Estimation of Chatter Vibration and Quality Assessment of EN 24 Steel Turning

N K Mandal N K Singh UC Kumar

Abstract— Prediction of chatter vibration of a machining process is important as it ultimately affect the quality of the product. Proper combination of cutting parameters like spindle speed, feed, depth of cut etc. may give optimal productivity as well as optimal quality of the product. In addition, high rotational speed of spindle motor and feed motor may create undesirable chatter vibrations which ultimately damage the machineries also. Such undesirable vibrations can spoil the cutting surface with chatter marks and ultimately makes the machining system unstable. In the present study, 30 no. of experiments were conducted on a All Gear Lathe Machine with 30 no. of cylindrical shafts of EN24 which is 32 mm in diameter and 70cm long. The experiments are performed wet machining condition to find out the ranges of cutting parameters for which the machining systems are in dynamically stable condition.

Index Terms— Turning, Stability stability limit, chatter, Regenerative, Productivity Turning tool, vibration,

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1 INTRODUCTION

Metal cutting process involves continuous removal of material from the work piece in the form of chips. Cutting process with a single point cutting tool like forming on a lathe, the heterogeneity of work piece material, the run-out or misalignment of the work piece may cause occasional disturbances to the cutting process resulting vibration of the work piece with respect to the cutting tool. If the cutting process is stable, the resulting vibration dies out quickly because of damping. However, under certain conditions, the magnitude of the ensuing vibration becomes ever increasing. This phenomenon is termed as chatter.

In case of occurrence of chatter, the amplitude of the self-excited vibration increases until nonlinearity limits [1]. Results of chatter are rough surface finish, poor accuracy, shortened tool life and low metal-removal rate. Chatter becomes even more critical when machining materials that are difficult to cut. Some advanced cutting tool materials such as ceramic, silicon nitride and CBN require strict chatter control to prevent brittle breakage [2]. For high precision manufacturing, even mild vibration is undesirable. Furthermore, since modern machining systems, have become more flexible, frequently changing working conditions increase the possibility of bringing machining process into unstable operating regions [3].The productivity of expensive machining systems is often limited by chatter. Chatter is defined as self-generative vibrations that occur when the chip width is too great versus dynamic stiffness. This phenomenon leads to a bad surface aspect and high noise level. As it reduces tool life, it increases production costs. For instance, the cost due to chatter is estimated to be around 0.35 h per piece on a cylinder block.

With such a cost, prediction of chatter becomes highly necessary and a chatter criterion has to be chosen. Conditions of chatter was first stated by Taylor in 1907 and then by Schlesinger in 1936. A first comprehensive study was led by Doi in 1937 [2] and then with Kato in 1956 [3]. Tlusty and Polacek published their criterion the next year [4] and Tobias proposed his chatter maps the year after [5]. During the early 1960s, Peters and Vanherck ran some tests and developed measurement techniques in order to discuss Tlusty and Tobias criterions [6]. The 1970s have shown some work on the dynamic parameters. Hanna and Tobias worked on the non-linearity of the stiffness [7] while the Peters and Vanherck team produces highly interesting thesis on the identification of dynamic parameters during the cutting operations [8, 9]. At the end of 1970s, Tusty presented his CIRP keynote paper on the topic [10]. Up to now major developments have been designed for aeronautic industry where tools are mostly more compliant than work pieces. In this way, Altintas and Budak have proposed an analytic method for computing stability lobes corresponding to Tobias's chatter maps in 1995 [11]. This work has been extended in 1998 [12] by taking the work piece's behavior into account under the form of compliance-damping systems in two directions. A comprehensive summary of recent developments of the topic has been proposed by Altintas and Weck under the form of a CIRP keynote [13].

2.0 Definition of Regenerative Chatter

During a turning process, the heterogeneity of the work piece material causes variation of cutting forces and hence results in vibration (Lin, 1990). In most cases of practical interest, chatter observed in turning operation is due to the regenerative effect (Rao and Shin, 1998). As the single point cutting tool cuts a surface, the undulations generated in the previous revolution sustain the tool work piece vibration, which is coupled with the cutting force. Some external perturbations or a hard spot in the work piece material causes initial variation in cutting forces and results in vibration of the dynamic system. The vibration leaves a wavy tool path on the work piece surface. This wavy surface will affect subsequent chip thickness as a result variation in cutting force. Because of this uneven chip thickness, the system vibrates. If the magnitude of this vibration does not die out, the system becomes unstable. This phenomenon is known as the regenerative chatter.

N. K. Mandal : National Institute of Technical Teacher Teachers' and Research, Kolkata
N. K. Singh : Indian Institute of Technology, Dhanbad
U C Kumar: National Institute of Technical Teacher Teachers' and Research, Kolkata

3.0 Mathematical Modelling of Chatter Vibration

Assume that a flat-faced orthogonal grooving tool is fed perpendicular to the axis of a cylindrical shaft held between the chuck and the tail stock center of a lathe (Fig.1).

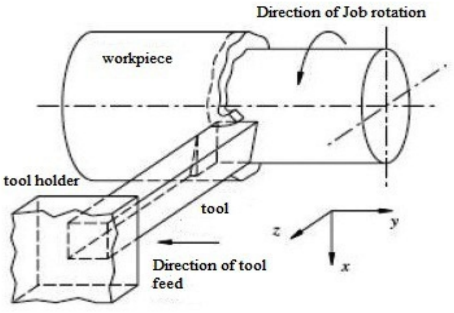

Fig.1: Turning Model

As shown in Fig. 2, the initial surface of the shaft is smooth without waves during the first revolution but the tool starts leaving a wavy surface behind because of bending vibration of the shaft in feed direction ,when the second revolution starts ,the surface have waves in both inside the cut where tool is cutting(inner modulation y(t)and also outside surface of cut owing to vibrations during the previous revolution of cut(outer modulation y(t-T)).Hence the general dynamic chip thickness can be expressed.

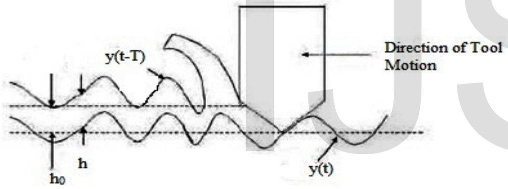

Fig.2: Regenerative Chatter Dynamics

$h(t) = h_0 - [y(t) - y(t-T)]$………(Eq.1)

Where, h_0 is intended chip thickness or feed rate, y(t) is inner modulation, y(t-T) is outer modulation. The equation of motion of the system can be expressed as [13]

$$m\ddot{y}(t) + c\dot{y}(t) + ky(t) = F_f(t) = K_f\, a h(t) = K_f\, a[h_0 + y(t-T) - y(t)]$$

………………………(Eq.2)

3 Where , F(t) is feed cutting force ,a is width of cut or depth of cut ,h(t) is dynamic chip thicknessThe fundamental equation put in laplas domain and gets a characterists equation

$$-1 + (1 - e^{-sT}) K_f\, a\Phi(s) = 0$$

The root of the characteristic equation is $s = \sigma + j\omega_c$.When the real part is zero, the system is critically stable and the work piece oscillates with constant vibration amplitude at chatter frequency. The chatter vibration frequency does not equal to natural frequency, is still close to the natural mode of the structure. For critical borderline stability analysis, the characteristic function becomes

$$\{1 + K_f\, a_{lim}[G(1 - \cos\omega_c T) - H\sin\omega_c T]\} + J\{K_f\, a_{lim}[G\sin\omega_c T + H(1 - \cos\omega_c T)]\} = 0$$

………. (Eq.3)

Where a_{lim} is the maximum axial depth of cut for chatter vibration-free machining, the critical axial depth of cut can be found by equating the real part of the characteristic equation to zero:

$$1 + K_f\, a_{lim}[G(1 - \cos\omega_c T) - H\sin\omega_c T] = 0$$

$$a_{lim} = \frac{-1}{K_f\, G\left[(1 - \cos\omega_c T) - \left(\frac{H}{G}\right)\sin\omega_c T\right]}$$

Substituting and rearranging this equation yields [14]

$$\frac{H}{G} = \frac{\sin\omega_c T}{(\cos\omega_c T - 1)} \quad \text{and} \quad a_{lim} = \frac{-1}{2K_f\, G(\omega_c)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\text{Eq. }4)$$

Where

$$G(\omega_c) = \frac{1}{k}\frac{(1 - r^2)}{[(1 - r^2) + (2\zeta r)^2]}$$

The excitation to natural frequency ratio $r = \frac{\omega}{\omega_n}$, and ζ is Damping coefficient. The spindle speed and chatter vibration frequency have a relationship that affects on dynamic chip thickness, the no. of vibration waves left on the surface of the work piece is- $2\pi f_c\, T = 2k\pi + \epsilon$

Where, K is integer no. of waves, ε-phase shift between inner and outer modulation, T- Spindle revolution period

$$T = \frac{2k\pi + \epsilon}{2\pi f_c} \quad \text{where}\ , N = \frac{60}{T} \ldots\ldots\ldots (\text{Eq. }5)$$

4.0 Experimental Investigation

Machining tests were carried out by the orthogonal wet turning. Medium carbon steel AISI1045 was cut into 70 cm long test specimens (shafts) with 32 mm outside diameter, performed on All Gear Lathe Machine. The cutting tool was taken as HSS tool. The cutting parameters that are selected for determination of the stability limits are given here. Spindle speeds [110,160,240,400,575 rev/min], the feed rate [0.625, 1.25, 2.5, 5,8mm/rev] depth of cut [0.15, 0.25, 0.35, 0.45, 0.6mm], while these are used for studying the regenerative effects.

Instruments used are- piezoelectric Accelerometer, Signal Conditioner, and Analyzer (Picoscope-2202). The intensity of vibration was picked by accelerometer with the current and voltage sensitivity (1±1%) and (1±2%) respectively for Frequency Range (x1, x10 Gain) 0.15 to 100,000 Hz, accelerometer probe is fixed at a point on the tool holder close to cutting point to picked up the vibration frequency of tool in the feed direction, The calculation of frequency was taken using a portable vibration analyzer to investigate the vibration spectrum.

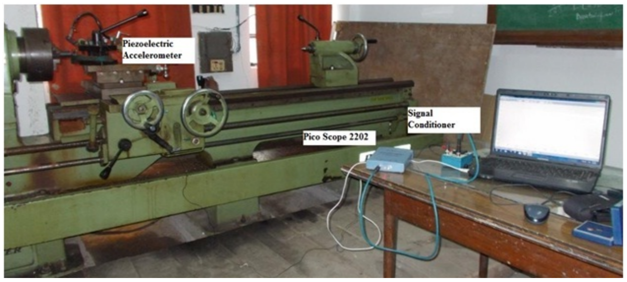

Fig. 3: Experimental Set Up

Table 1: Dynamic Cutting Coefficients, extracted from dynamic Tests

k_t cutting stiffness(MPa)	k_f cutting constant (MPa)	Damping coefficient (c)
5600	985	0.054

5.0 CATIA Model of the Beam

The cutting tool assumed as a cantilever beam configuration with a rectangular cross –section and with a point loaded at the end. Beam Specifications are: Length 12.0cm, Width 2.5cm, Height 3.0cm, Material cast iron, Density 7800kg/m^3, Young's modulus 2.1x10^{11} N/m^2 and Poisson's ratio 0.3.

6.0 FEM Modeling and Modal Analysis

After modelling, the cutting tool with CATIA model is exported to ANSYS-V13 environment. We have taken the model with 8721 elements and 1214 nodes and mechanical properties as stated above. Afterwards, boundary conditions on supporting are applied and finally modal analysis has-been done to obtain natural frequencies.

Figure 4 and Figure 5 figures show the modal frequencies of the beam

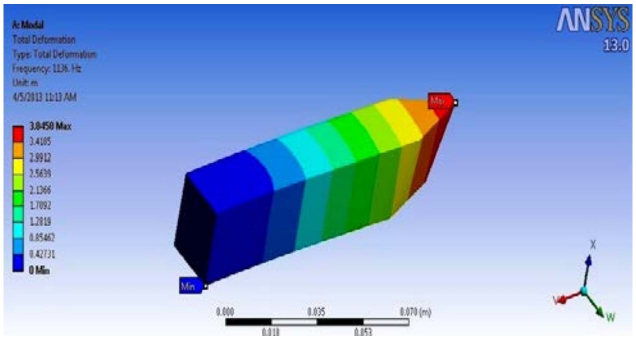

Fig. 4: 1st Modal Frequencies of the Beam

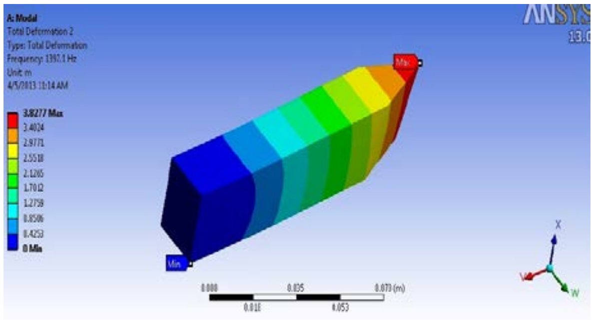

Fig. 5: 2nd Modal Frequencies of the Beam

Table 2: Modal frequencies of the beam

1st	2nd	3rd	4th
1136Hz	1397Hz	5480Hz	7025Hz

The values of the above natural frequencies are required to calculate the limit of stability (ω_c) –up to this frequency the system is dynamically stable, in different cutting conditions from equation 4&5 stated above.

Table 3 Experimented and Simulated Results

Serial no.	rpm	Feed rate (mm/rev)	Depth of cut(mm)	Chatter frequency (Hz)	Natural frequency (Hz)	Max. limit of stability (Hz)
1	110	0.625	0.25	3254	5480	5425.2
2	110	1.25	0.25	2000	1397	1365.21
3	110	2.5	0.25	1200	1136	1124.64
4	110	5	0.25	950	1136	1124.64
5	110	8	0.25	700	1136	1124.64
6	160	0.625	0.25	2978	5480	5425.2
7	160	1.25	0.25	2139	5480	5425.2
8	160	2.5	0.25	1225	1397	1365.21
9	160	5	0.25	1048	1136	1124.64
10	160	8	0.25	960	1136	1124.64
11	240	0.625	0.25	3226	5480	5425.2
12	240	1.25	0.25	2024	5480	5425.2
13	240	2.5	0.25	1436	1397	1365.21
14	240	5	0.25	1036	1136	1124.64
15	240	8	0.25	1730	1397	1365.21
16	400	0.625	0.25	4304	5480	5425.2
17	400	1.25	0.25	3813	5480	5425.2
18	400	2.5	0.25	3260	1397	1365.21
19	400	5	0.25	5439	1397	1365.21
20	400	8	0.25	1420	1397	1365.21
21	575	0.625	0.25	7002	7025	6954.75
22	575	1.25	0.25	6196	7025	6954.75
23	575	2.5	0.25	5320	5480	5425.2
24	575	5	0.25	4767	5480	5425.2
25	575	8	0.25	2698	1397	1365.21
26	110	0.625	0.15	3125	5480	5589.60
27	110	0.625	0.25	3451	5480	5370.40
28	110	0.625	0.35	3650	5480	5315.60
29	110	0.625	0.45	3778	5480	5255.32
30	110	0.625	0.55	3870	5480	5265.23

7.0 Feed Rate and Limit of Stability

From figures (6a, 6b, 6c, 6d, 6e) it can be observed that the fluctuating level of Vibration frequency for different feed rates is restricted around a closed value with limit of stability.Influence of feed rate on chatter vibration can be explained considering any of the following graphs. Experimental result (Fig. 6a) shows that if feed rate is increased then tool vibration frequency decreases. At the initial condition when feed rate is 0.625 mm/rev tool vibration frequency is highest but it decreases gradually when feed rate is increased up to 8mm/rev. This graphical pattern is followed in each case when cutting speed is gradually increased 110rpm, 160rpm, 240rpm, 400rpm, and 575rpm.

1.

2. The feed rates have an effect in increasing the vibration frequency at low speeds, as the speed increases the frequency get down which agree with the fact of BUE.It means that when cut-

ting the ductile material with low speeds the friction between the tool and chip is high, some particle of chip adhere to the tool rake face near the tool tip, this termed as BUE. By virtue of work hardening BUE is harder than the present work material. Thus increases the system instability. With considerable increase in the speed, it will disappear and the vibration frequency will get down and the current cutting processes will stabilize more than the previous ones. BUE produces discontinuous chip resulting in periodic fluctuating in the cutting forceand its frequency represents the cutting agent which may be equals to the frequency of cutting tool or its carriers. Thus causes the resonance which causes maximum instability in a machining system.

Critical cutting conditions are usually illustrated in a stability chart. Various methodologies have been used to obtain the stability chart; Lin (1990) investigated the stability of a lumped mass system using an analytical method. Lin separates the characteristic equation of this dynamic system into a real part and an imaginary in the frequency domain, the chatter frequency and critical cutting conditions may be obtained analytically or numerically. Based on the stability analysis and parameter measurements, the stability chart is obtained to predict chatter-free cutting conditions. The calculated stability limits in Figures (6a, 6b, 6c, 6d, 6e) is similar to that theoretical stability graph obtained by Liu. The stability limits clearly divided the stable and unstable zone. All graphs shows that the machining processes are in stale mode except the cutting conditions stated in the table 3,these cutting conditions are called as critical cutting conditions .These unstable conditions should be avoided to get a good quality of machining.

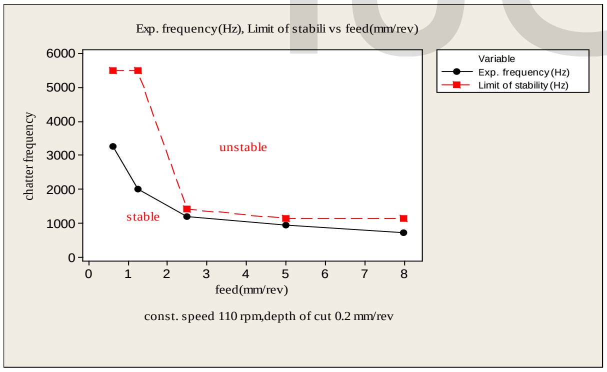

Fig.6a: The effect of feed rate on the stability limit through cutting the steel with speed (110rpm)

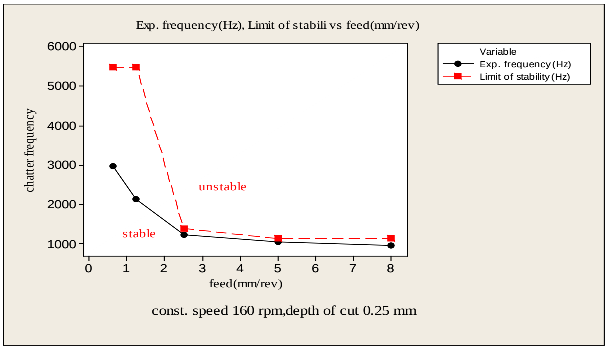

Fig. 6b: The effect of feed rate on the stability limit through cutting the steel with speed (160rpm)

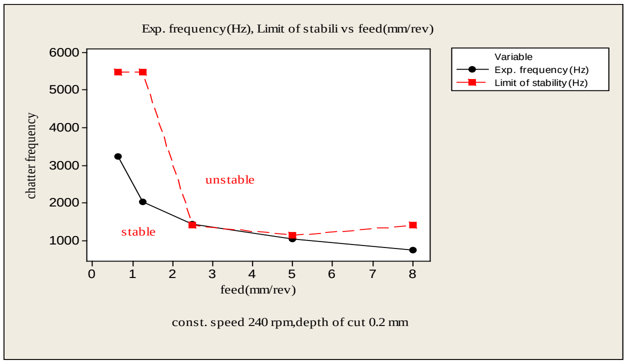

Fig .6c: The effect of feed rate on the stability limit through cutting the steel with speed (240rp.m)

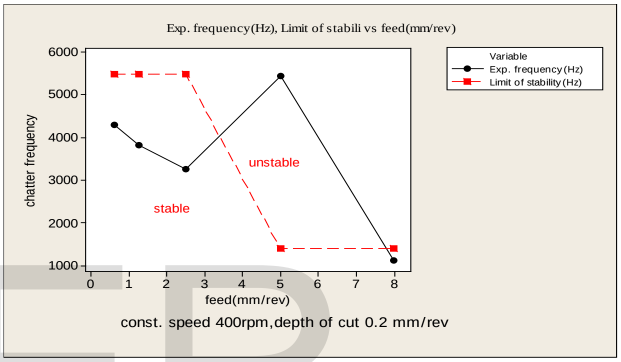

Fig .6d: The effect of feed rate on the stability limit through cutting the steel with speed (400rpm)

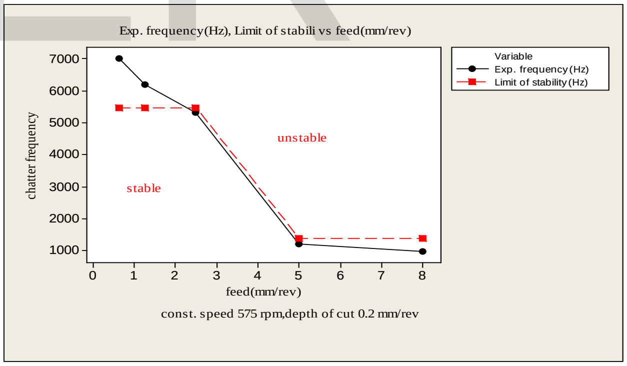

Fig .6e: The effect of feed rate on the stability limit through cutting the steel with speed (575rpm)

Table 4: Unstable conditions

Spindle speed(rpm)	Feed rate(mm/rev)	Depth of cut(mm)
400rpm	3.2- 7.8 mm/rev	0.25mm
575rpm	0.625-2.3 mm/rev	0.25mm

8.0 Cutting Speed and Limit of Stability

From figures (7a, 7b, 7c) it can be observed that the fluctuating level of Vibration frequency for different spindle speed is restricted around a closed value with limit of stability. Influence of spindle speed on chatter vibration can be explained considering any of the following graphs. Experimental result (Fig. 7a) shows that if spindle speed is increased frequency of tool vibration decreases up to certain condition and then increases further. At the initial condition when machining with 110 rpm spindle speed there is a noticeable increase of chatter frequency, but increasing speed up to 240 rpm chatter frequency continuously decreases .after that frequency increases up to spindle speed 575rpm.And that pattern of changing frequency with speed is also followed in case of changing the feed rate (1.25mm/rev &2.5mm/rev) Fig 7b, 7c, though increasing feed rate frequency of tool vibration shifted in more comfort zone.

A typical stability lobe is the function of spindle speed and machining chatter frequency .Thus, the borderline of stability that represents the back engagement (critical diagram, which predicts system depth of cut) is a function of speed for a given tool geometry, was obtained bydrawing a curves for specified feed rate to distinguish stable from unstable cutting conditions. The concurrent points of lobes confirms that obtained by Liu (1993) who studied the effect of tool geometry on stability limits of the machining system. Based on the stability analysis and parameter measurements, thestability chart is obtained to predict chatter-free cutting conditions.Thecalculated stability limits in Figures (7a, 7b, and 7c) is similar to that theoretical stability graph obtained by Liu. The stability limits clearly divided the stable and unstable zone. All the graphs shows that all the machining processes are in stale mode except the cutting conditions stated in the Table 4, these cutting conditions are called as critical cutting conditions .These unstable conditions should be avoided during machining.

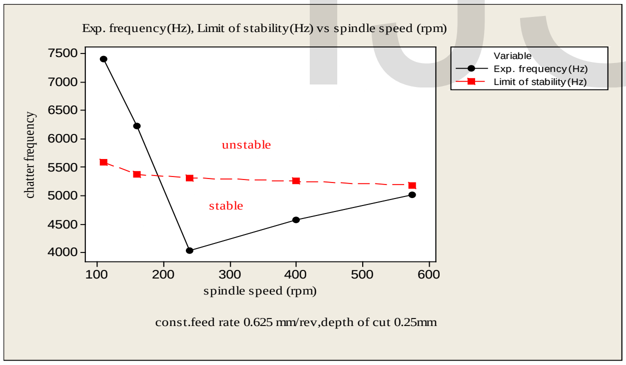

Fig.7a: The effect of speed on the limit of stability through cutting steel with feed rate (0.625mm/rev)

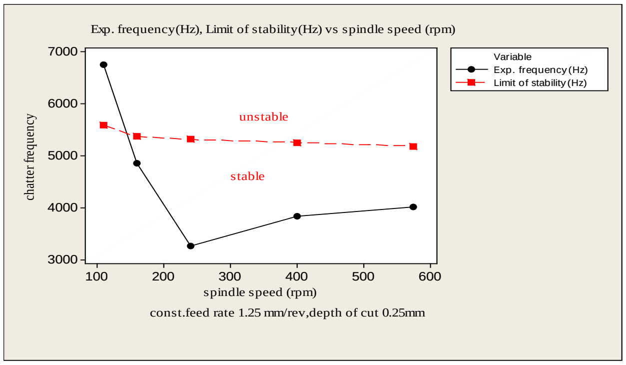

Fig. 7b: The effect of speed on the limit of stability through cutting steel with feed rate (1.25mm/rev)

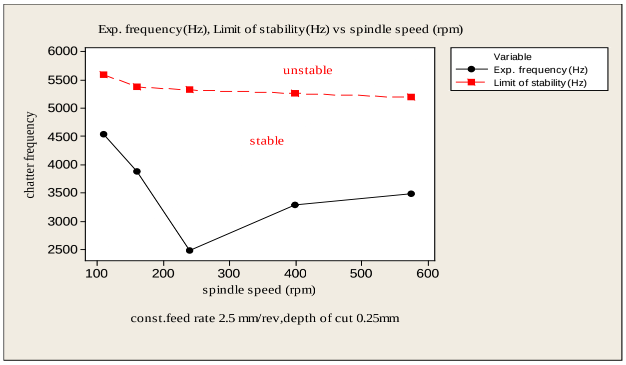

Fig .7c: The effect of speed on the limit of stability through cutting steel with feed rate (2.5mm/rev)

Table 5: Unstable conditions

	Feed rate(mm/rev)	Depth of cut(mm)
110rpm	1.25mm/rev	0.25mm
110&160 rpm	0.625mm/rev	0.25mm

9.0 Depth of Cut and the Limit of Stability

Generally, at a small amount of depth of cut the vibration will be quite enough to separate the cutting tool form its engagement to work specimen during a period of time foreach revolution.To improve the system stability, controlling the relative displacement of the tool with respect to the work piece, is a good solution which does not reduce the productivity but requires expensive control equipments.

Influence of depth of cut on chatter vibration can be explained considering any of the following graph. Experimental result (8a) shows that if depth of cut is increased and other cutting parameters remains constant; then there is decrease in frequency of tool vibration. The decreasing of tool vibration frequency is quiet gradual; the pattern is most likely followed when spindle speed increases 110 rpm to 575 rpm. The tool vibration frequency is quiet high in case of machining conditions stated in table 5. The unstable conditions lead to the concept of resonance, the cutting tool gets a periodic disturbing force during the machining of the specified cutting conditions, which has afrequency equal to the natural frequency of the cutting tool or its holders. Thus causes the rapid increase of chatter frequency. These critical cutting conditions should be avoided during machining.

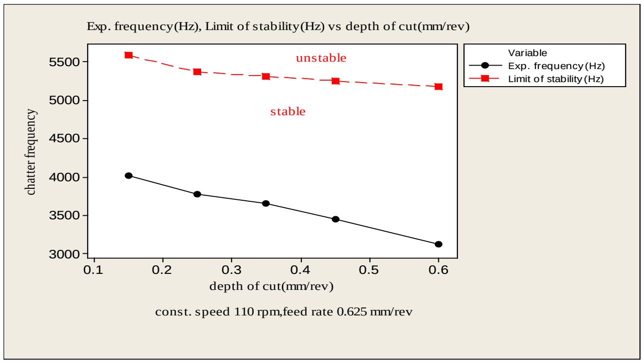

Fig .8a: The effect of depth of cut on stability through cutting steel with speed (110rpm)

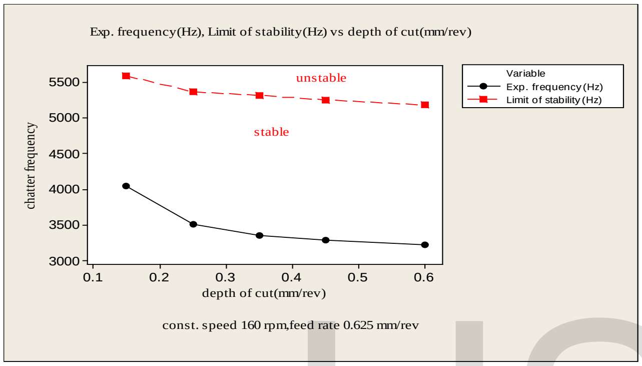

Fig .8b: The effect of depth of cut on stability through cutting steel with speed (160rpm)

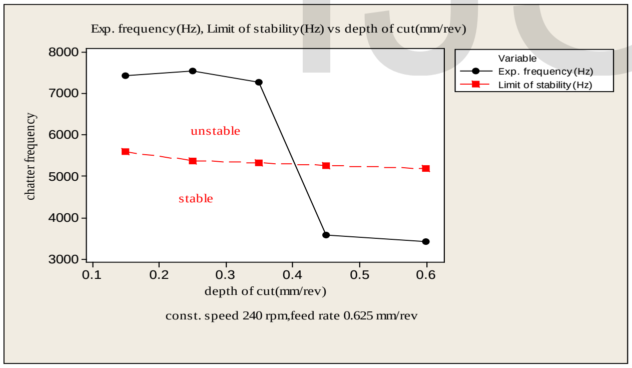

Fig .8c: The effect of depth of cut on stability through cutting steel with speed (240rpm)

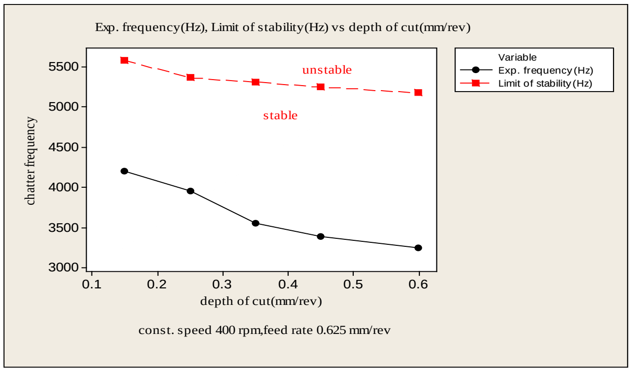

Fig .8d: The effect of depth of cut stability through cutting steel with speed (400rpm)

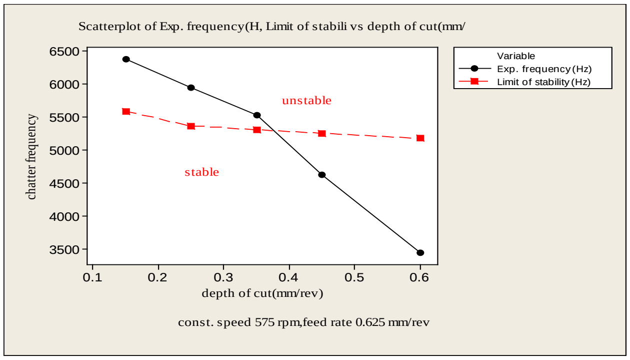

Fig .8e: The effect of depth of cut on stability through cutting steel with speed (575rpm)

Table 6: Unstable conditions

Spindle speed(rpm)	Feed rate(mm/rev)	Depth of cut(mm)
240rpm	0.625(mm/rev)	0.15 to 0.36mm
240rpm	0.625(mm/rev)	0.15to 0.37mm

10.0 Conclusion

An approach for identification of dynamic instability in turning process has been presented in this paper. This approach is based on determination of natural frequencies of the tool with holder which is carried out here with ANSYS software. This further helps to determine the maximum limit of stability in the machining process in different cutting conditions. The experimental results show that if depth of cut is increased then frequency of tool vibration decreases. If feed rate is increased frequency of tool vibration decreases. If spindle speed is increased frequency of tool vibration and surface roughness decreases up to 240 rpm and then increases further. Test results suggested that it is possible to achieve good quality on machined surface if unstable machining conditions, which stated in Table 4, 5 and 6 are avoided during machining.

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