Investigation of chatter stability in high speed milling on thin ribs

Ilanthirayan Pachaiyappan1, Mohanraj Selvakumar2, Prasanth Kumar TS3 and Nobel Thamildorai4
1,2,3 Department of Mechanical Engineering, PSG College of Technology, Peelamedu, Coimbatore-641004, India
4 School of Mechanical Engineering, SASTRA University, Thanjavur- 613401, India

E-mail: sithirayan2196@gmail.com

Abstract. Chatter is a self-excited vibration that occurs during high speed machining of parts which is an undesirable phenomenon that affects work piece and also the tool. Chatter mainly depends upon the stiffness, the damping ratio of the material, the force applied and the clamped area. As the machined area continuously changes, the chatter stability of the work piece also changes continuously. The change in natural frequency of Aluminium 7010 T7651 thin rib during milling is calculated by using Modal analysis in ANSYS Workbench. The model is validated with published journal results and experimentally. Also, the scaled-down model of thin rib for same geometry is analysed for any change in natural frequency. The polynomial fit equation for finding instantaneous frequency of thin rib has been found which is applicable for same geometry irrespective of its scale. Using the equation, Stiffness is found and 2D Stability Lobe Diagram has been plotted and chatter free machining has been carried out experimentally in both stable and unstable regions to prove chatter zones. Also it was found that varying spindle speed is easier approach to avoid chatter during milling.

1. Introduction

High Speed Machining (HSM) has brought advancement in machining complex shapes in thin walled ribs used in the aviation sector. The problems faced during HSM is the chatter vibration which leads to dimensional inaccuracy, poor surface finish, disproportionate tool wear and machine tool damage. Numerous parameters such as axial and radial depth of cut, cutting speed, material properties, tool path, work piece set-up, the geometry of both tool and workpiece have an influence over the chatter during HSM. These parameters were controlled by trial and error method and by the experience of the worker. Hence the full capability of the machine tool is not utilized. Two-dimensional Stability Lobe Diagrams have been developed to properly select the axial depth of cut and its respective spindle speed to make the work piece free from chatter during machining.

S A Tobias et al [1] and Tlusty et al [2] done the first work on regenerative chatter in orthogonal cutting and developed the two-dimensional stability lobe theory. Y Altintas et al [3] presented an analytical form of the stability lobe theory for milling. These help operators to select the appropriate spindle speed and axial depth to avoid chatter in machining processes. W X Tang et al [4] predicted the
chatter in milling for multi-mode dynamics, higher excited frequency and also validated his prediction. Also found that tooth passing frequency is proportional to the number of tool teeth, a tool with a larger number of teeth can be selected to increase the Material Removal Rate (MRR). R P H Faassen et al [5] and E Solis et al [6] investigated the regenerative chatter for different parameters such as spindle speed, depth of cut, material and machine dynamics. Predicted results were to correlate with experimental values. Guillem Quintana et al [7] developed a new type of experimental technique for identifying SLD using a microphone which is suitable for small companies. O B Adetoro [8] developed a mathematical model for predicting chatter during milling. Antonio Scippa [9] studied the effects of fixturing, tooltip dynamics and material removal during high speed machining of monolithic components. Jens Friedrich [10] introduced a new approach to determine the stability based on the measured acceleration signals. The multidimensional stability lobe diagram (MSLD) are derived using continuously learning algorithms. This learned MSLDs are evaluated against analytically calculated MSLDs as well. Budak et al [11] developed simplified analytical equations for chatter stability in milling and results are validated numerically with their previous paper [18]. Time taken for analysis is reduced using Analytical equations derived for single degree and two degrees of freedom. Schmitz [12] incorporated receptance coupling substructure analysis to predict the tool dynamics and frequency which matched with empirical results [19]. It is found that the number of experimental measurements is reduced. Kim et al [13] developed a simple model for vertical milling center based on linear differential difference equations and predicted the chatter. Zhao and Balachandran [14] developed a unified mechanics based model to study workpiece tool dynamics. The study involves immersion effects, regenerative effects, tooth passing period, feed rate and feed direction. Tekeli et al [15] presented an analytical method in which the machining stability depends on both axial and radial depth of cut. Hence both limits have to be considered in order to maximize productivity. Also another method to determine chatter limit in terms of radial depth of cut is presented. Bravo et al [16] stated that during high material removing of monolithic components rigidity of both workpiece and machine tool are to be included. Also 3D Stability Lobe Diagram has been developed based on the relative movement and validated for series of thin walls. Lionel Arnaud et al [17] modelled the milling process using a dynamic mechanistic model with time domain simulation and the dynamic parameters of the system using step by step finite element analysis.

2. Finite Element Model and Validation

2.1. Model

Finite Element Model (FEM) of thin rib made of Aluminium Al7010 T7651 with dimensions of Length (L) 260 mm, Breadth (B) 30 mm and Thickness (T) 3 mm were used. The material properties used are Density - 2.823 x 103 Kg m$^{-3}$, Young’s Modulus - 69.809 GPa and Poisson Ratio - 0.337. For the study, two different models of same geometry were used in which one being a scaled-down model. The dimensions of the scaled-down model to the ratio of 1:2 is of Length (L) 130 mm, Breadth (B) 15 mm and Thickness (T) 1.5 mm. Hereafter, 3 mm refers to the original model and 1.5 mm refers to the scaled-down (1:2) model of the thin rib.

The milling cutter is able to move linearly in 3 axis, along lengthwise (X-axis), breadthwise (Y-axis) and thicknesswise (Z-axis) as shown in Figure 2. These linear movements by the milling cutter in X, Y and Z axis are termed as the length of cut (L$_0$), axial depth of cut (A$_0$) and radial depth of cut (R$_0$) respectively which is shown in Figure 1. These linear movements are made dimensionless by dividing the L$_0$, A$_0$, and R$_0$ by length (L), breadth (B) and thickness (T) of thin rib respectively. These ratios L$_0$/L, A$_0$/B and R$_0$/T are the parameters which are to be varied during machining. For analysis, radial depth of cut (R$_0$) and axial depth of cut (A$_0$) is fixed and length of cut (L$_0$) is varied in steps for the whole rib. Again in next step, an increase in axial depth of cut (A$_0$) is only made and the steps are repeated in same order until the whole work piece is machined. The whole process is simulated in the Modal and Harmonic analysis in ANSYS Workbench. The chatter frequency and axial depth of cut for milling have been calculated analytically.
2.2. Validation

A Finite Element Model (FEM) of thin rib made of Aluminium Al7010 T7651 with dimensions of length (L) 260 mm, breadth (B) 30 mm and thickness (T) 3 mm were used. As shown in Figure 2, the thin rib is made fully fixed at the bottom side and the natural frequency of Aluminium thin rib is obtained by Modal analysis using ANSYS Workbench. The natural frequency of the model is compared with published journal values [8]. Figure 3 shows the experimental setup to find the natural frequency of thin ribs using impact hammer and accelerometer. Variation in natural frequencies in both experimental testing and journal values are limited to a maximum difference in values of 6.11%.

Figure 1. Milling of Thin rib [20]

Figure 2. Simulated thin rib model of Al7010 T7651

Figure 3. Experimental modal testing of thin rib
Table 1. Difference in natural frequency values

| Mode Number | Natural Frequency as in [8] $f_n$ (Hz) | Simulated Natural Frequency $f_n$ (Hz) | Natural frequency from experimental testing $f_n$ (Hz) | % of variation of $f_n$ values from simulation | % of variation of $f_n$ values from experiment |
|-------------|----------------------------------------|---------------------------------------|-------------------------------------------------------|---------------------------------------------|-----------------------------------------------|
| 1           | 2830.5                                 | 2871.1                                | 2860.2                                                | 1.43                                        | 1.04                                          |
| 2           | 3204.5                                 | 3047.7                                | 3101.3                                                | 4.89                                        | 3.22                                          |
| 3           | 3406.0                                 | 3197.7                                | 3265.7                                                | 6.11                                        | 4.12                                          |
| 4           | 3798.0                                 | 3616.1                                | 3698.8                                                | 4.78                                        | 4.78                                          |
| 5           | 4372.0                                 | 4205.2                                | 4581.2                                                | 3.81                                        | 4.77                                          |

3. Results and Discussion

3.1. Change in natural frequency for two thin ribs

The natural frequency of thin rib varies continuously during machining due to change in volume of the thin rib. The change in instantaneous natural frequency to initial natural frequency ($f/f_n$) of the thin rib is analysed for different milling steps using Modal analysis in ANSYS Workbench. Another thin rib of the scaled-down ratio (1:2) is also analysed in same way. As shown in Figure 4, a surface plot of the change in frequency ($f/f_n$) for two thin ribs is plotted using cftool in MATLAB v2017a for a constant value of $R_0/T = 0.2$. The polynomial fit equation obtained from surface plots can be used to find the instantaneous natural frequency for different aspect ratios but of the same geometry.

![Figure 4. Change in natural frequency of two thin ribs](image)

Table 2. Polynomial equation of natural frequency for two thin ribs

| Thin rib equation of 3 mm thickness                                                                 | Thin rib equation of 1.5 mm thickness                                                                 |
|---------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| $f(x, y) = p_{00} + p_{10} * x + p_{01} * y + p_{20} * x^2 + p_{11} * x * y + p_{02} * y^2 + p_{30} * x^3 + p_{21} * x^2 * y + p_{12} * x * y^2 + p_{03} * y^3 + p_{40} * x^4 + p_{31} * x^3 * y + p_{22} * x^2 * y^2 + p_{13} * x * y^3 + p_{04} * y^4$ (1) | $f(x, y) = p_{00} + p_{10} * x + p_{01} * y + p_{20} * x^2 + p_{11} * x * y + p_{02} * y^2 + p_{30} * x^3 + p_{21} * x^2 * y + p_{12} * x * y^2 + p_{03} * y^3 + p_{40} * x^4 + p_{31} * x^3 * y + p_{22} * x^2 * y^2 + p_{13} * x * y^3 + p_{04} * y^4$ (2) |
| $p_{00} = 1.132$ (1.047, 1.218)                                                                    | $p_{00} = 1.135$ (1.049, 1.22)                                                                    |
\[ p_{10} = -0.01692 \ (0.3339, 0.3) \]
\[ p_{01} = -1.186 \ (-1.854, -0.517) \]
\[ p_{20} = -0.3763 \ (-1.233, 0.4799) \]
\[ p_{11} = 1.059 \ (0.3061, 1.812) \]
\[ p_{02} = 3.097 \ (1.212, 4.982) \]
\[ p_{30} = 0.1827 \ (-0.8599, 1.225) \]
\[ p_{21} = 0.9413 \ (0.1635, 1.719) \]
\[ p_{12} = -2.706 \ (-3.671, -1.741) \]
\[ p_{03} = -2.828 \ (-5.032, -0.6239) \]
\[ p_{40} = 0.1559 \ (-0.3043, 0.616) \]
\[ p_{31} = -0.9486 \ (-1.324, -0.5729) \]
\[ p_{22} = 0.6379 \ (0.2538, 1.022) \]
\[ p_{13} = 0.8668 \ (0.3878, 1.346) \]
\[ p_{04} = 0.7943 \ (-0.1156, 1.704) \]

The goodness of fit:
R-square: 0.9948
Adjusted R-square: 0.9927

The goodness of fit:
R-square: 0.9946
Adjusted R-square: 0.9924

The % of deviation in change in natural frequencies for the two ribs are

\[ \text{% of change} = \frac{1.005 - 0.996}{1.005} \times 100 \]

\[ = 0.895 \% \]

As the % of deviation is very less, it can be inferred that there is very less change in values for two different aspect ratios and any one of the equations derived can be used for different aspect ratios of ribs for same geometry. From the equations (1) and (2), it is clear that the instantaneous frequency at any axial depth of cut and length of cut can be found as long as \( R_0/T \) is kept constant as 0.2.

3.2. Stability Lobe Diagram and milling study

For this model, the stiffness depends upon Young's modulus of the material, the geometry of the thin rib and clamping conditions of the thin rib. Harmonic analysis is carried out for a different length of cuts (\( L_0 \)) on the whole thin rib with a force of 1 N being applied in Z-direction as shown in Figure 5. The maximum value of Frequency Response Function (FRF) is calculated using Harmonic analysis as shown in Figure 6. The stiffness (\( K \)) of the thin rib is calculated using the Equation (3),

\[ K = \frac{-1}{2\zeta \text{Im}(\text{FRF})} \]

where \( \zeta \) is damping ratio which is taken constant as 0.005.
Using the stiffness ($K$) and FRF from Harmonic analysis, Stability Lobe Diagram (SLD) have been plotted. As shown in Figure 7, the thin rib is clamped at the bottom surface by using a vice and machined in Vertical Milling Centre (VMC) based on the Stability Lobe Diagram found as shown in Figure 8 a) and b). Two trials are done with same axial depth of cut as 2 mm, in which one spindle speed is taken as 1200 rpm (n) which is within the stable region and another one spindle speed is taken as 1450 rpm (n) which is above stable region. As the axial depth of cut is not within stability region as shown in Figure 8 a) and b), chatter is generated during machining. Figure 8 c) shows the thin rib affected by chatter and hence having a poor surface finish. Figure 8 d) clearly indicates that the thin rib is having a superior surface finish which again proves that the chatter effect is nullified. Hence varying the spindle speed (n) is an effective and simpler approach to avoid chatter and improve surface finish.
As discussed, the equations (1) and (2) are used to find the instantaneous frequency at any step in the milling process. Also with the found natural frequency values, stiffness of thin rib during machining are calculated and SLD is plotted. Due to this, the trial and error method followed by operators will be avoided. These equations will serve as an input for the algorithms from which the SLD can be automatically plotted and depth of cuts will be selected from it. Hence it can used in CNC machines, where operation can be made directly with less manual control with increased the material removal and no chatter.

4. Conclusion

In summary, the following conclusions are drawn giving further insight on chatter prediction and avoidance in thin ribs during the high speed milling process.
The polynomial fit equation for finding the instantaneous natural frequency and the stiffness of thin ribs is derived. The equations developed in the study are used to improve the productivity of thin ribs by process planning prior to production.

2) Based on derived equations, 2D Stability Lobe Diagram has been plotted.

3) The experiment was conducted under two different conditions showing that varying the spindle speed is a much simpler approach to avoid chatter during milling.

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