A study on effect of process parameters on vibration of cutting tool in turning operation

Rupam Das and Manjuri Hazarika
Mechanical Engineering Department, Assam Engineering College, Guwahati, Assam, India
manjurih@gmail.com

Abstract. Vibration of cutting tool, machine tool and work piece is a common phenomenon in machining. Vibration causes harm to the quality of the product and the performance and life of the cutting tool and the machine tool. Cutting parameters play a major role in machining which also influence vibrations. This work makes a study on vibration of cutting tool, as affected by cutting parameters. Effect of depth of cut, feed and cutting speed on vibration (acceleration) of cutting tool in turning operation has been studied. Mathematical modeling is performed using Regression Analysis, ANOVA, Artificial Neural Network and Response Surface Methodology and a comparative analysis is performed among the predicted values of vibrations as given by the different models. It is observed that the most influencing parameter for vibration of cutting tool is depth of cut, followed by feed and cutting speed. The comparative study reveals that the percentage deviation between actual and predicted values of vibration (acceleration) is the least for Artificial Neural Network model.

Keywords: Vibration; cutting tool; turning; modeling.

1. Introduction
Vibration is one of the major problems in machining. It is mostly undesirable in machining as it increases stress, wear, fatigue and load on the machine tool, cutting tool and work piece and degrades quality of product. The main cause of vibration is the lack of dynamic stiffness of the whole machine tool system. Generally, two types of vibrations occur in machining, forced vibration due to some imbalance, misalignment etc. and self-excited vibration like chatter due to instability in cutting process.

Effect of vibration on cutting tool, machine tool, work piece and its prevention are widely investigated as found from literature. A vast number of research works are devoted to the study of causes of vibration and its minimization. Cutting parameters, such as depth of cut, feed and cutting speed play a major role in machining which also influence vibration of the different components of a machining system. Several researchers investigated the effect of cutting parameters on vibration of single point cutting tool with experimental study [1][2][3]. It was observed that depth of cut, feed and spindle speeds have significant effect on vibration of cutting tool in turning. Chattering is considered a common as well as complex problem in machining. For detection of chatter conditions, the sudden change of the vibration amplitude is to be identified. Technique like attaching an accelerometer to the cutting tool and detecting the sudden change is used by the researchers [4]. A review of chatter vibration and methods for reducing and optimizing chatter are found in literature [5][6]. Prediction as
well as control of vibration is of utmost importance in machining. Vibration of cutting tool can be controlled by passive damping [7]. Machine tool performance can be enhanced by adaptive control of machine structural vibration [8]. Real time monitoring and feed back of data is required for adaptive control methods. Fuzzy logic has been used to control the uncertainties associated with vibration [9]. It is evident that enhancement of the dynamic stiffness of the machining system and optimizing the cutting parameters is an effective way to control vibration in machining. In view of it, the present work is dedicated to the study of the effect of cutting parameters on vibration of cutting tool during turning operation.

2. Single degree of freedom model

A single degree of freedom model is chosen for modeling where the turning operation is considered to be orthogonal. Spring force, inertia force, damping force and the cutting force acting on the physical system is considered in the model. A single point cutting tool with only one cutting force in the radial direction and tool vibration in radial direction is considered. A mathematical model considering a Single Degree of Freedom (SDOF) orthogonal turning process is developed. The equation of motion of the dynamic system (with usual notations) can be represented as:

\[ m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t) \]  

(1)

Considering, \( x(t) \) as the co-ordinate of the wave generated during the current revolution and \( x(t-T) \) as the co-ordinate of the wave generated during the previous revolution of the workpiece, the cutting force can be expressed as:

\[ F(t) = K_F \times b \times [x(t-T) - x(t)] \]  

(2)

Where, \( K_F \) is cutting force co-efficient in the radial direction, \( b \) is chip width, \( T \) is time delay between current time and previous time and the term \([x(t-T) - x(t)]\) is dynamic chip thickness due to tool vibration.

3. Modeling and comparative study

In this work, effect of speed, feed and depth of cut on the vibration of cutting tool (acceleration) during turning operation is analyzed. The experimental data for modeling is taken from the reference [3]. Regression Analysis, Artificial Neural Network (ANN) and Response Surface Methodology (RSM) are used for modeling and a comparative study is performed between the predicted values of vibrations by Finite Element Analysis as in [3], Regression Analysis, and ANN. Results of ANOVA are also presented. In reference [3], SS 304 is taken as the work piece material and cutting tool used is ISO 6L 2525, which is a brazed carbide tipped tool. Table 1 to Table 3 show the detail information of the cutting tool, cutting parameter range considered and the experimental data from Reference [3]. Vibrometer is used to measure the vibration (acceleration) of cutting tool in Reference [3]. The vibrometer provides an overall vibration reading that measures vibration signals from the machine and automatically compares them to pre-programmed international organization for standardization. While performing measurement, it produces two different measurements; velocity and acceleration. The quantities to be measured are displayed on a screen in the form of electric signal which can be readily amplified and recorded. The output of the electric signal will be proportional to the quantity which is to be measured. Here, the vibrometer is made to touch the turning tool during turning operation and peak acceleration for each set of parameters is recorded from the front-panel LCD display.

| Tip | Length (mm) | Breadth (mm) | Height (mm) | Depth of Cut (mm) | Corner Radius (mm) | Rake Angle (degree) | Side Cutting Edge Angle (degree) |
|-----|-------------|--------------|-------------|-------------------|--------------------|-------------------|---------------------------------|
| C10 | 140         | 12           | 12          | 20                | 1.2                | 12°               | 0°                              |
Table 2. Cutting Parameters and Levels [3].

| Cutting parameters | Level 1 | Level 2 | Level 3 |
|--------------------|--------|--------|--------|
| Cutting speed (n) (rpm) | 140    | 220    | 360    |
| Feed (f) (mm/rev)      | 0.10   | 0.16   | 0.25   |
| Depth of cut(D) (mm)   | 0.50   | 0.60   | 0.70   |

Table 3. Experimental Data [3].

| Experiment number | Depth of cut (mm) | Feed (mm/rev) | Cutting speed (rpm) | Peak acceleration (m/s²) | Peak acceleration (m/s²) | Deviation in % |
|-------------------|------------------|---------------|--------------------|--------------------------|--------------------------|----------------|
| 1                 | 0.5              | 0.1           | 140                | 0.0500                   | 0.0480                   | 4.00           |
| 2                 | 0.5              | 0.1           | 220                | 0.0560                   | 0.0540                   | 3.57           |
| 3                 | 0.5              | 0.1           | 360                | 0.0710                   | 0.0680                   | 4.22           |
| 4                 | 0.5              | 0.16          | 140                | 0.0580                   | 0.0539                   | 7.07           |
| 5                 | 0.5              | 0.16          | 220                | 0.0620                   | 0.0595                   | 4.03           |
| 6                 | 0.5              | 0.16          | 360                | 0.0670                   | 0.0648                   | 3.28           |
| 7                 | 0.5              | 0.25          | 140                | 0.0710                   | 0.0713                   | 0.42           |
| 8                 | 0.5              | 0.25          | 220                | 0.0790                   | 0.0710                   | 10.13          |
| 9                 | 0.5              | 0.25          | 360                | 0.0800                   | 0.0820                   | 2.50           |
| 10                | 0.6              | 0.1           | 140                | 0.0860                   | 0.0845                   | 1.74           |
| 11                | 0.6              | 0.1           | 220                | 0.0920                   | 0.0877                   | 4.67           |
| 12                | 0.6              | 0.1           | 360                | 0.1140                   | 0.1102                   | 3.33           |
| 13                | 0.6              | 0.16          | 140                | 0.1070                   | 0.1079                   | 0.84           |
| 14                | 0.6              | 0.16          | 220                | 0.0830                   | 0.0807                   | 2.77           |
| 15                | 0.6              | 0.16          | 360                | 0.0980                   | 0.0990                   | 1.02           |
| 16                | 0.6              | 0.25          | 140                | 0.1170                   | 0.1138                   | 2.74           |
| 17                | 0.6              | 0.25          | 220                | 0.1080                   | 0.1040                   | 3.70           |
| 18                | 0.6              | 0.25          | 360                | 0.1150                   | 0.1090                   | 5.22           |
| 19                | 0.7              | 0.1           | 140                | 0.1020                   | 0.0990                   | 2.94           |
| 20                | 0.7              | 0.1           | 220                | 0.0690                   | 0.0678                   | 1.74           |
| 21                | 0.7              | 0.1           | 360                | 0.0760                   | 0.0736                   | 3.16           |
| 22                | 0.7              | 0.16          | 140                | 0.0830                   | 0.0820                   | 1.20           |
| 23                | 0.7              | 0.16          | 220                | 0.0960                   | 0.0930                   | 3.13           |
| 24                | 0.7              | 0.16          | 360                | 0.1100                   | 0.1050                   | 4.55           |
| 25                | 0.7              | 0.25          | 140                | 0.0940                   | 0.0910                   | 3.19           |
| 26                | 0.7              | 0.25          | 220                | 0.1120                   | 0.1145                   | 2.23           |
| 27                | 0.7              | 0.25          | 360                | 0.1060                   | 0.0977                   | 7.83           |

3.1 Multiple regression prediction model

In this work, multiple linear regression model is used for modeling vibration of cutting tool. Multiple linear regression method is one of the most popular methods for prediction of numerical values and it is widely used in prediction models. More precisely, multiple regression analysis helps to predict the values of the dependent variable Y for a given set of independent variables X<sub>1</sub>, X<sub>2</sub>, X<sub>3</sub>, ..., X<sub>k</sub>. In multiple regression analysis, modeling is done with one dependent variable and two or more independent variables. In this model, peak acceleration is the predicted or dependent variable and depth of cut, feed, and cutting speed are the predictors or independent variables. In order to judge the accuracy of the multiple regression prediction model, percentage deviation is used which is defined as:
where, $A = \text{Measured peak acceleration}$

$A_p = \text{Predicted peak acceleration generated by a multiple regression equation}$

This method is used to test the percentage deviation between actual peak acceleration and predicted peak acceleration. 70% of the experimental data from reference [3] is used for modelling and the validity of the model is tested with the remaining 30% experimental data. The assumed multiple regression model for this work is:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3$$

where, $Y = \text{Peak acceleration (m/s}^2\text{)}$

$\beta_0 = \text{Intercept}$

$\beta_1, \beta_2, \beta_3 = \text{Regression Co-efficient}$

$X_1 = \text{Depth of cut (mm)}$

$X_2 = \text{Feed (mm/rev)}$

$X_3 = \text{Cutting speed (rpm)}$

Table 4 and Table 5(a) and (b) present the results of regression model and Analysis of Variance (ANOVA).

Table 4. Regression Statistics Table.

| Regression Statistics |   |
|-----------------------|--|
| Multiple R           | 0.721909 |
| R Square              | 0.521153 |
| Adjusted R Square     | 0.458695 |
| Standard Error        | 0.014829 |
| Observations          | 27       |

Table 5(a). ANOVA Table for Peak Acceleration.

| Degrees of freedom | Sum of squares | Mean sum of squares | F-value | P-value | Percentage contribution |
|--------------------|----------------|---------------------|---------|---------|------------------------|
| Regression model    | 3              | 0.005505            | 8.34    | 0.001   | 52.12%                 |
| Depth of cut (mm)   | 1              | 0.003584            | 16.3    | 0.001   | 33.93%                 |
| Feed (mm/rev)       | 1              | 0.001597            | 7.26    | 0.013   | 15.12%                 |
| Cutting speed (rpm) | 1              | 0.000324            | 1.47    | 0.237   | 3.07%                  |
| Residual            | 23             | 0.005058            |         |         | 47.88%                 |
| Total               | 26             | 0.010563            |         |         | 100%                   |
Using the values of co-efficient from ANOVA table for peak acceleration, the required model can be expressed as:

\[ Y = -0.027534 + 0.141111X_1 + 0.124756X_2 + 0.000038X_3 \]  

(5)

where, \( Y \) is the predicted peak acceleration and \( X_1, X_2 \) and \( X_3 \) are the depth of cut, feed and cutting speed respectively. From Table 5(a), it is observed that percentage contribution of depth of cut is 33.93% which is the most significant parameter for vibration (acceleration) followed by feed at 15.12% and cutting speed at 3.07% contribution. From Table 5(b) too, it is observed that depth of cut is the most significant parameter followed by feed and cutting speed that influences peak acceleration of cutting tool. The developed regression model is used for prediction of vibration (peak acceleration) of cutting tool for the conditions given in Table 3 and percentage deviations are calculated and compared with experimental results from [3]. Comparison is presented in Table 6.

3.2 Artificial neural network model (ANN)

In this work, feed forward back propagation neural network is used as another technique for modeling vibration of cutting tool in turning. ANN consists of three distinct layers: the input layer, the hidden layer (invisible) and the output layer. The input layer is used to present data to the network, the output layer provides information to the users and the hidden layer maintains a relation between the input and output layers. Each layer consists of a number of neurons. The neurons in the input layer receive input signals from the user and provide the output through the neurons in the output layers. Only the neurons in the input and output layers interact with the user, the rest are hidden. The accuracy of the model depends upon the number of neurons in the hidden layer. The accuracy of the model increases with the number of neurons in the hidden layer.

The development and training of the neural network model is carried out using Neural Network Toolbox of MATLAB software. The ANN configuration is represented as 3:8:1, \( i.e. \) the input layer consists of three neurons, the hidden layer is of eight neurons and the output layer is of one neuron. The number of neurons in the input layer consists of cutting speed, feed and depth of cut which are used to assess the vibration of the cutting tool in turning operation. The number of output node is taken to be one which indicates the value of peak acceleration. The neural network model is trained using the data sets from experimental results from Reference [3]. They are randomly divided into three data sets of which 70% of data is used for training, 15% for validation and remaining 15% for testing. The processing function for input, output layers is mapminmax. TRAINGDX, LOGSIG and Mean Square Error (MSE) are used as training function, transfer function and performance function respectively. The accuracy of the network was evaluated by the Mean Square Error (MSE) between the measured and the predicted values for the training. Figure 1 shows the training results of the developed ANN model.
Figure 1. Neural Network training results

The comparison of predicted values of vibration by ANN with experimental results from [3] is performed. Table 6 presents a comparative study of the prediction models (FEA model as in [3] and regression and ANN models developed in the present work). It is observed from Table 6 that percentage deviation is the least for the ANN model followed by the FEA model and then regression model.

| Experiment number | Peak acceleration (m/s²) Experimental | Peak acceleration (m/s²) FEA | Deviation in % | Peak acceleration (m/s²) Regression Analysis | Deviation in % | Peak acceleration (m/s²) ANN | Deviation in % |
|-------------------|----------------------------------------|-----------------------------|----------------|---------------------------------------------|----------------|-------------------------------|----------------|
| 1                 | 0.0500                                 | 0.0480                      | 4.00           | 0.0608                                      | 21.60          | 0.0501                        | 0.20           |
| 2                 | 0.0560                                 | 0.0540                      | 3.57           | 0.0639                                      | 14.11          | 0.0501                        | 10.54          |
| 3                 | 0.0710                                 | 0.0680                      | 4.22           | 0.0692                                      | 2.54           | 0.0771                        | 8.59           |
| 4                 | 0.0580                                 | 0.0559                      | 5.07           | 0.0683                                      | 17.76          | 0.0501                        | 13.62          |
| 5                 | 0.0620                                 | 0.0595                      | 4.03           | 0.0714                                      | 15.16          | 0.0621                        | 0.16           |
| 6                 | 0.0670                                 | 0.0648                      | 3.28           | 0.0767                                      | 14.48          | 0.0676                        | 0.90           |
| 7                 | 0.0710                                 | 0.0713                      | 0.42           | 0.0795                                      | 11.97          | 0.0718                        | 1.13           |
| 8                 | 0.0790                                 | 0.0710                      | 10.13          | 0.0826                                      | 4.56           | 0.0791                        | 0.13           |
| 9                 | 0.0800                                 | 0.0820                      | 2.50           | 0.0879                                      | 9.88           | 0.0808                        | 1.00           |
| 10                | 0.0860                                 | 0.0845                      | 1.74           | 0.0749                                      | 12.91          | 0.0838                        | 2.56           |
| 11                | 0.0920                                 | 0.0877                      | 4.67           | 0.0780                                      | 15.22          | 0.0942                        | 2.39           |
| 12                | 0.1140                                 | 0.1102                      | 3.33           | 0.0833                                      | 26.93          | 0.1058                        | 7.19           |
| 13                | 0.1070                                 | 0.1079                      | 0.84           | 0.0824                                      | 22.99          | 0.1073                        | 0.28           |
| 14                | 0.0830                                 | 0.0807                      | 2.77           | 0.0855                                      | 3.01           | 0.0896                        | 7.95           |
| 15                | 0.0980                                 | 0.0990                      | 1.02           | 0.0908                                      | 7.35           | 0.1020                        | 4.08           |
| 16                | 0.1170                                 | 0.1138                      | 2.74           | 0.0937                                      | 19.91          | 0.1181                        | 0.94           |
| 17                | 0.1080                                 | 0.1040                      | 3.70           | 0.0967                                      | 10.46          | 0.1034                        | 4.26           |
| 18                | 0.1150                                 | 0.1090                      | 5.22           | 0.1020                                      | 11.30          | 0.1136                        | 1.22           |
| 19                | 0.1020                                 | 0.0990                      | 2.94           | 0.0891                                      | 12.65          | 0.0997                        | 2.26           |
| 20                | 0.0690                                 | 0.0678                      | 1.74           | 0.0921                                      | 33.48          | 0.0692                        | 0.29           |
| 21                | 0.0760                                 | 0.0736                      | 3.16           | 0.0974                                      | 28.16          | 0.0761                        | 0.13           |
| 22                | 0.0830                                 | 0.0820                      | 1.20           | 0.0965                                      | 16.27          | 0.0827                        | 0.36           |
| 23                | 0.0960                                 | 0.0930                      | 3.13           | 0.0996                                      | 3.75           | 0.0962                        | 0.21           |
| 24                | 0.1100                                 | 0.1050                      | 4.55           | 0.1049                                      | 4.63           | 0.1123                        | 2.09           |
| 25                | 0.0940                                 | 0.0910                      | 3.19           | 0.1078                                      | 14.68          | 0.0932                        | 0.85           |
| 26                | 0.1120                                 | 0.1145                      | 2.23           | 0.1108                                      | 1.07           | 0.1136                        | 1.43           |
| 27                | 0.1060                                 | 0.0977                      | 7.83           | 0.1161                                      | 9.53           | 0.1063                        | 0.28           |

Average percentage deviation 3.53 13.57 2.78
3.3 Response surface methodology (RSM)

Response Surface Methodology (RSM) is a statistical technique which is useful for the modeling of problems in which output is influenced by several input variables. Objective is to optimize the response i.e. vibration (peak acceleration). The response can be represented graphically as contour plots that help visualize the shape of the response surface. A contour plot is the projection of a 3D graph on a 2D plot which shows relationship between two variables plotted on x and y axes and response values represented by contours. Response surface plot is a graph showing relationship between three variables. Two variables are plotted on x and y axes and response variable is represented by a smooth surface. Since there are three input parameters in the present work, each time one parameter will be held at a constant level when plotting the other two parameters. The response surface changes when the holding levels are changed. The values of low levels have been taken as hold values for each parameter. Since, response surface is a plane, the contour plots are parallel straight lines. Figure 2 (a) and (b) show the contour plot and surface plot of peak acceleration as feed and cutting speed varies and the depth of cut is kept at hold value of 0.5 mm. From figure 2 (a), it is observed that peak acceleration is minimum in the blue region and maximum in the dark green region. From figure 2 (b), it is observed that peak acceleration reaches maximum when cutting speed is at 360 rpm and feed is at 0.25 mm/rev. It is the minimum when cutting speed is at 140 rpm and feed is at 0.1 mm/rev. Feed has more effect on peak acceleration compared to cutting speed.

![Contour Plot of Peak acceleration vs Feed (mm/rev), Cutting speed (rpm) and Surface Plot of Peak acceleration vs Feed (mm/rev), Cutting speed (rpm)](image)

(a) (b)

**Figure 2.** (a) Contour plot of peak acceleration vs feed, cutting speed (b) Surface plot of peak acceleration vs feed, cutting speed.

Figure 3 (a) and (b) show the contour plot and surface plot of peak acceleration as depth of cut and cutting speed varies and the feed is kept at hold value of 0.1 mm/rev. Peak acceleration is the maximum at 360 rpm and 0.7 mm doc and the minimum at 140 rpm and 0.5 mm doc. Effect of depth of cut on peak acceleration is more than cutting speed.

![Contour Plot of Peak acceleration vs Depth of cut (mm), Cutting speed (rpm) and Surface Plot of Peak acceleration vs Depth of cut (mm), Cutting speed (rpm)](image)

(a) (b)

**Figure 3.** (a) Contour plot of peak acceleration vs depth of cut, cutting speed (b) Surface plot of peak acceleration vs depth of cut, cutting speed.
Figure 4 (a) and (b) show the contour plot and surface plot of peak acceleration as depth of cut and feed varies and cutting speed is at hold value of 140 rpm. Peak acceleration is the maximum at 0.7 mm doc and 0.25 mm/rev feed and the minimum at 0.5 mm doc and 0.1 mm/rev feed. Effect of depth of cut on peak acceleration is more than cutting speed. It is observed from these plots that depth of cut has more influence on peak acceleration followed by feed and then cutting speed.

Figure 5 represents the main effects plot of machining parameters on peak acceleration. The main effects plot is helpful in visualizing which factors affect the response the most. From figure 5, it can be observed that as each parameter increases, peak acceleration increases from low level to high level. The parameters depth of cut and feed have greater effect on peak acceleration with a steep slope and effect of cutting speed is negligible as compared to depth of cut and feed.

4. Conclusion
Vibration in machining is an important issue that should be dealt with utmost care. Judicious selection of cutting parameters can reduce vibration. Present study reveals that both depth of cut and feed have more influence on peak acceleration of the cutting tool compared to cutting speed. The comparative study shows that the percentage deviation between actual and predicted value of peak acceleration is the least for ANN model followed by FEA model and then Regression Analysis. More research works
are to be devoted towards reducing vibration in machining for enhancing product quality, performance and productivity.

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