the micro-end motor system is implemented in MATLAB. The mounting matrices and static condensation method are included in the software and initially assume that the rotating degree of freedom is completely rigid.

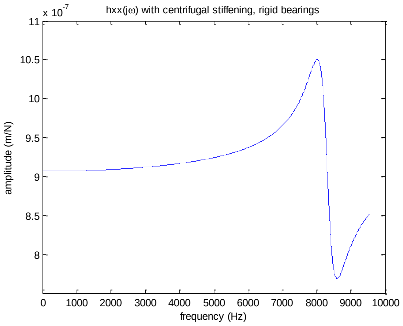

Fig. 3: Tool tip FRF of at 30,000 rpm

As shown in Fig. 4, the natural frequencies and mode forms of the first mode. The Z-axis reflects without deformation the axial direction of the tool. Finite element results indicate that the first mode is the taper portion bending and the tool edge. The difference between the validation in the beam theory and the prediction of the end factor shows that the limiting condition in the tool's clamping point causes a shift in tool dynamics.

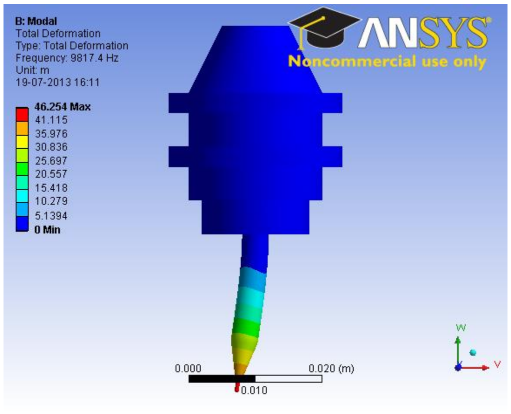

Fig. 4: Deformation of tool shank and tip

The study of the harmonic reaction is performed for the purpose of predicting the continued dynamic behaviour of micro-end moulds and thus, we can see that the maximum reactions are generally displaced by the frequencies as shown in Fig. 5. In order to verify natural frequencies, the superposition mode approach is used. In accordance with harmonic plots, phase responses were also designed to display a response over a range of phase angles such that the response lags behind the applied load as shown in Fig. 6.

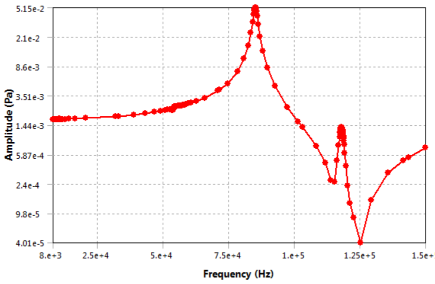

Fig. 5: Harmonic response of micro end-mill spindle system

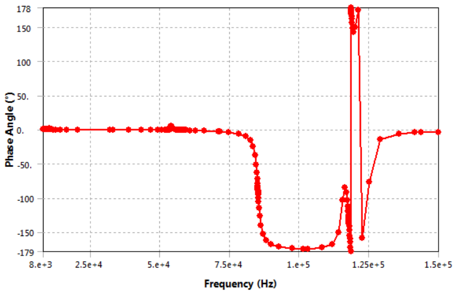

Fig. 6: Phase response of micro end-mill spindle system

However, the feed-to-tool ratio for micro end milling in comparison with traditional end-friction is considerably higher. Therefore it is very important to set the cutting conditions. Earlier studies on mechanism modelling of traditional milling operations were done by a number of authors. A new method is developed to calculate cutting force coefficients of numerical simulation results which are capable of taking into account the ploughing effect in micro machining. These coefficients are an instantaneous chip-thickness, non-linear function. The cuts can be predicted within the time domain, based on the existing structure, by taking the cutting force coefficients and different cutting conditions into account. For the programming of the simulation procedure, the MATLAB software presents the results, as indicated in the Fig.7-10. And full immersion slot grinding, which is equal to the diameter of the cutter by radial cutting depth, is considered.

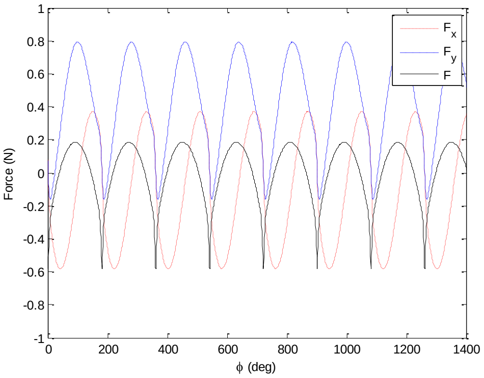

Fig. 7: Simulated Cutting forces at Ω=30,000rpm, f_t=1μm/tooth, a=50μm

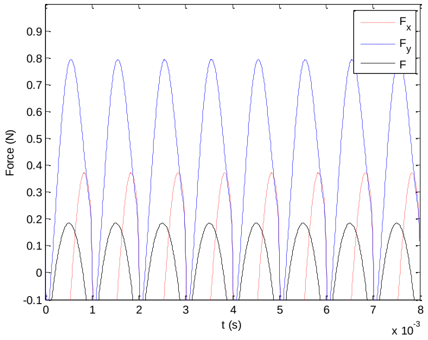

Fig. 8: Simulated Cutting forces at Ω=30,000rpm, f_t=1μm/tooth, a=50μm

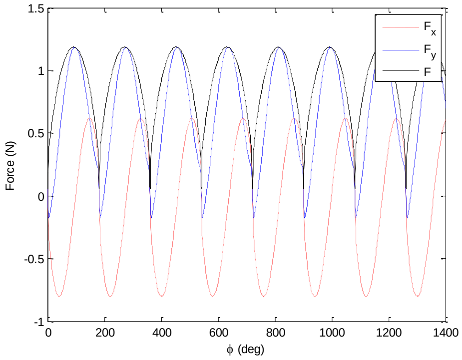

Fig. 9: Simulated Cutting forces at Ω=30,000rpm, f_t=2μm/tooth, a=50μm

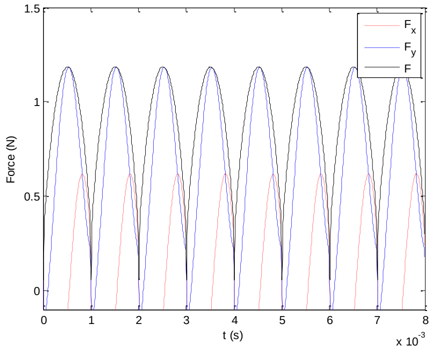

Fig. 10: Simulated Cutting forces at Ω=30,000rpm, f_t=2μm/tooth, a=50μm

5. CONCLUSIONS

The spindle unit is evaluated in this work using the Timoshenko finite element beam model by considering gyro and centrifugal terms. From the model of the dynamic spindle, frequency response functions are obtained. The resulting FRF from the micro-end mill model is used for the precise stability lobe diagrams of high-speed machining of existing analytical and numerical models. The second step consists of a sound system model, which is derived from the 3D analysis of the finite element. A analysis of cutting actions and strength findings regarding the main parameters of the process has shown that the propriety and depth of the cutting tool have a major impact on device dynamics. The feedrate and the instrument edge radius have a significant impact on the cutting powers. A growth pattern of cutting force is caused by the increase of feed.

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