Influence of Milling Cutter Dynamics on Stability Lobe Diagrams

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Abstract

In milling, both dimensional accuracy and productivity depend on several parameters of milling. As these parameters influence the material removal rate and the stability of process in terms of vibrations and chatter, it is important to examine the role of these parameters on the level of vibration and chatter. Since 1960s, the researchers have studied chatter problems with a view to understand the mechanism, parameters responsible for this phenomena and its behaviour in milling operation. Out of several methods that can be followed for minimizing and avoiding chatter, stability lobe diagram is considered to be the most reliable way of identifying the cutting parameters for chatter free condition. Since the chatter depends on the interaction of milling cutter with work piece during milling of parts on the milling machine, it is essential to examine the influence of dynamic parameters of milling cutter on the stability of cutting process. This paper covers the generation of stability lobe diagrams experimentally for CNC milling machine, following the approach proposed by Altintas et al. (1995). These diagrams are obtained for two milling cutters, having the same geometrical parameters and holding conditions but made of different materials. Effect of different parameters that influence milling cutter dynamics on stability lobe diagrams is studied and an attempt is made to explain the related physics behind the chatter phenomenon.

Keywords: Milling, Chatter, Stability lobe diagram.

1. INTRODUCTION

Dimensional accuracy and productivity are two fundamental requirements of any machining operation. Excessive vibrations and chatter phenomena restrict the operating range of machine tools thus limiting these fundamental requirements. Figure 1 shows the several adverse effects of chatter phenomena on the tool life, machine parts and quality of work surface. As the milling operation is the most widely used for material removal across the industries, it is very important to study the mechanism involved and the effect of various parameters on chatter phenomena. Various researchers have studied chatter in orthogonal and oblique machining. Tobias [1] and Tlusty [2] explained the chatter phenomena by self-excited regenerative effect. Based on the theory proposed by Tobias [1], Altintas [3] developed an analytical approach to predict the chatter behaviour in milling by considering milling cutter vibrations in two degrees of freedom system.

To control and suppress the chatter phenomena in milling operation, several methods such as machining with variable spindle speeds, parameter selection based on the simulated results, stability lobe diagrams etc. have been developed [4, 7]. Altintas [4] explained the chatter phenomena in various metal removal operations and summarized various methods of adding active and passive damping to reduce the chatter phenomena. Out of these methods, stability lobe diagram is the most reliable way of identifying cutting parameters for chatter free condition. Since the chatter is dependent upon the interaction of milling cutter with work piece during milling of parts on the milling machine, it is essential to examine the influence of dynamic parameters of milling cutter on the stability of cutting process.

Most of the literature covers the effect of cutting parameters on the stability lobe diagrams [1, 7]. A very few attempts have been made to study the effect of material properties and cutter tool dynamics on the stability lobe diagrams. Dynamic parameters such as natural frequency and damping ratio of milling cutter depend on several factors such as geometrical parameters, material properties, holding conditions and cutting conditions. In order to improve the stability of machine tool, it is essential to study the effect of material composition, heat treatment, coating material and its composition on the dynamics of milling cutter.

This paper covers the approach used for generating stability lobe diagrams. These diagrams are created for two milling cutters, having the same geometrical parameters but made of different materials. In order to study the effect of material properties on the stability lobe diagrams, tool holding conditions were kept the same for both the cutters. Experimental study consists of force measurement with dynamometer and transfer function estimation by performing experimental modal analysis on the milling cutter.

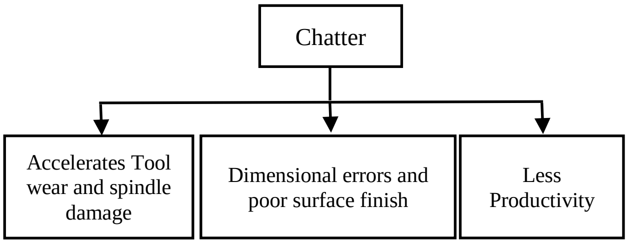

Fig.1. Detrimental effects of chatter on machine tools and workpiece

2. THEORETICAL BACKGROUND AND METHODOLOGY

A step by step methodology followed for generating stability lobe diagram is shown in figure 2. The first step is to find out the cutting force coefficients in the feed direction i.e. X-axis, and transverse direction i.e. Y-axis, figure 2 [12]. The equations (1) and (2) were used for calculating these coefficients. Here, $F_x$and $F_y$are the average forces per tooth per revolution in the feed direction and transverse direction respectively. $K_r$andK_t are the cutting force coefficients in X and Y directions respectively. Edge effect of cutting forces were not considered for these calculations i.e. $K_{re}$and K_{te}were neglected. ‘c’ is the feed rate per revolution per tooth and ‘a’ is the axial depth of cut.

$$F_x = -\frac{Na}{4}K_r c - \frac{Na}{\pi}K_{re} \quad (1)$$

$$F_y = \frac{Na}{4}K_t c + \frac{Na}{\pi}K_{te} \quad (2)$$

In the second step, the transfer functions at the milling cutter tip were estimated in X and Y directions for both cutters. Dynamic parameters i.e. natural frequencies and damping ratios, were estimated from the measured transfer functions.

Limiting depth of cut (a_{lim}) and corresponding spindle speed (n) were estimated with the equation (3) and (4) by the application of cutting force coefficients and transfer functions.

$$a_{lim} = -\frac{2\pi A_r}{NK_t}(1+\kappa^2) \quad (3)$$

$A_r$is the real part of the complex Eigen value (A) estimated by using directional dynamic milling force coefficients (α_{xx}, α_{xy}, $\alpha_{yx}$and α_{yy})and transfer functions (Φ_{xx}, Φ_{yy}) of the tool holder system by using equation (4). κ is the ratio of imaginary part and real part of the Eigen value. N is the number of flutes on the cutter and n is the spindle speed in revolutions per minute.

$$a_0A^2 + a_1A + 1 = 0 \quad (4)$$

Here, $a_0 = \Phi_{xx}\Phi_{yy}(\alpha_{xx}\alpha_{yy} - \alpha_{xy}\alpha_{yx})$ and

$$a_1 = \alpha_{xx}\Phi_{xx} + \alpha_{yy}\Phi_{yy}$$

$$n = \frac{60}{NT} \quad (5)$$

Here T is given by the equation (6).

$$T = \frac{\varepsilon + 2k\Pi}{2\Pi f_c} \quad (6)$$

Here, $\varepsilon$is the phase angle of the Eigen value and f_c is the chatter frequency in Hz. Chatter frequency is selected near to the natural frequency of the dominant mode of the tool holding system. $k$is the lobe value.

3. EXPERIMENTAL WORK

3.1 Experiments for determining cutting force coefficients

Experiments were performed on the high speed CNC vertical milling machine, using two geometrically similar end milling cutters. Technical specifications of these cutters are given in table1. Slotting operation was done on the mild steel workpiece with the following cutting parameters.

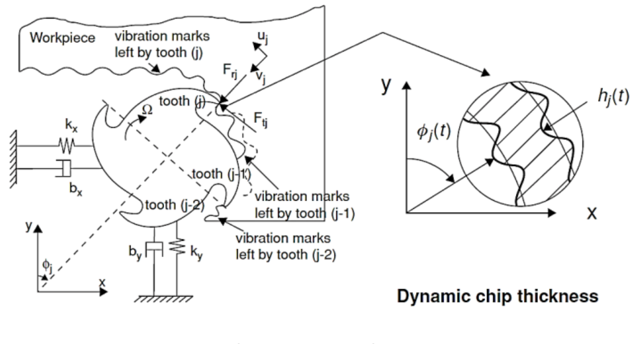

Fig. 2. Mechanism of chatter by self -excited regenerative vibrations (Altintas et al. [12])

End milling cutter of base material tungsten steel alloy with TiAlN coating:

- Spindle speed: 8000 rpm.
- Depth of cut was varied, in steps of 0.5 mm, from 0.5 to 1.5 mm.
- Ten different feed rates in steps of 25 mm/min from 50 mm/min. to 275 mm/min.

Carbide end milling cutter:

- Spindle speed: 10,000 rpm.
- Depth of cut was varied, in steps of 0.5 mm, from 0.5 to 1.5 mm.
- Ten different feed rates, in steps of 50 mm/min from 50 mm/min. to 500 mm/min.

Forces were measured in three directions by tri-axial dynamometer. Experimental arrangement is shown in figure 4.

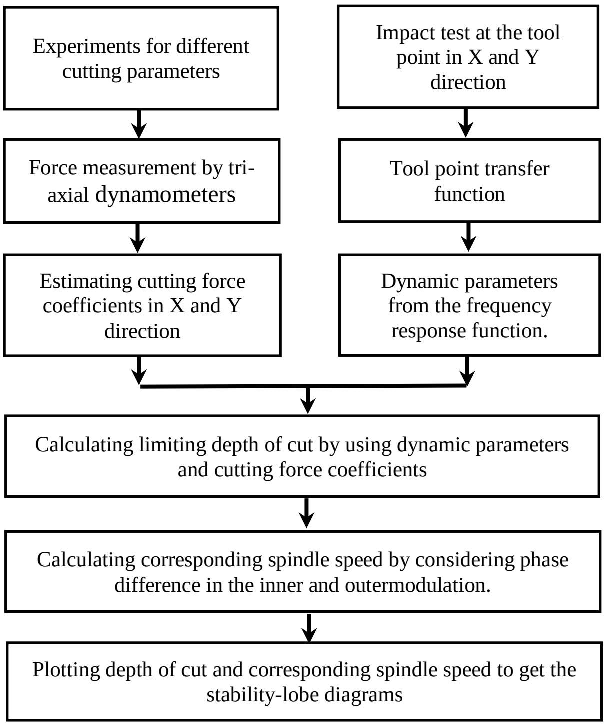

Fig.3. Flow chart for developing the stability lobe diagrams

3.2 Experiments for estimating dynamic parameters

Impact tests were performed at the milling cutter to find out tool point transfer functions and frequency response functions in X and Y directions. Equipment used and their specifications are shown below:

1. Uniaxial accelerometer (DYTRAN 3145AG, Sensitivity 100mv/g)
2. Impact hammer (DYTRAN 5800B4, 10mv/lbf sensitivity).
3. Data acquisition system (Photon + LDS Dactron).

Table 1: Technical specifications of milling cutters

Length	75 mm
Overhang	50 mm
Flutes	4
Diameter	12 mm

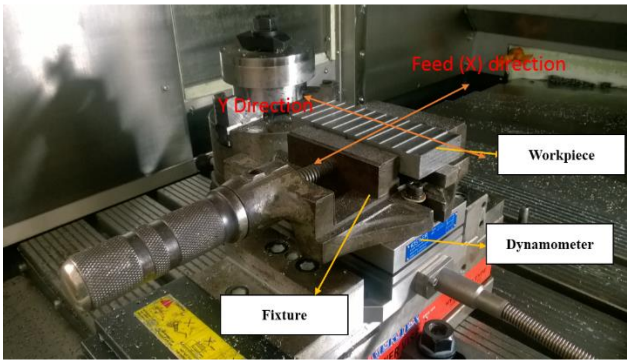

Fig.4. Experimental setup for measurement of cutting forces in X, Y and Z directions.

4. RESULTS AND DISCUSSION

4.1 Estimation of cutting force coefficients

First step required for estimating the cutting force coefficients is to estimate the cutting force per tooth per revolution from the experimentally measured cutting force data in feed and transverse directions. Cutting forces per tooth per revolution were estimated by keeping a constant axial depth of cut and varying the feed rates. Next step is to fit a linear regression model for estimated forces and corresponding feed rates.

Final step is to estimate the cutting force coefficients by the application of equation (1) and (2). One such example of linear regression is shown in figure 5, in which the dotted point represents the measured cutting force per tooth per revolution for a particular feed rate. The linear regression corresponding to the measured cutting forces gives the best fitted linear curve as shown in figure 5. Cutting parameters for this case were: spindle speed was 10,000 rpm, axial depth of cut was 1mm and feed rate was varied from 50 mm/min to 500 mm/min with a step size of 50mm/min.

By following the same methodology, the cutting force coefficients (K_t and K_r) were calculated for both milling cutters. Table 2 shows the experimentally calculated cutting force coefficients for carbide and coated milling cutters.

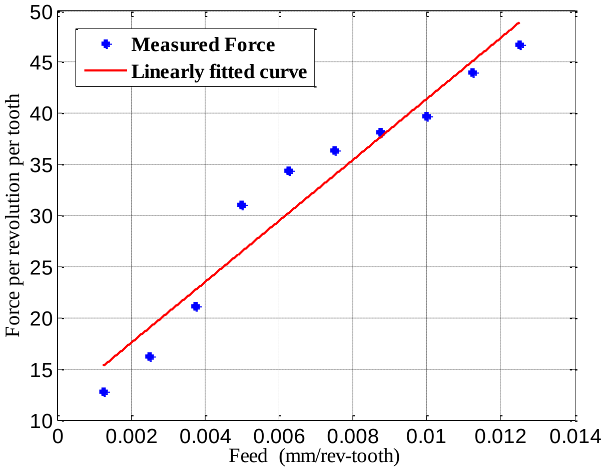

Fig. 5. Linear regression for calculating K_r (cutting force coefficient in X direction) from the measured force data. Calculated $K_r$value is 2985 N/mm^2

Table 2: Cutting force coefficients for milling cutters

	Carbide end milling cutter	Coated end milling cutter
K_r(N/mm^2)	2985	2686
K_t(N/mm^2)	4629	4362

4.2 Dynamic parameters from tool point frequency response function

Dynamic parameters were estimated from the tool point frequency response functions (FRF) for milling cutters in feed and transverse directions. Natural frequencies were estimated by plotting the imaginary part of the frequency response function with respect to frequency. Natural frequencies lie on the minima of this plot. Figure 6 shows the same plot in the feed direction for carbide milling cutter. Natural frequencies of first nine modes were estimated by the following graph. Damping ratios are estimated by applying half power method on the magnitude of FRF vs. frequency plot.

4.3 Comparison of stability lobe diagrams for carbide and coated milling cutters

Stability lobe diagrams were drawn by plotting limiting depth of cut vs. spindle speed by the application of dynamic parameters and cutting force coefficients. Figure 7 and 8 show the stability lobe diagrams for carbide end milling cutter and coated end milling cutter respectively. The maximum depth of cut that can be achieved for different spindle speeds without chatter phenomena can be obtained from these stability lobe diagrams. Lobes define the boundaries between stable and unstable cutting conditions. Area under the lobes represents the stable cutting conditions. By comparing stability lobe diagrams for both the cutters, it is clear that higher depth of cut and higher productivity can be attained by using coated end milling cutter.

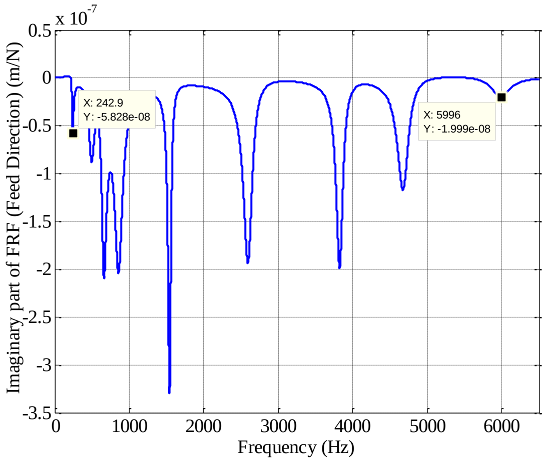

Fig. 6. Plot of imaginary part of FRF vs. frequency in the feed direction for carbide end milling cutter

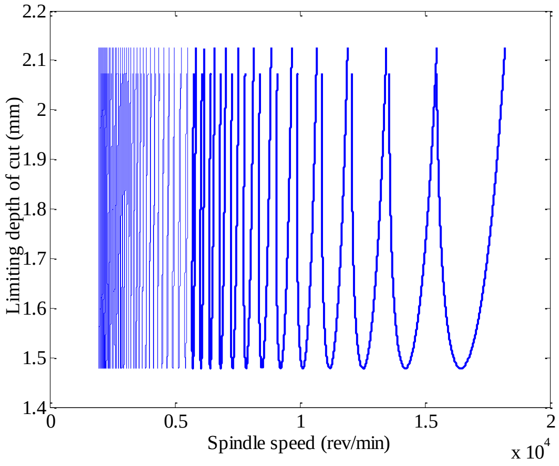

Fig. 7. Stability lobe diagrams for carbide end milling cutter

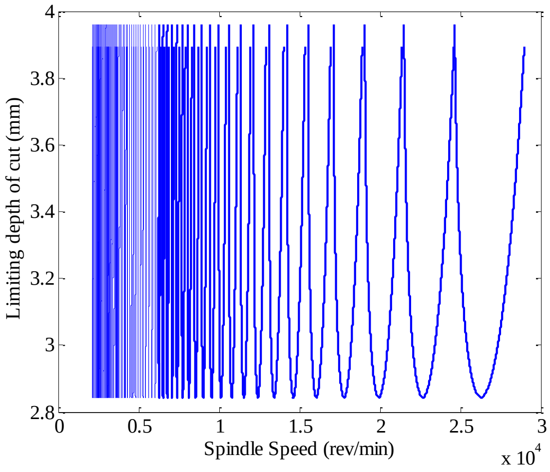

Fig. 8. Stability lobe diagrams for coated end milling cutter

5. CONCLUSION

Stability lobe diagrams were generated for two end milling cutters of different materials. As the geometrical parameters, holding conditions and cutting conditions were kept similar for both milling cutters, the effect of material properties on the dynamics of milling cutters and ultimately on the machine stability were studied. It can be concluded from figure 7 and 8, higher depth of cuts can be achieved with coated end milling cutter without chatter.

For further understanding the relation between dynamic parameters and material properties, it is required to study the effect of microstructures on dynamic parameters.

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