Comparative analysis of chatter in micro end milling operations

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Abstract

The advancement in microfabrication in pursuit of miniaturization is cutting a dynamic role for micro-milling. Micro-milling is a fast and cost-efficient three-dimensional fabrication method with the ability to achieve good accuracy, low surface roughness and extraordinary material removal rate (MRR) compared to some other micro manufacturing processes. Given the need for components with high dimensional integrity, identification of appropriate machining conditions is very vital to getting good surface finish. It is also required to couple different complex dynamics which are associated with this machining technique. Chatter during milling and micro-milling process bring adverse effects in surface quality, dimensional accuracy and in tool life. There is need for versatile modelling of micro end-milling dynamics in order to understand how chatter affects the micro end milling operation and to advance the synthetic application of several chatter stability parameters to overcome the limitation imposed by the single chatter stability criterion. This study performs a linear and non-linear analysis of chatter in micro end milling based on the major influential parameters. In addition, a detailed time domain simulation for micro end milling was performed to predict the force a displacement resulting from variable cutter geometries. This dynamic simulation results have significant impact on the actual micro milling process towards the manufacturing of miniaturized parts.

Keywords: Dynamic simulation, Micro end milling, dynamic simulation, Chatter, Linear and non-linear analysis.

Nomenclatures

F_n = Normal cutting force
F_t = Tangential cutting force
F_a = Axial cutting force
K_n = Cutting coefficient in the normal direction
K_t = Cutting coefficient in the tangential direction
K_a = Cutting coefficient in the axial direction
b = Chip width
h = chip thickness
\( \phi \) = Instantaneous angle of cutter
F_x = Directional cutting force of X-axis
F_y = Directional cutting force of Y-axis
F_z = Directional cutting force of Z-axis
1. Introduction

The main objective of miniaturization is to manufacture components in the range of hundred microns which are application in various fields of human endeavours. The popularity which have been associated with miniaturized technology is related to making a part which is environmentally friendly [1] and can be easily maintained [2]. Given the global attention which has been given to the increased integration of miniaturized technologies into our product stocks, the issues around the design, operation, and analysis of equipment and processes need to be given detailed attention. In specific, miniaturized products have been applied in chemotherapy, fuel cells, pumps, fuel cells, fibre optics, micromold, nozzles, high temperature jet, and so on. This development in manufacturing of micro-scale products require a tailor-made fabrication technique which may not be accurately achieved based on traditional machining operations. Even though, non-traditional methods such as laser beam machining, electro discharge machining and so on are capable of producing high precision micro-component, their mass production is limited by high initial cost, limited materials selection and poor productivity. Moreover, micro manufacturing technique such as X-ray lithography, electro deposit moulding, deep reactive ion etching, computer numerical control (CNC) micromachining is expensive [1, 2]. This has engendered the ongoing research into the efficient and high dimensional technologies for the manufacturing of the components on the micro scale. Therefore, miniaturized milling, drilling, and turning tools are preferred to produce micro scale products. Generally, micro milling operation include the production of various kinds of configurations [3, 4] such as threads, grooves, slots, recesses, contoured surface and so on. Micro-milling is a fast and cost-efficient three-dimensional fabrication method with the ability to achieve good accuracy, low surface roughness and extraordinary material removal rate (MRR) compared to some other micro manufacturing processes. It is established that micro end milling is more acceptable in industrial practices when compared to conventional milling [5]. Micro end milling is scaled down to as low as 1micron/tooth feed rates and depth of cut of around 100micron. This differentiates, micro end milling from the convectional milling operation. It has been widely used in the production of 3D free form features in the aerospace, medical, electronics and energy industries.

Micro end milling is attributed with mechanical interaction between the tool and work piece leading to vibration along a definite path and eventual removal of chips. This vibration may eventually lead to a phenomenon called Chatter. Chatter is the most unwanted property in any machining operations given its impact on the product quality such as the inaccuracy in dimension and production rate due to excessive tool wear. The main cause of chatter is associated with the regenerative effects in micro machining process [3, 6]. The hard spot in the workpiece material leads to the initial variation in cutting force which result into the vibration. The contour on the surface of the workpiece may subsequently affect the chip removal load. Also, under some situations, the amplitude of vibration may increase leading to a phenomenon called regenerative chatter [3]. Useful information regarding the tool and workpiece behavior can be harvested through dynamic tool prediction. The success of micro milling is closely related to the development of models which can be used to account for the operational characteristics of tool and machining parameters. Several studies have been carried out on the micro end milling operation [3, 4, 6-8]. Specifically, Song et al. [5] proposed a mechanistic model to predict the forces in flat end mill for micro milling operation based on different cutting regimes. The model assumed that a critical chip thickness determines the possibility of chip formation. Also, Singh et al. [4] developed a mechanistic force model based on the velocity and chip load depending on the cutting coefficient. The model was in better agreement with the experimental result obtained. In an attempt to reduce...
the energy consumption in micro milling operation, Zhang et al. [1, 2] developed a novel analytical energy consumption model. The optimum cutting parameters which minimise the total energy consumption was assessed. It was suggested that the optimisation model which was developed could reduce energy consumption by 7.89% compared to the empirical selection. Also, based on systematic assessment of micro milling process, a more accurate surface generation model which considered tool run out and stochastic tool wear was presented by Zhang et al. [1]. Chen et al. [3] developed a micro milling force model which considered non-linear change in cutting coefficients caused by feed rate and process damping in shearing dominated regimes. The dynamic parameters of tool-machine relationship were simulated, while the progressive change in feed rate was considered in 3D micro milling stability. Kumar et al. [9] investigated damper which was inserted in end mill cutters to study the influence of cutting speed and type of damping insert on the surface integrity. It was noted that the design modification of end mill cutter could reduce the chatter vibrations.

It is important to carry out a non-linear static and dynamic analysis of micro end milling with an emphasis on the cutter in order to further the discuss on optimum design of mechanical damper for micro machining operations. Therefore, the major aim of this study is to perform the linear and nonlinear analysis of chatter in micro end milling operation. This study was validated based on the modal testing results obtained by Cao et al [10]. This will assist in understanding chatter phenomenon in micro end milling operation.

2. Experimental Methods

The governing equation of machine chatter is derived from general equation of vibration and regenerative chatter equation. As shown in Figure 1, micro end milling is a system with two degree of freedom [10].

$$M_x \ddot{X} + C_x \dot{X} + K_x X = F_x$$  \hspace{1cm} 1

$$M_y \ddot{Y} + C_y \dot{Y} + K_y Y = F_y$$  \hspace{1cm} 2

Figure 1: The two-degree of freedom system of micro-end milling is given by Cao et al [10]
In describing the forces which is acting along different directions, the formula is expressed in equation 3.

\[
\begin{pmatrix}
F_x \\
F_y \\
F_z
\end{pmatrix} = 
\begin{bmatrix}
\cos \phi & \sin \phi & 0 \\
\sin \phi & -\cos \phi & 0 \\
0 & 0 & -1
\end{bmatrix}
\begin{pmatrix}
F_x \\
F_y \\
F_z
\end{pmatrix}
\]

The resultant force can then be obtained as:

\[
F = \sqrt{F_x^2 + F_y^2 + F_z^2}
\]

The normal, tangential, and axial cutting force components are given as a function of the chip area and specific cutting force as equation 4, 5, and 6;

\[
F_n = K_n b h
\]

\[
F_t = K_t b h
\]

\[
F_a = K_a b h
\]

Based on Newby (2005) evaluation h is given as;

\[
h \approx h_s \sin \phi
\]

since \( h_s \ll D \) instantaneous chip thickness

Based on equation (3), equation (8);

\[
F_x = F_t \cos \phi + F_n \sin \phi = K_t b h \cos \phi + K_n b h \sin \phi
\]

By substituting equation (7) into equation (8), equation 6 is obtained;

\[
F_x = K_t b h_s \sin \phi \cos \phi + K_n b h_s \sin \phi \cos \phi
\]

Further simplification of equation (9) lead to equation (10)

\[
F_x = \frac{h_s}{2} \left[ K_t \sin^2 \left( \alpha t - \frac{2\pi m}{N} + \alpha \right) - K_n \cos^2 \left( \alpha t - \frac{2\pi m}{N} + \alpha \right) + K_n \right]
\]

In the same manner, equation (11) and (12) are formulated

\[
F_y = F_t \sin \phi + F_n \cos \phi = K_t b h s \sin \phi - K_n b h \cos \phi
\]

\[
F_x = \frac{h_s}{2} \left[ K_t \left( \alpha t - \frac{2\pi m}{N} + \alpha \right) + K_n \sin^2 \left( \alpha t - \frac{2\pi m}{N} + \alpha \right) \right]
\]

Where \( \alpha = \frac{\tan \beta}{M \rho} \) \( \beta \) = helix angle, \( R \) = The radius of cutter. If we substitute equation 11 and 12 into equation 1 and 2 then equation 13 and 14 is obtained.

\[
M_x X + C_x Y + K_x X = \frac{h_s}{2} \left[ K_t \sin^2 \left( \alpha t - \frac{2\pi m}{N} + \alpha \right) - K_n \cos^2 \left( \alpha t - \frac{2\pi m}{N} + \alpha \right) \right]
\]

Hence equation 13 and 14 could be written as;

\[
M_x X + C_x Y + K_x X = h_s \left[ K_t \left( \sin^2 \omega t \cos^2 \left( \frac{2\pi m}{N} - \alpha \right) - \sin^2 \left( \frac{2\pi m}{N} - \alpha \right) \right) + K_n \left( \cos^2 \omega t \cos^2 \left( \frac{2\pi m}{N} - \alpha \right) + \sin^2 \omega t \sin^2 \left( \frac{2\pi m}{N} - \alpha \right) \right) + K_n \right]
\]
\[ M_y Y + C_y Y + K_y Y = \frac{b h_y}{2} \left[ K_t \cos 2 \omega t \cos 2 \left( \frac{2 \pi m}{N} - \alpha \right) + K_n \sin 2 \omega t \sin 2 \left( \frac{2 \pi m}{N} - \alpha \right) \right] \]

Equation 15 and 16 can be transformed using Laplace transformation technique; these will lead to 17 and 18. Equation (17) is given below;

\[
\bar{X} = \frac{1}{M_y} \left[ \frac{A_1 - A_4}{(s^2 + \frac{C_y}{2 m^2}) (s^2 + 4 \omega^2)} - \frac{(A_2 + A_3)}{(s^2 + \frac{C_y}{2 m^2}) (s^2 + 4 \omega^2)} \right] + \frac{A_5 K_n}{s (s^2 + \frac{C_y}{2 m^2}) (s^2 + 4 \omega^2)}
\]

Where

\[ A_1 = \frac{b h_y}{2} K_t \cos 2 \left( \frac{2 \pi m}{N} - \alpha \right) \]

\[ A_2 = \frac{b h_y}{2} K_n \sin 2 \left( \frac{2 \pi m}{N} - \alpha \right) \]

\[ A_3 = \frac{b h_y}{2} K_n \cos 2 \left( \frac{2 \pi m}{N} - \alpha \right) \]

\[ A_4 = \frac{b h_y}{2} K_n \sin 2 \left( \frac{2 \pi m}{N} - \alpha \right) \]

\[ A_5 = b h_y K_n \]

Also, by applying inverse Laplace transform to equation 16, equation 18 is obtained;

\[
y = \frac{1}{m_y} \left[ \frac{B_5}{s (s^2 + \frac{C_y}{2 m^2}) (s^2 + 4 \omega^2)} - \frac{(B_1 - B_4) s}{s^2 + 4 \omega^2} \left( s^2 + \frac{C_y}{2 m^2} \right) + \frac{(B_2 + B_3) s}{s^2 + 4 \omega^2} \left( s^2 + \frac{C_y}{2 m^2} \right) \right] \frac{1}{s (s^2 + \frac{C_y}{2 m^2}) (s^2 + 4 \omega^2)} \]

Further factorization of equation (18), lead to equation (19)

\[
y (s) = \frac{1}{m_y} \left[ \frac{B_5}{s} - \frac{(B_1 - B_4) s}{s^2 + 4 \omega^2} \right] \frac{1}{s^2 + \frac{C_y}{2 m^2}} \frac{1}{s^2 + 4 \omega^2} \]

where

\[ B_1 = \frac{b h_y k_t}{2} \cos 2 \left( \frac{m n}{N} - \alpha \right) \]

\[ B_2 = b h_x \omega k_t \sin 2 \left( \frac{m n}{N} - \alpha \right) \]

\[ B_3 = b h_x \omega k_n \cos 2 \left( \frac{m n}{N} - \alpha \right) \]

\[ B_4 = \frac{b h_y k_n}{2} \sin 2 \left( \frac{m n}{N} - \alpha \right) \]

\[ B_5 = \frac{b h_x k_t}{2} \]
Multiple degrees of freedom in each axis can then be accommodated by addition of individual contribution of the modal point.

3. Results and discussions

To evaluate the dynamic model which has been developed, the simulation parameters obtained by Cao et al. [10] based on their experiment was used. They machined aluminum alloy with two and four tooth end mills at a feed of 0.5micron per tooth. The specific values of the modal coordinates are given below.

\[ f_n1 = 1000\text{Hz}, \]
\[ k_1 = 2.6 \times 10^6 \text{N/m}, \]
\[ \zeta_1 = 0.03; \]
\[ f_n2 = 1200\text{Hz}, \]
\[ k_2 = 1.8 \times 10^6 \text{N/m}, \]
\[ \zeta_2 = 0.02. \]

Given that a particular force value \( k_s \) is 950N\text{mm}^{-1} and the force angle is given as 60\(^{o}\), the corresponding cutting force coefficients are \( k_{t_1} = 1510\text{N mm}^{-1} \) and \( k_{n_1} = 1264\text{Nmm}^{-2} \) respectively [10]. The axial coefficient, \( k_a \), is taken to be equal to \( k_n \). \( f_n \) is natural frequency, \( k \) is stiffness, and \( \zeta \) is damping ratio.

3.1 Comparative analysis of two and four flutes end mill cutters and spindle speeds with chip thickness

The simulation of the chip thickness and instantaneous cutter angle were reported to show the effect of the spindle speed on the chip thickness. This is shown in Figure 1 and Figure 2. The chip thickness shows greater increase with a decreasing spindle speed. Also, as the instantaneous cutter angle is increasing, the chip thickness also increases, though with further increase in the instantaneous cutter angle, the chip thickness continues until it reaches zero value. Figure 1 shows the simulation for 2flutes end mill cutter while Figure 2 is for 4 flutes end mill cutter. It is obvious that the spindle speed is inversely proportional to the chip thickness and also the more flutes the cutter has, the thinner the chip thickness as can be seen that the greatest chip thickness for the 4flutes cutter is slightly above 2x10^{-4}mm, while for the 2flutes cutter the maximum chip thickness is closer to 5x10^{-4}mm.

![Figure 2: Effect of spindle speed on chip thickness](image2.png)

![Figure 3: Effect of spindle speed on chip thickness](image3.png)
3.2 Effect of feed on cutting forces versus instantaneous cutter angle

Two different cases are considered for each of the three cutting forces (Normal, Tangential, Specific cutting forces) using 2 and 4 tooth cutter, at feeds of 0.01m, 0.0075m and 0.005m. From figures 4, 5, 6, 7, 8 and 9. It can be seen from the six simulations that they all behave in a sinusoidal way with the cutting forces increasing with increase in the feed, it can be deduced that the cutting forces are all proportional to the feed. The Tangential cutting force is the highest of all the cutting forces. Also, it can be observed that the cutting forces are lesser for 4-tooth cutter than in 2-tooth cutter, so the cutting forces are all inversely related to the number of tooth on the cutter.

![Figure 4: Tangential cutting force (2 tooth cutter)](image1)

![Figure 5: Tangential cutting force (4 tooth cutter)](image2)

![Figure 6: Normal cutting force (2 tooth cutter)](image3)

![Figure 7: Normal cutting force (4 tooth cutter)](image4)
The resultant cutting force is presented in the x-y plane (Figure 10) for a minute-time fraction of the simulation outcome with \( b = 0.5 \text{mm} \) and helix angles 0 rad. A side-by-side evaluation of figures 11 and 12 shows notable variations. First, the maximum cutter force is low down the x-direction. Second, the force extends to its maximum value and then reduce in a more saw tooth pattern which goes below zero value to the negative, but it moves to a negative value. Also, in x and y axis, the cutting force decreases with the increase in feed.
It can be concluded from Figures 13 and 14 that the tool end displacement rises to around 12 μm at all instances in the x-direction and about 1.2 μm in the y-direction. Therefore, chatter is observed in both directions but more pronounced in the x-direction which could lead to poor surface integrity and cut short the life of the tool in the real milling operation.
4. Conclusions
This study presents linear and non-linear analytical approach to determine the force and displacement interaction in micro end milling operation. The study took cognizance of the dynamic cutting thickness, resultant cutting force and tool end displacement. It can be seen that the numbers of tooth on the cutter has a great effect on the chip thickness, for thinner chip thickness 4 flutes end mill cutter should be recommended. Further study should analyse the Z-axis forces and likely displacement since the dynamic stiffness in this direction are often higher than x and y axis.

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