EVALUATION OF CHATTER VIBRATION FREQUENCY IN CNC TURNING OF 4340 ALLOY STEEL MATERIAL

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Abstract: In this study, an experimental investigation of chatter in CNC turning for 4340 Alloy Steel material was carried out. Empirical study of chatter and critical cutting condition in CNC turning has been conducted through a well-designed three-factor three-level experiment, and regression models developed for chatter frequency prediction with up to 99.5% accuracy for the material. The arising model and the mean-effect plots of the cutting speed, feed rate, and depth of cut against Signal-to-Noise (S/N) ratio indicates that increasing feed rates and depth of cuts would bring about increase in chatter vibration frequency while high cutting speeds would have attenuating effects on chatter vibration frequency, thereby suppressing it. The percentage contribution of the cutting parameters to chatter vibration frequency established, and optimal machining condition for the machine chatter optimization obtained at a cutting speed of 320 m/min, feed rate of 0.05mm/rev and depth of cut of 0.5mm. The optimal chatter vibration frequency for the turning tests was found to be 130.00 Hz. With the obtained optimum input parameters for chatter vibration frequency, production operations will be enhanced.

Keywords: Chatter Vibration, CNC Turning, Cutting Stability, Taguchi Method

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1. INTRODUCTION

Machine tool chatter is one of the major constraints that limit productivity of the turning process; hence, monitoring of chatter is of essence considering the economy of machining operation and competitiveness in the market. CNC machining is the mainstay of modern production systems. Its high capital involvement calls for economic need to operate CNC machines as efficiently as possible, in order to obtain the required pay back. Since the cost of machining on CNC machines is sensitive to the machining parameters, optimal values which would ensure manageable chatter have to be determined before a part is put into production. Chatter is broadly classified in two categories: Primary chatter and secondary chatter. Primary chatter is sub classified as frictional chatter, thermo-mechanical chatter and mode-coupling chatter. Primary chatter arises as a result of the friction between tool and work piece and it tends to diminish with the increase in spindle speed. Secondary chatter is a consequence of the regeneration of waviness of the surface of the workpiece (Ezugwu et al, 2016). This chatter is also referred to as regenerative chatter or self-excited chatter.

Chatter is the most obscure and delicate of all problems facing the machinist. A stability analysis on regenerative chatter for orthogonal cutting process was done by Tlusty (2002) . He obtained a stability lobe diagram (SLD) on the basis of stability analysis which was able to shows the boundary between stable an unstable cuts. By using SLD, operator may select chatter free operations for the turning and milling machines for an established quality control parameters. More detailed discussions regarding SLD can be seen in many papers. Chatter vibration has various negative effects such as:

- Poor surface quality and unacceptable accuracy,
- Tool wear and tool damage,
- Excessive noise,
- Low material removal rate (MRR),
- Low productivity rate.

The knowledge of tool and cutting parameters can stem from either pure experimental analysis or hybrid of experimental and numerical/theoretical analysis (Okonkwo et al, 2015).

Turning is one of the foremost, highly efficient conventional machining processes. Typically the work piece is rotated on a spindle and the tool is fed into it radially, axially or both ways simultaneously to give the required surface. In general, during the cutting processes, three different mechanical vibrations can occur due to the fact that the assembly of elements within a machining system can never be infinitely rigid. These three types of vibrations are known as free vibrations, forced vibrations and self-excited vibrations. The tendency of the various structures (work-piece material, cutting tool, spindle, tool holding sub-assembly etc.) to vibrate at their natural frequencies while interacting during machining and the possibility of synchronization of the vibrations leads to chatter vibration – a phenomenon which is known to be regenerative and is associated with so many negative effects. Chatter vibration defines the maximum values of the cutting parameter thereby operating as the limiting factor to production set-ups.

Srejith (2008) conducted investigations in the turning process of aluminium alloys and stated that when the speed of machining increased from 50 to 400 m/min, the adhesion between the tool and the chip also increased correspondingly. This could be due to the increase in thermal softening of the chip as the temperature increased with the increase in cutting speed

Predictive modeling of machining processes is the first and the most important step for process control and optimization. A predictive model is an accurate relationship between the independent input variables and dependent output performance measures. There are two well-known approaches to obtain this relationship: the empirical approach and, the fundamental approach involving analytical means. The empirical approach is considered a short-term and practical method, and it is the most suited approach for industrial applications (Okokpujie et al, 2015). A number of modeling mechanisms have been developed for better investigation of the machining dynamics and chatter. For example, Tobias and Fishwick (1958) presented a graphical method of stability analysis using the Nyquist plot of the transfer function G(s) for the flexible system. Chatter was also investigated analytically by Tobias (1965) who developed the stability lobe diagram that describes the relationship between the depth of cut and spindle speed. The analytical prediction was then reproduced based on control system theory.

The dynamics of the cutting process and chatter were analyzed and modeled in the frequency domain or in the time domain. The frequency domain analysis leads to the identification of chatter-free cutting conditions such as spindle speed, axial and radial depth of cut. Merritt (1965) presented an elegant stability theory using a system theory terminology and derived a comprehensive stability criterion. Minis and Yanushevsky (1993) redeveloped the analysis by applying the theory of periodic differential equations to the milling dynamic equations. This method was applied to a theoretical turning system to predict the critical depth of cut for chatter-free turning under various rotational speeds. Shi and Tobias (1984) proposed a theory of finite amplitude machine tool instability to consider the effects of the two non-linear phenomena caused by: the tool leaving the work piece material, and a non-linear characteristic of the cutting force. The former arises in all cutting processes when the vibration amplitudes are sufficiently large. The latter is specific and depends on the work piece material and other factors, such as tool geometry. Altintas and Budak (1995) presented an alternative method for the analytical prediction of stability lobes in milling. This was extended to turning and the stability analysis of the dynamic turning system leads to analytical relations for the chatter limits which can be used to generate the stability diagrams.

Time domain models are used to predict cutting forces, torque, power, dimensional surface finish and the amplitudes and frequency of vibration (Altintas, 2000). Tlusty and Ismail (1983) used the time domain digital simulations to describe the dynamic behaviour of milling and investigated the boundary region between the stable and the unstable conditions. Okonkwo et al (2015) also investigated the dynamics of high-speed milling using the time domain simulation. In addition Li (2003) employed a numerical method to solve the differential equations governing the dynamics of both milling and turning systems. In his work, it was proposed that the ratio of the predicted maximum dynamic cutting force to the predicted maximum static cutting force was used as a criterion for the chatter stability. More recently, Sims (2005) developed a new method called the self-excitation damping ratio for analyzing the chatter stability of time-domain milling. The method relies on signal processing of the predicted vibrations, and has been studied to aid analysis of a related case of turning.

2. Materials and Methods

The work piece material used for the study is AISI 4340 round steel bars with nominal dimensions of 381 mm (length) and 38.1 mm diameter. Cutting process was orthogonal turning and workpieces were unstopped.
Parameters for experiments were selected from analytical results for both stable and unstable zones. All experiments were performed using the METEX sound signal and frequency analyser. Experimental investigation was done at the Mechatronics Workshop of Akanu Ibiam Federal Polytechnic, Unwana, Ebonyi State, Nigeria.

Detailed information on chemical composition and the physical properties of the 4340 alloy steel is provided in table1, table 2, and details of the experimental outlay for the turning tests is shown in table 3.

Table 1: Chemical Composition of 4340 Alloy Steel

Carbon	0.38 - 0.43%
Chromium	0.7 - 0.9
Iron	Balance
Manganese	0.6 - 0.8
Molybdenum	0.2 - 0.3
Nickel	1.65 – 2
Phosphorus	0.035 max
Silicon	0.15 - 0.3
Sulphur	0.04 max

Table 2: Physical Properties of 4340 Alloy Steel

Properties	**Units**
Density	7850 Kg/m^3
Melting point	1427°C
Tensile strength	745 MPa
Yield strength	470 MPa
Bulk modulus	140 GPa
Shear modulus	80 GPa
Elastic modulus	190-210GPa

Table 3: Details of the Experimental Outlay

EXP. RUNS	INPUT PARAMETERS	RESPONSE PARAMETERS
1 to 9	Cutting speed	Chatter Frequency (ω_c) in Hz
	Feed rate	
	Depth of cut	

Experiments were performed by cutting AISI 4340 material using uncoated carbide inserts (TPG 322) on Fanuc 0i TC CNC lathe. The boundary condition of the work piece at chuck end is *clamped* while the other end of the work piece is *free*. Natural frequency of the work piece was determined experimentally using the accelerometers and the data acquisition system. The results of the experiment were measured using DTO 32105 frequency analyzer and MXC-1600 digital frequency counter. The experimental setup is shown in figure 1

Figure 1: Experimental Setup for the Turning testsn

Design of the experiment for the current research is based on the Taguchi method. Taguchi Parameter Design as a type of factorial design is similar to traditional DOE methods in that multiple input parameters can be considered for a given response**.** The Taguchi method allows us to predict our ideal combination of independent variables (or input variables) to give the best result on a dependent variable. It can also be used to find which input variable has the greatest effect.

The L9 orthogonal array with all values selected for the experimental run is shown in table 3. There are 9 parameter combinations that need to be tested. Each parameter combination is tested for three replications for effective error reduction and for accurate S/N ratio with reasonably low and stable chatter frequency.

This can be achieved through either of the following method:

1.) MiniTAB 7.5 was employed to minimize the full Factorial design by following the following steps: **Stat > DOE > Taguchi > Create Factorial Design** and go through all of the sub-menus to select a fractional factorial design. A fractional factorial design would allow you to select only a subset or "fraction" of the runs from your design to analyze. This way, an optimal subset of design points was selected.

2.) According to the rule that degree of freedom for an orthogonal array should be greater than or equal to sum of chosen quality characteristics, (DOF) can be calculated through the formula stated in eqn1, Okafor et al (2012):

$$(DOF)R = P * (L - 1) \qquad (1)$$

where (DOF)R = degrees of freedom, P = number of factors, L = number of levels

==≫(DOF)R = 3(3 – 1) = 6

Therefore, total DOF of the orthogonal array should be greater than or equal to the total DOF required for the experiment. Thus L9 orthogonal array was selected and applied with the observation of the balancing property of OAs. The model response is Chatter Vibration Frequency; and the desired characteristic for chatter is “the lower the chatter frequency, the better”.

In the current study, the vector expression for the relationship between the cutting conditions and the output signal (chatter) may be expressed as Sabahudin et al (2011):

$$F_{ch} = \psi\ (v, f, d) \qquad (2)$$

where F_{ch} is the desired Chatter Frequency aspect and ψ is the response function, the approximation of F_{ch} is proposed by using a non-linear mathematical model, which is suitable for studying the interaction effects of process parameters on chatter turning characteristics. In the present work, the predictive chatter model may be stated as:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + e \qquad (3)$$

where, x_1, x_2, x_3, are logarithmic transformation of factors: cutting speed, feed rate, and depth of cut respectively, e is the error term, and β values are the estimates of corresponding parameters. These coefficients can be obtained through least-square method for multiple regressions by minimizing the sum of the squares of the residual. However, more efficient tools have been employed for the computation of the regression coefficients and the establishment of the mathematical chatter model. Some the statistical software packages have been employed to ease computations and ensure accuracy of outputs. MINITAB 7.5 was used for the determination of optimal experimental run number as well as in the development of the ANOVA table.

The experimental plan was developed to assess the influence of cutting speed (v), feed rate (f), and depth of cut (d) on the Chatter Frequency **(ω_c)**. Three levels were allocated for each Parameter (Factors) as given in table 5. The factors levels are typical of the turning machine used and were chosen within the intervals recommended by cutting tool manufacturer. Three cutting variables at three levels led to a total of 9 tests for 4340 alloy steel turning operation according to the **Taguchi** L9 orthogonal array design.

Table 5: Factor levels to be used in the experimental design

Parameters (Factors)	Levels		
	-1	0	1
Cutting speed, v	140	230	320
Feed, f (mm/rev)	0.05	0.10	0.15
Depth of cut, d (mm)	0.10	0.30	0.50

3. Mathematical Models

Vector expression relationship between the Chatter Frequency **(ω_c)** and cutting independent variables can be represented by the following equation Okokpujie and Okonkwo (2015) .

$$F_{ch} = K.V^a.f^b.d^c \qquad (4)$$

Where, K is constant, and a, b, c are the exponents. The constant K, and exponents a, b, c can also be determined by least squares method. Equation (4) can be represented in mathematical form as follows:

$$\ln F_{ch} = \ln k + a.\ln v + b.\ln f + c.\ln d \qquad (5)$$

If we set

$y = \ln F_{ch}$, $\beta_0 = \ln k$, $x_1 = \ln v$, $x_2 = \ln f$, and $x_3 = \ln d$

The predictive linear chatter model developed from the equation can be represented as follows:

$$y = \beta_0 + \beta_1 x_2 + \beta_2 x_2 + \beta_3 x_3 \qquad (6)$$

where, the associated parameters are as earlier defined. The experimental result that will be used to develop the mathematical model for the prediction of chatter vibrations frequency is shown in table 6

Table 6: Experimental results of Chatter vibrations Frequency for the uniform bars of 4340 Alloy Steel

Experiment No	Speed (m/min)	Feed rate (mm/rev)	Depth of Cut (mm)	Chatter Frequency **(ω_c)** ln Hz
1	140	0.05	0.1	150.25

2	140	0.10	0.3	366.21
3	140	0.15	0.5	610.94
4	230	0.05	0.3	135.33
5	230	0.10	0.5	355.56
6	230	0.15	0.1	532.44
7	320	0.05	0.5	130.00
8	320	0.10	0.1	228.04
9	320	0.15	0.3	463.54

For the current research, the desired characteristic for chatter is "the lower the chatter frequency, the better. Computation of signal-to-noise ratio is required for this investigative study. A basic explanation of the signal-to-noise ratio is: a ratio of the change in output due to the changing variable vs. changes in things we cannot control. The equation to find the S/N ratio for this characteristic (chatter frequency) is given below:

$$S/N = -10\log_{10} [\text{Mean of sum of squares of measured data}] \qquad (7)$$

$$= -10\log_{10} [(\Sigma y^2)/n]$$

where n is the number of measurements in a trial and y is the measured value in a trial. The S/N ratio obtained for the turning test is shown in the table 7

Table 7: S/N ratio for Chatter Frequency

Exp. No	Speed (m/min)	Feed rate (mm/rev)	Depth of Cut (mm)	S/N Ratio
1	140	0.05	0.1	-43.53628961
2	140	0.1	0.3	-51.27460399
3	140	0.15	0.5	-55.71997121
4	230	0.05	0.3	-42.62788164
5	230	0.1	0.5	-51.01825795
6	230	0.15	0.1	-54.5254135
7	320	0.05	0.5	-42.27886705
8	320	0.1	0.1	-47.16022065
9	320	0.15	0.3	-53.32174433

Table 8: Response Table for Chatter Vibration Frequency S/N Ratios

Process Parameter	Mean S/N Ratio			Max – Min	Rank	Optimum
	Level 1	Level 2	Level 3			
v	-50.1769	-49.3905	-47.5869	2.5900	2	<u>230</u>
d	-42.8143	-49.8176	-54.5223	11.708	1	<u>0.05</u>
f	-47.2382	-49.0747	-49.6723	2.4341	3	<u>0.5</u>

Based on the analysis of S/N ratios shown on table 8 above - *the response table of Signal-to-Noise ratios for chatter frequency*, the optimal machining performance for the machine chatter optimization is obtained at a cutting speed of 320 m/min (level 2), feed rate of 0.05mm/rev (level 1) and depth of cut of 0.5mm (level 3) for the material. In the analysis, feed rate is shown as the most influencing parameter followed by cutting speed and depth of cut.

Determination of Regression Coefficients and Formulation of the Predictive Models using SPSS software package

Table 9: SPSS Output

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.995[a]	.991	.985	22.0021504

a. Predictors: (Constant), depth of cut, feed rate, speed

Coefficients[a]

Model	Unstandardized Coefficients		Standardized Coefficients	T	Sig.
	B	Std. Error	Beta		
1 (Constant)	16.957	32.939		.515	.629
Speed	-.566	.100	-.245	-5.674	.002
feed rate	3971.133	179.647	.953	22.105	.000
depth of cut	154.808	44.912	.149	3.447	.018

a. Dependent Variable: chatter frequency

Hence, the mathematical model of 4330 Alloy steel for the turning operation for the coded factor is

$$\mathbf{Y/(\omega c) = 17.0 - 0.566\, v + 3971\, f + 155\, d} \qquad \mathbf{(8)}$$

The regression equation can be used to make predictions about the response for given values of the control factors

Based on computed data of this work, the outputs of the statistical package- SPSS shown above, it is observed that the correlation coefficient, r is 0.995 which implies that there is a very strong relationship between the dependent variable (chatter frequency) and independent variables (cutting speed, feed rate and depth of cut). The coefficient of determination r^2 = 99.0% means that the explanatory variables [cutting speed(v), feed rate(f) and depth of cut(d)] explain changes in the chatter frequency as high as 99%, while the remaining 1% is accounted for by disturbance terms (error) which are accommodated in the model specified. Also the regression models indicates that feed rate (f) and depth of cut (d) will bring a positive increase to the dependent variable chatter frequency (Y/ω_c) while speed (v) will cause a decrease to Response variable (chatter frequency) based on the model fit.

Table 10: Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	3	257888	257888	85963	177.574	0.0000169
A- cutting speed (m/min)	1	15588	15588	15588	32.200	0.0023661
B- feed rate(mm/rev)	1	236548	236548	236548	488.641	0.0000035
C- depth of cut(mm)	1	5752	5752	5752	11.881	0.0182977
Error	5	2420	2420	484		
Total	8	260308				

From table 10: the regression model F-value of 177.574 implies the model is significant.

Values of "Prob > F" less than 0.0500 indicate model terms are significant.

In this case A, B, C, are significant model terms. This implies that the three cutting parameters which are cutting speed, feed rate and depth of cut are Significant.

Table 9: Comparison between Measured Data and Predicted Data

S/N	Speed(v)	Feed Rate (f)	Depth of Cut(d)	Chatter Freq, $\omega_{c\,(e)}$	Predicted y values, $\omega_{c\,(m)}$	Percentage deviation (φ_i)
1	140	0.05	0.1	150.25	151.81	-1.038
2	140	0.10	0.3	366.21	381.36	-4.137
3	140	0.15	0.5	610.94	610.91	0.005
4	230	0.05	0.3	135.33	131.87	2.557
5	230	0.10	0.5	355.56	361.42	-1.648
6	230	0.15	0.1	532.44	497.97	6.474
7	320	0.05	0.5	130.00	111.93	13.900
8	320	0.10	0.1	228.04	248.48	-8.963
9	320	0.15	0.3	463.54	478.03	-3.126

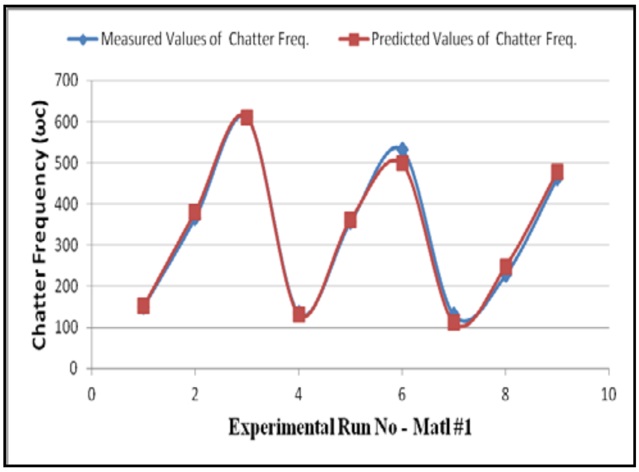

Figure 2: A plot of Actual and Predicted Values of Chatter Frequency

The actual values gotten from the experiment and the predicted values obtained from the developed mathematical models are depicted in Figure 2. It can be seen that they have good agreement.

In order to judge the accuracy of the predictive mathematical model developed, percentage deviation φ_i and average percentage deviation $\bar{\varphi}$ were used. The percentage deviation φ_i is stated thus: (Okokpujie and Okonkwo, 2015)

$$\varphi_i = \left(\frac{F_{ch\,(m)} - F_{ch\,(e)}}{F_{ch\,(e)}}\right) \times 100\,\% \qquad (9)$$

Where φ_i : percentage deviation of single sample data, $F_{ch(e)}$: experimental/measured values, $F_{ch(m)}$: predicted/model values from the multiple regression equation.

Similarly, the average percentage deviation $\bar{\varphi}$ is stated as:

$$\bar{\varphi} = \frac{\sum_{i=1}^{n} \varphi_i}{n} \qquad (10)$$

where $\bar{\varphi}$: is the average percentage deviation of all sample data, and n is the size of sample data.

For training data

$$\varphi_i = \left[100 - \left[\frac{4.024}{9}\right]\right]\%$$
$$= 99.5\%$$

The result of average percentage deviation shows that the mean (average) percentage deviation (error), $\bar{\varphi}$ = 99.5%. This means that the statistical models could predict *(on an average basis)* chatter frequency with about 99.5% accuracy.

4. Effects of Process Parameters on Chatter Vibration Frequency During The Machining Of 4340 Alloy Steel Turning Operation

The main effect plot of the three most influential cutting parameters (cutting speed(v), feed rate(f), and depth of cut (d)) on chatter for the turning experiments are shown below in Figures 3.

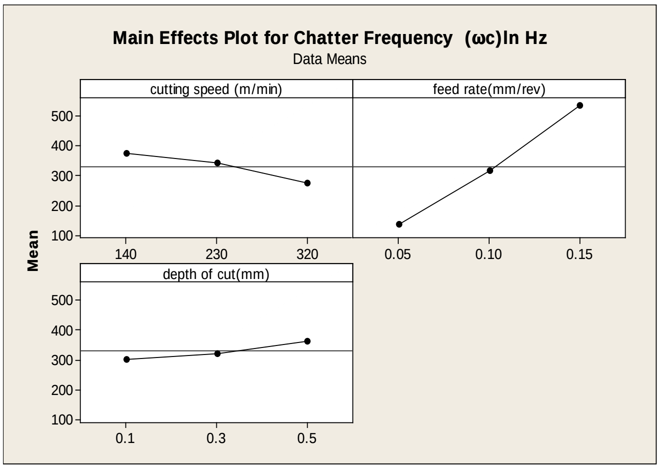

Figure 3: Effect Plot for Chatter Frequency vs. Cutting Speed, Feed Rate and Depth of Cut

Figure 3 shows the plots for the process parameters which are the cutting speed (v), feed rate (f) and depth of cut (d) respectively. The main effects plot shows graphically, the influence of each control factor on chatter vibration frequency. These plots reveals that as cutting speed increases, chatter vibration frequency decreases, increasing the cutting speed will increases the cutting force and eliminates the built-up edge (BUE) tendency. At low cutting speed, the unstable larger BUE is formed and also the chips fracture readily producing the chatter vibration. As the cutting speed increases, the BUE vanishes, chip fracture decreases, and hence, the chatter vibration frequency decreases. this result is in line with observation made by Ezugwu et al (2016). This is consistent with the negative sign of *v* (the cutting speed) as seen in the predictive mathematical models of equation. Increase in feed rate and depth of cut leads to increase in chatter vibration frequency. As the feed rate and depth of cut is increased, chips become discontinuous and are deposited between work piece and tool leading to increased coefficient of friction, as has been portrayed in the positive sign of the coefficients of feed rate (f) and depth of cut (d) in the arising model of equation (8).

The 3D surface plots of the response function are shown below. MatLab codes were used to generate the plots. Emphasis laid by surface plots of Figures (4, 5 & 6) is the interplay of the input signals (v, f, and d) on chatter vibration frequency.

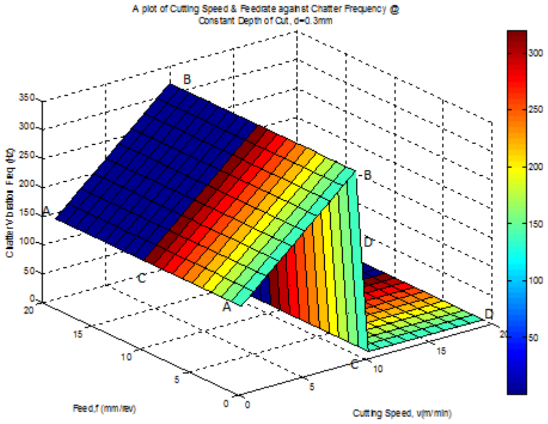

Figure 4: A plot of cutting speed and feedrate against chatter frequency at constant depth of cut

The Figure indicates that at very low cutting speeds, chatter vibration can increase steadily with increasing federate (region A – B). This trend is however reversible after the attainment of a critical cutting speed that is high enough to mitigate chatter vibration (region B – C). From the mathematical chatter models developed in the current work, there is a theoretical possibility of mitigating chatter to almost zero-value (region C – D) with ever increasing speeds within a range of feeds provided that depth of cut is kept constant. The emphasis laid by the parameters-interaction is the dominance of feed on chatter vibration frequency over the other controllable machining parameters within the first region, and the dominance of cutting speed within the second and third regions.

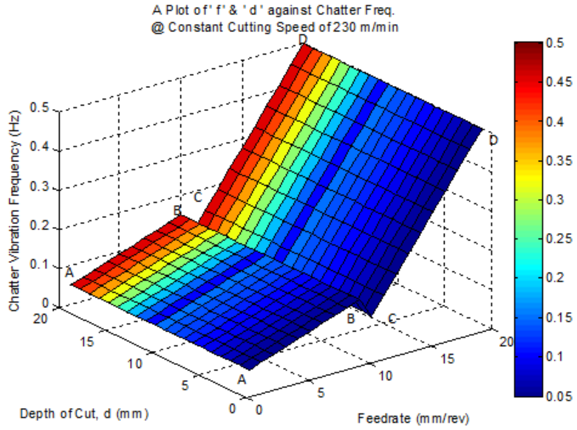

Figure 5: A Plot of Feedrate and Depth of Cut against Chatter Vibration Frequency

The surface plot above shows that chatter vibration frequency increases at somewhat slow pace (region A – B) as turning proceeds. Momentary decline in chatter frequency (region B – C) is possible due to destructive interference. In real-life turning operations, this does not last for so long before regeneration (or regenerative chatter) sets in. Regenerative chatter and the combined effect of increasing federate and depth of cut would bring about sharp rise in chatter vibration frequency (region C – D), given that cutting speed is kept constant. It has been reported in different works and confirmed true during experimentation that speed modulation has the capacity to interfere with the regenerative process, thereby mitigating chatter to manageable levels.

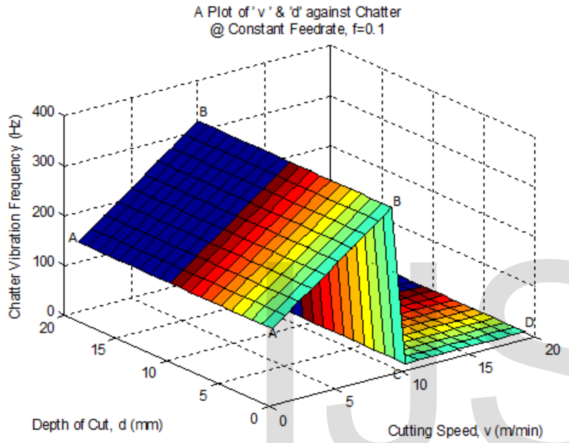

Figure 6: A Plot of Cutting Speed and Depth of Cut against Chatter Frequency

This Figure is seen to be similar to Figure 4, which means that the interaction between v, d, and ω_c is similar to that between v, f, and ω_c. This can be seen from the 'positive' coefficients of *f* and *d* in the arising mathematical model of equation 8. However, statistical evaluations conducted using model-coefficients from ANOVA tables reveals that the mean percentage contribution of depth of cut to chatter vibration frequency is lesser than that due to feedrate.

The arising models reveal that the interplay of input signals (v, f, and d) on ω_c is inherently linear, devoid of cross product effects among the individual factors. This observation is plausibly as a result of the fact that the control parameters are purely independent of one another.

5. CONCLUSIONS

In this study, the effects of process parameters on chatter vibration frequency during orthogonal turning operation of AISI 4340 Alloy Steel were established. By constructing the response table for signal-to-noise (S/N) ratio, the characteristics of the main effects were seen and optimal cutting condition obtained. The use of SPSS 22.0 statistical software package facilitated handling of the experimental data, development of the ANOVA table and formulation of high performance chatter vibration predictive (regression) models for the 4340 Alloy Steel material. The significant conclusions drawn from the present research are summarized as follows:

- The mathematical model developed is capable of predicting the chatter vibration frequency for the turning operation with 99.5% accuracy. The linear models developed to predict the chatter vibration frequency could provide predictive values pretty close to the actual values by applying the values of the control parameter on the model.
- From the experimental results, the optimal machining performance for the machine chatter optimization is obtained at a cutting speed of 320 m/min, feed rate of 0.05mm/rev and depth of cut of 0.5mm. The value of the optimized chatter vibration frequency is 130.00 Hz.
- In the order of influence to chatter vibration frequency, feed rate was found to be the most influencing factor contributing 89.84% to chatter frequency, cutting speed 5.79% and depth of cut 3.92% respectively for the test material used. The effect of each factor was found to be *mainly* linear, and there exists no cross product effects (interactions) among the individual factors.

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