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An Analytical Method of Prediction of Stability and Experimental Validation using FFT Analyzer in End Milling process

P. Palanisamy[1,*], M. Subramanian[2] and N.P. Manojkumar [3]

[1]*Department of Mechanical Engineering, Kuppam Engineering College, Kuppam–641006, Andhra Pradesh, India.*
**Corresponding author*

[2]*Department of Mechanical Engineering, SNS College of Technology, Coimbatore-641035, Tamil Nadu, India.*

[3]*Department of Mechanical Engineering, Dr.Mahaligam College of Engineering and Technology, Pollachi, Tamil Nadu, India*

Abstract

End milling is one of the mostly used cutting processes for machining surfaces. Machine tool performance can be strongly limited by the dynamic properties of a machine structure. There is a well-known problem of chatter occurrence. Chatter is the fundamental reason which limits the efficiency of the machining process. It will result in undesirable finishing surface, decrease tool's life and produce excessive loads on the structure of the machine. The prediction of chatter vibrations between the cutter and work piece is important as a guidance to the machine tool user for an optimal selection of depth of cut and spindle rotation, resulting in maximum chip removal rate without this undesirable vibration. At this point, it is possible to plot the Stability Lobe Diagram (SLD) to this dynamic system. This curve relates the spindle speed with axial depth of cut, separating stable and unstable areas, allowing the selection of cutting parameters resulting maximum productivity, with acceptable surface roughness and absence of chatter vibrations. Stability Lobe Ddiagram (SLD) has been developed for chatter-free vibrations for machining of AISI 1020 steel. Experimental end milling tests have been performed on AISI 1020 steel work piece using Twin channel FFT (Fast Fourier Transform) analyzer and Polymate software to validate the SLD plot in a Universal milling machine using a HSS cutter. The surface roughness measured using surface roughness tester clearly indicates the accuracy and effectiveness of the stability lobe diagram.

Keywords: Milling; Stability; Surface roughness

INTRODUCTION

The milling operation is a metal cutting process using a rotating cutter with one or more teeth. It will be the most efficient if the material removal rate is as large as possible while maintaining a high quality level. During the milling process, chatter can occur at certain combination of axial depth of cut and spindle speed. Chatter is an unwanted and sometimes undesirable phenomenon in machining. Since 1950s, chatter phenomenon in machining has been investigated by several researchers. Chatter arises from the self-excited vibrations through regeneration and/or mode coupling mechanisms, both of which depend on the interaction between the machining process and the machine-tool system structure. In regeneration, the tool encounters a wavy uncut work-surface left out from the previous cut and the interaction between the current and the previous wave patterns determines the stability. Each tooth pass leaves a modulated surface on the work piece due to the vibrations of the tool and the work piece structures, causing a variation in the expected chip thickness. The other major factors that influence chatter are hardness of work piece material, damping capacity and stiffness of the machine tool, large tool nose radius, unsupported work piece, and part geometry. The consequence of chatter includes a poor surface finish due to chatter marks; excessive tool wear reduced dimensional accuracy and tool damage. Chatter may also be accompanied by a disturbing noise. Using SLD plot, it is possible to find the specific combination of machining parameters, which results in maximum chatter-free material removal rate. In this paper, Stability Lobe Diagrams have been developed for machining of AISI 1020 steel. Experiments are conducted to measure amplitude of vibration to validate SLD plot. The machining tests showed perfect agreement between prediction and the actual machine behavior**.**

CHATTER PREDICTION CURVE (STABILITY LOBE DIAGRAM)

The stability Lobe Diagram (SLD) relate the spindle speed with the maximum depth of cut is commonly employed to assess the process stability and it is developed by selecting the cutting parameters, which include the process-dependent specific cutting energy coefficients, radial immersion and system dynamics. The areas below the curve represents the stability region for the system, free of chatter vibrations. The areas above the curve represent the unstable region where chatter vibrations occur. The chip removal rate can be maximised without possible damages caused by excessive vibration. Understanding the mechanism that causes chatter leads to stability lobe diagram, which identify the limit of stability. Stability curve is valid for a specific kind of milling (down), work piece material (AISI 1020 steel) and cutter material (HSS).

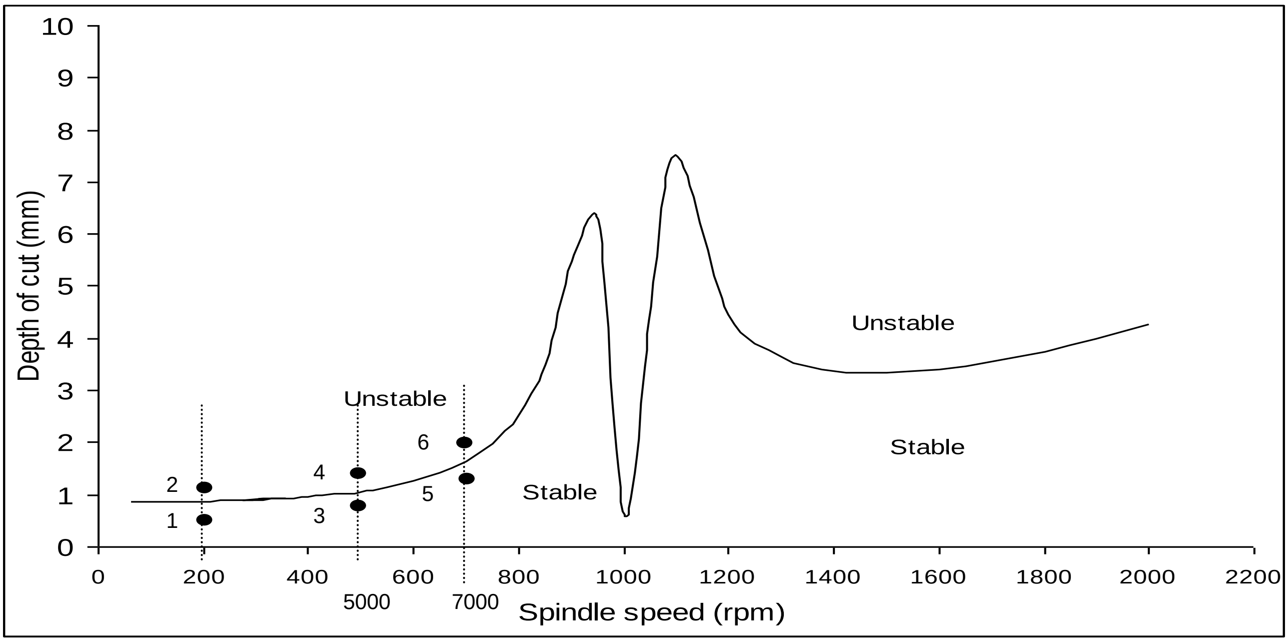

Figure 1. Stability Lobe Diagram for AISI 1020 steel material

The problem of **stability analysis** is often reduced to determining the maximum limiting depth of cut b_{min} at which **chatter** will not occur. The allowable depth of cut for milling operation is limited by process variables [cutting stiffness (k) and system dynamics (G)]

$$b_{lim} = \frac{-1}{2k\mu.m.\mathrm{Re}(G(\omega))} \quad \text{with reference to solis[5]} \qquad (1)$$

μ –Direction orientation factor

r- Damping ratio (ω/ω_n),

m- Average number of teeth in contact with work piece = $(z^*b_r)/(2^*D)$

Re[G(ω)] - Real part of system dynamics (tool's transfer function)

$$\mathrm{Re}[G(\omega)] = \frac{1}{k}\frac{1-r^2}{(1-r^2)+(2\xi r)^2} \qquad (2)$$

If machining is done in a manner that $b < b_{lim\ min}$, the system is stable or amplitude of vibration is within safe limit. Using the equation (1), the SLD is plotted for AISI 1020 steel work piece material as shown in Fig. 1 taking specific cutting energy U as 2400 N/mm^2, and stiffness of the system k as $5\mathrm{x}10^6$N/mm.

EXPERIMENTAL STUDIES

Milling operation was carried out on a STAR MILL - ATC Universal milling machine on AISI 1020 steel work piece material using HSS cutter. The cutter has been made using 6-teeth, 20 mm diameter cutter (HSS) mounted in a shrink-fit tool holder. Amplitude of vibrations has been measured and monitored by using DI-2200 Twin channel FFT (Fast Fourier Transform) analyzer with accelerometer pickup. The purpose of the experiment is to validate the SLD plot. The experimental setup is shown in Fig 2. The work piece was a block of 220x50x10. The tests were conducted along 220 mm edge. The work piece was rigidity mounted on a vice of the machine. An accelerometer with magnetic base is attached to the spindle bearing. The accelerometer signal is connected to Twin channel FFT (DI-2200) analyzer. The FFT is interfaced with computer for vibration analysis in polymate software. The spindle speed and the depth of cut have been varied from 63 to 2000 rpm and from 0.5 mm to 3 mm respectively. The cutting speed of v = 28.2 m/minute (180 rpm) and table feed rate of f = 60 mm/minute are maintained constant for all tests. The experimental tests consist of two parts, 1) Machining tests for depths of cut around the predicted limit using FFT analyzer. 2) Surface tests using surface tester for the predicted limit.

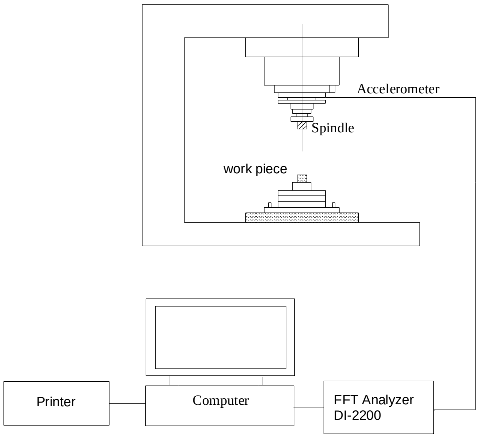

Figure 2. The experimental setup

VALIDATION OF STABILITY LOBE DIAGRAM USING FFT ANALYZER

The curves validation is done with experimental vibration tests where the depth of cut and spindle speed combinations were selected by points below and above the stability curves. The cutting parameters at six test point of Fig.1 are given in Table 1. The feed rate is the same in all tests. The vibration level has been measured by accelerometer positioned at the spindle bearing.

Table 1: Cutting parameters at test points of Fig. 1

Test points	AISI 1020 Steel	
	Speed, rpm	Depth of cut, mm
1	200	0.5
2	200	1.0
3	500	0.8
4	500	1.2
5	700	1.0
6	700	1.7

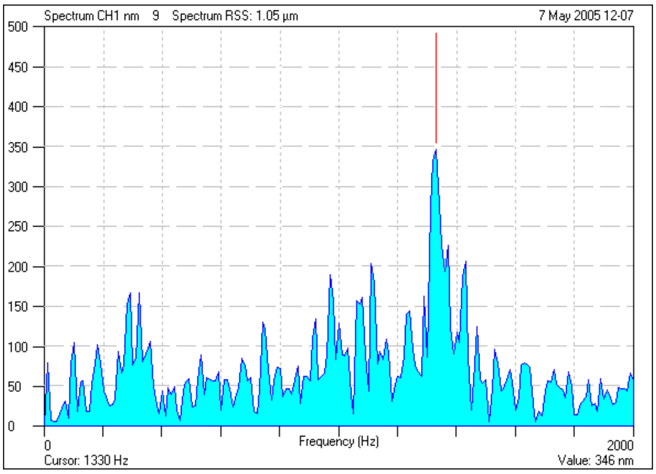

Figure 3a. At test point 1

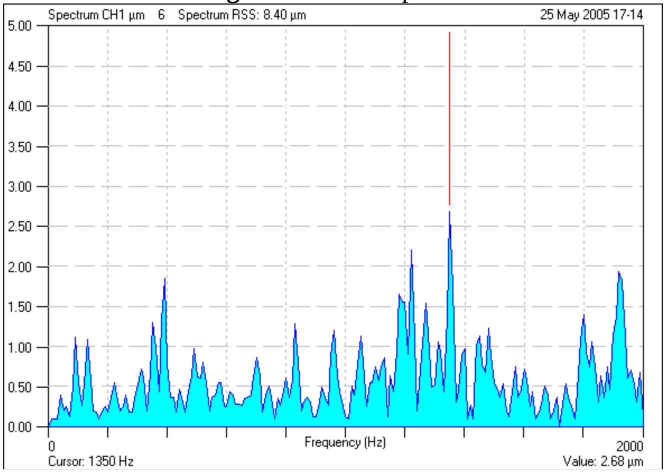

Figure 3b. At test point 2

The output of FFT analyzer for all six test points is given in term of frequency and displacement as shown in Fig. 3. The graphs in Figs 3 a and b show the displacement signal obtained for test points 1 and 2 marked in SLD Fig. 1. The speed remains same and the point 1 has vibration level of 346 nm, because it is in the stable region. The test point 2 in the graph is unstable region and the vibration level is 2.68 µm which is eight times greater than point 1, with the chatter vibration characteristic sound and superficial marks, as predicted by the stability curve.

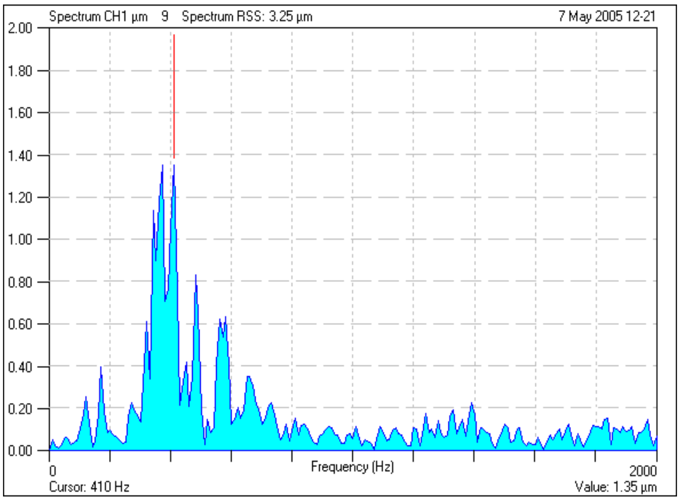

Figure 3c. At test point 3

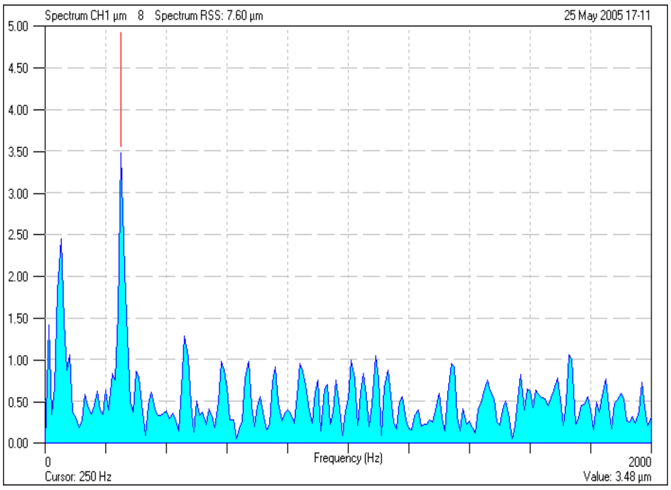

Figure 3d. At test point 4

Figs 3 c and d show the displacement signal obtained in the test points 3 and 4 of Figure.1. The spindle speed is the same in both tests. The point 3 is in stable region, presenting a vibration level of 1.35 µm, which is smaller than that of points 2 and 4, as expected. The test point 4 showed has a chatter vibration level of 3.40 µm, as predicted by the stability curve. Figs 3 e and f present the test points 5 and 6 displacement signal. The test point 5 presented a vibration level of 1.66 µm and test point 6 resulted severe chatter vibrations of 6.16 µm, as predicted by the stability curve in Fig.1. It is interesting to note that test point 5 has a reduced vibrations level when compared with test point 6.

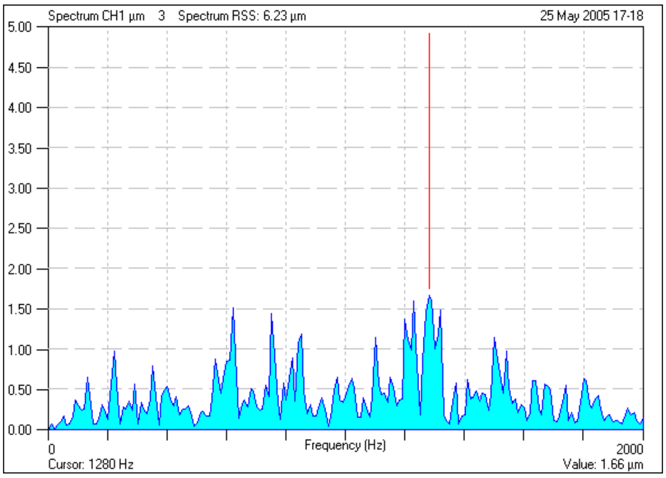

Figure 3e. At test point 5

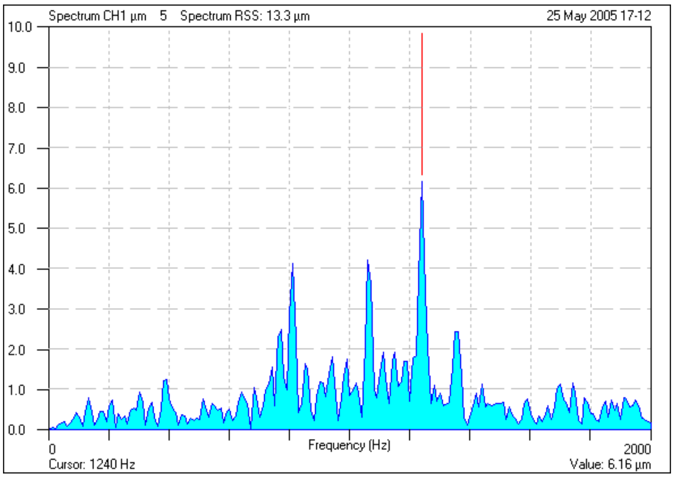

Figure f. At test point 6

Figure 3. Frequency Spectrum signal at test points using FFT Analyzer

For a better comparison, the peak value of all the six test points displacement signals is shown as bar chart in the Fig 4. It is found that the displacement at points 1, 3 & 5 is less than 2 µm within stable region with reference to Lacerda and Lima [2] whereas at points 2, 4 & 6 is found very high resulting severe vibrations

SURFACE ROUGHNESS

R_a is the most commonly used parameter to describe the average surface roughness and is defined as an integral of the absolute value of the roughness profile measured over an evaluation length:

$$R_a = (1/l)\int_0^l |z(x)|dx \tag{3}$$

The average roughness is the total area of the peaks and valleys divided by the evaluation length; it is expressed in µm (thousand of a millimeter). The surface roughness values measured with surface roughness tester (Mitutoyo make) for all test points. The surface roughness measured at different test points are shown as bar chart in Figure 4. It is found that points 1, 3 & 5 are with in the permissible limits whereas points 2, 4 & 6 are found above the permissible limits.

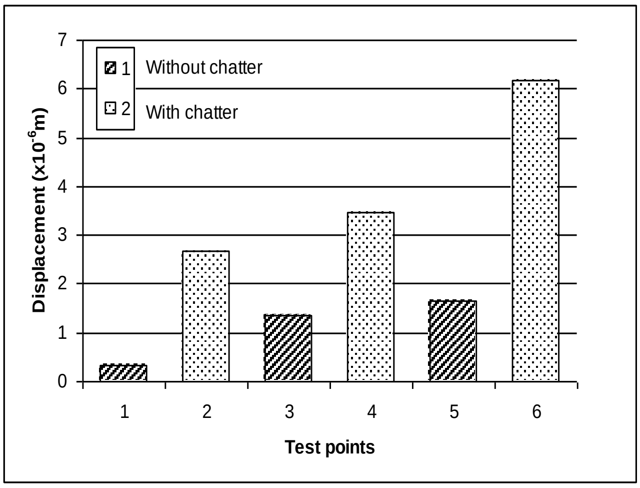

Figure 4. Peak amplitudes for AISI 1020 Steel at test points

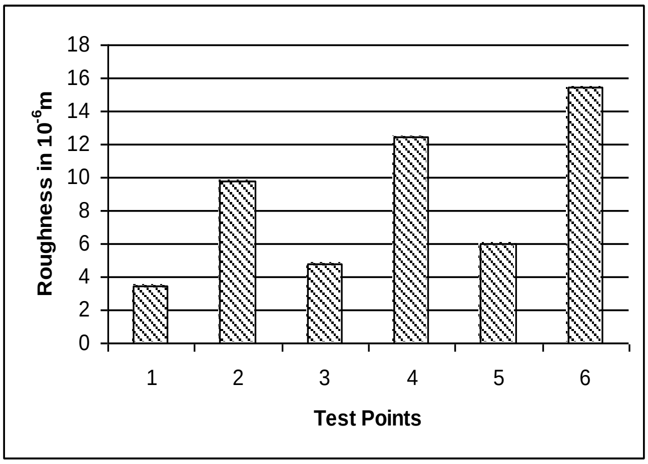

Figure 5. Surface roughness values at test points

CONCLUSIONS

In this paper, an analytical and experimental method to obtain the information related to the stability of a machine tool – work piece system for an end milling process has been proposed. We have considered vibrations of a tool-work piece system in an orthogonal cutting process. The analytical method of predicted values presented in terms of Stability Lobe diagram is applied in order to predict the occurrence of chatter vibrations using FFT analyzer for AISI 1020 steel work piece material in end milling process. The machining tests showed perfect agreement between the prediction and the actual machine tool behavior. The main advantage of the chatter prediction through the stability lobe diagram is the metal removal rate maximization, at the same time avoiding the adverse effects of chatter vibrations like the poor surface finish, the noise and the breakage of tools. The SLD plot also validated with reference to surface roughness. The surface roughness measured is within the permissible limit for test points 1, 3 and 5, i.e. if the cutting parameters lie in the stable region. It exceeds the permissible limit if the cutting parameters lie in the unstable region. The surface roughness measured using surface roughness tester clearly indicates the accuracy and effectiveness of the stability lobe diagram. The stability lobe diagram can be used to select the best combination of speed and depth of cut to maximize the material removal rate without chatter.

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