Effects of Process Parameters on Vibration Frequency in Turning Operations of Perspex Material

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***Abstract*— Effects of process parameters on vibration frequency of Perspex round plastic bars was investigated experimentally under clamped - free (C - F) boundary condition during turning operation. Mathematical models were developed using Taguchi L9 orthogonal array design. Spindle speed (V), feed rate (f), and depth of cut (d) were selected as input variables in order to predict the effects of vibration frequency on the work-piece. Nine samples were run in a CNC lathe machine, and each of the experimental result was measured using DTO 32105 frequency analyser and a MXC-1600 digital frequency counter. A minimum vibration frequency of 104.8 Hz was obtained at a cutting speed of 320 m/min, feed rate 0.05 min/rev and at a depth of cut of 0.5 mm. The mathematical model developed shows the accuracy of predicting the vibration frequency to be 99.5% and the various combinations of parameters that results in the minimum vibration frequency were determined. Obtained optimum input parameters for vibration frequency indicated that production operations of Perspex round plastic bars could be enhanced.**

***Index Terms*— Machining, Perspex, Turning operation, orthogonal array design, CNC machine**.

I. Introduction

Machining is the most noticeable aspects of engineering practice that has been with man for centuries.

It has remained one of the cardinal means of production and manufacturing which cuts across every face of engineering technology.

In recent years, machining technology has experience speedy development; the innovative technology in certain has substantial variations such as the integration of computer mathematical regulator systems. Emerging trends at trade-fairs, conferences research institutes and the industrial sector has shown that production capabilities have increased tremendously with machining operations [1]. The correctness and efficiency are being improved constantly with inventive solutions to attain market demands or even increase them to good quality standards. For numerous years, investigation of machine tool vibrations and unsteadiness problems has received substantial attention in order to improve the metal removal procedure. Researchers across the globe have also delved into investigations, “known and ambiguous” with the view to proffering solutions to machining vibration and other optimization problems. Increasing interest in machining, have led to advancing the scope of existent dynamic optimization solutions, and exploring new aspects and areas of concern [2].

The operating principle of CNC is to rule the motion of the work-head relative to the work-part and to control the order in which the motions are carried out. A CNC scheme consists of four (4) basic components which are, Part Program, Machine Control Unit, MCU, and machining Equipment.

In turning operations carried out on a CNC or conventional lathe machine, the work-piece is rotated on a spindle and the instrument is fed into it radially, axially or concurrently to give the desired surface finishing.

Perspex is a transparent plastic, sometimes called acrylic glass or Poly (methyl methacrylate) (PMMA). Durable and very transparent, is widely used in most fields and used such as: rear-lights and instrument groups for vehicles, appliances and lenses for glasses.

Machining process, there are many kinds of diverse parameters which may contribute to vibration build-up, thus affecting machining performance. It is impossible to consider all the factors at once in an experimental vibration studies. The most important factor(s) are often selected as objective function and constraints in machining process models. Some of the most important factors are listed as follows. [3] - [5]. Structural: stiffness, damping, modes of vibration, cutting parameters/conditions: feed rate (chip thickness), cutting speed (spindle speed), depth of cut, tool geometry, cutting forces, appropriate units are usually pre-set on the CNC machines to conform to those used in the part programmed.

The most important machining parameters affecting the machining performance of CNC milling and turning machines are cutting speed, feed rate, and cutting depths (axial depth of cut and radial depth of cut) [6] – [9]. Hence, these three parameters have been considered as the control

Manuscript received January 05, 2018; revised March 31, 2018.

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variables for the experimental determination of the response function for vibration frequency.

Economy of machining process plays a significant role in affordability in the market. It is therefore expedient to understand the mechanisms of vibration and vibration control strategies, for optimizing machining parameters, which is of high significance in manufacturing considering economic factors [10]. Given the fact that vibration is associated with numerous negative effects such as; bad surface roughness, high surface roughness, undesirable extreme noise, unequal tool wear, machine tool damage, decrease material removal rate, increased prices in terms of manufacturing period, excess of resources, excess of energy, ecological impact in terms of materials, costs of recycling and energy, consequently the review of vibration improvement techniques as presented in this study would help in vibration control and avoidance which is an issue of great interest. Furthermore, the study would assist machining operators to reduce vibration either passively or actively by applying absorbers, damping vibration isolators, varied speed or other alternatives [11]. The study of vibration is important in the prediction of machining stability and enhancement of tool life. [12].

Several methods of simulation methods have been designed for study of machining dynamics and vibration. Tlusty [1] work on the steadiness part diagram that explains the correlation between the depths of cut and spindle speed. The theoretical calculation was then repeated based on the system control hypothesis, were the cutting process and vibration was analysed and modelled in the frequency domain. [13].

Nevertheless, it is well known that when chatter occurs, it does not generate for an indefinite period but stabilises at limited amplitude of vibration. Throughout this period, the force is not proportional to chip thickness but purely zero. [13] – [17] study the effects of cutting process on the work-piece dynamics. Though, during applying time domain model to predict the margined of steadiness in milling process, is often complicated to differentiate between belongings of vibrations due to unsteadiness and cases of too much vibrations due to great periodic forces. Recently Li [10] design a statistical technique to resolve the differential equations controlling the subtleties of both milling and lathe machining systems and projected the ratio of the predicted extreme energetic machining force to the predicted maximum stationary cutting force were used as a standard for the chatter steadiness. When this process is not well defined during machining operation it can lead to fatigue, creep and can increase the rate of corrosions in our manufacturing product [24-31].

The current study aimed at resolving the problems posed by vibration frequency and also to conduct an empirical study of turning operation through a three-factor, three-level experimental design and to develop a mathematical model that can predict vibration frequency. The factors considered are the cutting speed, the depth of cut and feed rate which are the machined parameters.

II. MATERIALS AND METHODS

The material used for the investigation was Perspex round bars with actual dimensions of 381 mm (length) and 38.1 mm diameter. Cutting process was orthogonal turning and work-pieces processing were unstopped. Parameters for experiments were selected from analytical results for both stable and unstable zones. The experimental set-up was carried out by attaching the work-piece of the materials to the machine chuck of the CNC lathe. A microphone was placed near the tool-work-piece cutting zone to detect sound waves during machining operation. The microphone outlet was connected to a digital frequency counter and a frequency analyzer which recorded the vibration frequency. A dry-run was conducted: operating the CNC lathe at ‘no load’ – cutting does not take place, enabling recording of the machine noise using the frequency analyzer and the digital frequency counter. Actual machining was then carried out by executing the program file which contains the prescribed operating conditions from the designed experiments. 9 samples were then run on the CNC lathe machine experimentally. Vibration frequency data were recorded with DTO 32105 frequency analyzer and MXC-1600 digital frequency counter respectively.

Detailed information on chemical composition and the physical properties of the Perspex round bar is presented in Table I and details of the experimental outlay for the turning tests is presented in Table II.

Table I: Physical properties and chemical composition of Perspex

Properties	Composition/values
Chemical formula	$(C_5O_2H_8)_n$
Density	1180Kg/m^3
Melting point	160 °C
Boiling point	200°C
Refractive index (n)	1.4905 at 589.3 nm

Table II: The experimental outlay

Exp. Runs	Material	Cutting tool	Input parameters	Response parameters
1to 9	Perspex	TPG 322	Cutting speed Feed rate Depth of cut	Vibration Frequency,F_{vf} (Hz)

The experiments were performed using the metex sound signal and frequency analyzer. Experimental analysis was conducted at the Mechatronics Workshop of Akanu Ibiam Federal Polytechnic, Unwana, Ebonyi State, Nigeria. Experiments were performed by turning of Perspex material using uncoated carbide inserts (TPG 322) on Fanuc 0iTC CNC lathe. The boundary condition of the work piece at chuck end was clamped while the other end of the work piece was 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 Fig. I.

Fig. I: Experimental setup for Perspex turning operation

Experimental design for this research is based on the Taguchi method. The Taguchi method allows for the prediction of ideal combination of input variables to give the best result on a response variable. It can also be used to find which input variable has the most significant effect.

The investigational design was developed to evaluate the effect of cutting speed (v), feed rate (f), and depth of cut (d) on the vibration Frequency (F_{vf}) Three levels were assigned the three factors as expressed in Table III. The factors levels were selected within the specification by cutting tool manufacturer. Three cutting parameters at three levels led to a overall of 9 tests for Perspex turning operation according to the Taguchi L9 orthogonal array design. To select a suitable orthogonal array for carrying out the experiments, the degrees of freedom were calculated. Degrees of Freedom is one for Mean Value and two for each of the remaining three factors such as (3^2) = 8, therefore the total Degrees of Freedom is 9, the most suitable orthogonal array for this experimentation is L9 array with a total number of nine experiments runs as shown in Table IV.

Table III: Factors levels for experimental design

Cutting parameters (Factors)	Levels		
	-1	0	1
Cutting speed, v (m/min)	200	250	300
Feed, f (mm/rev)	0.15	0.20	0.25
Depth of cut, d (mm)	10	15	20

III. MATHEMATICAL MODELS

In the current study, the vector terms for the relationship between the turning conditions and the response parameter is expressed as [18]:

$$F_{vf} = \mathrm{k}\,(\mathrm{v}, \mathrm{f}, \mathrm{d}) \qquad (1)$$

Where F_{vf} is the response function, k is either a function operator of v, f, d, or a constant, F_{vf} is the wanted vibration frequency aspect and k is the response meaning, the estimation of F_{vf} is proposed by using a non-linear scientific model, which is appropriate for reading the interaction effects of process factors on vibration turning physiognomies. In current study, the predictive vibration model can be obtained by assuming that the operating parameters (v, f, d) contains exponent indices, taking the natural log of equation (1), it can hence be expressed by equation (2).

$$\mathrm{Y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \mathrm{e} \qquad (2)$$

Where, x_1, x_2, x_3, are logarithmic transformation of machining factors, namely, cutting speed, feed rate, and depth of cut (radial) 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 model. Statistical software packages were employed to ease computations and certify accuracy of outputs. SPSS and MINITAB 16 were used for the determination of optimal experimental run number.

Vector terms relationship between the vibration frequencies (F_{vf}) and process parameters can be represented by equation (3) [19].

$$\mathrm{F_{vf}} = \mathrm{K}.\mathrm{V}^{\mathrm{x}}.\mathrm{f}^{\mathrm{y}}.\mathrm{d}^{\mathrm{z}} \qquad (3)$$

Where, K is constant, and x, y, z are the exponents. Equation (3) can be represented in mathematical form as follows:

$$\ln \mathrm{F_{vf}} = \mathrm{lnk} + \mathrm{xlnv} + \mathrm{ylnf} + \mathrm{zlnd} \qquad (4)$$

Equating $\mathrm{y} = \mathrm{InF_{vf}}$, $\beta_0 = \mathrm{lnk}$, $\beta_1 = \mathrm{lnv}$, $\beta_2 = \mathrm{lnf}$, $\beta_3 = \mathrm{lnd}$

The constant and exponents K, x, y, z can also be determined by least squares method, Where, $\mathrm{x} = x_1$ $\mathrm{y} = x_2$, and $\mathrm{z} = x_3$

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

$$\mathrm{F_{vf}} = \beta_0 + \beta_1\, x_1 + \beta_2\, x_2 + \beta_3 x_3 \qquad (5)$$

In the current investigation, the desired characteristic for vibration frequency is “the lower the vibration frequency, the better. Computation of signal-to-noise ratio (S/N) is required for this study. A basic explanation of the signal-to-noise ratio is: a ratio of the change in output due to the changing variable versus changes in factors that cannot be controlled. The equation to find the S/N ratio for this characteristic (vibration frequency) is given by equation (6).

S/N = $-10\log_{10}$ [Mean of sum of squares of measured data] (6)

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

Where n is the number of measurements in a test and F is the measured value in a test.

ISBN: 978-988-14048-9-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

IV. RESULT AND DISCUSSION

Table IV shows the result of the experiments for the various process parameters and measured vibration frequency for the turning operation of Perspex.
Statistical Analysis of Variance in the turning operation:
The result of the vibration frequency is analyzed in Table V and Table VI, showing the model summary and coefficients of the analysis.

Table IV: Vibration frequency at various experimental variables

S / No	Cutting speed (m/min)	Feed rate (mm/rev)	Depth ofcut (mm)	Vibration Frequency, F_{vf} (Hz)
1	200	0.15	10	120.20
2	200	0.20	15	288.35
3	200	0.25	20	484.87
4	250	0.15	15	108.26
5	250	0.20	20	285.59
6	250	0.25	10	425.95
7	300	0.15	20	104.84
8	300	0.20	10	182.43
9	300	0.25	15	369.35

Table V: SPSS Output- Perspex material for model summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
0.995[a]	0.989	0.983	18.56417

Table VI: SPSS Output-Perspex material for coefficients

Model	Unstandardized coefficients B	Std. error	Standardized coefficients Beta	T	Sig.
(Constant)	11.871	27.79		0.427	0.687
V	-.439	.084	-.239	-5.208	0.003
F	3156.233	151.57	.954	20.823	0.000
D	122.267	37.89	.148	3.227	0.023

The R-Square was 0.989 which showed that 98.89 % of the observed variability in F_{vf} could be explained by the independent variable which are cutting speed, depth of cut and feed rate. This implies that there is very strong relationship between the dependent variable (vibration frequency) and independent variables (process parameters). The Adeq Precision is 18.56417 which meant that the correlation coefficient between the observed value of the dependent variable (vibration frequency) and the predicted value based on the regression model are in good conditions.

The comparison between the experimental data and the predicted data are presented in Table VII.
Hence, the mathematical model for vibration frequency is expressed by equation (7)

$$F_{vf} = 11.871 - 0.439v + 3156.233f + 122.267 \quad (7)$$

Table VII: Comparison between measured data and predicted data of Perspex material

S/N	Speed (m/min)	Feed Rate (min/rev)	Depth of Cut (mm)	Vibration Freq. (Hz)	Predicted values (Hz)	Percentage deviation (φ_i)
1	140	0.05	0.1	120.2	120.4	-0.207
2	140	0.10	0.3	288.4	302.7	-4.980
3	140	0.15	0.5	484.9	485.0	-0.022
4	230	0.05	0.3	108.3	105.4	2.652
5	230	0.10	0.5	285.6	287.7	-0.724
6	230	0.15	0.1	426.0	396.6	6.900
7	320	0.05	0.5	104.8	90.3	13.833
8	320	0.10	0.1	182.4	199.2	-9.214
9	320	0.15	0.3	369.4	381.5	-3.290

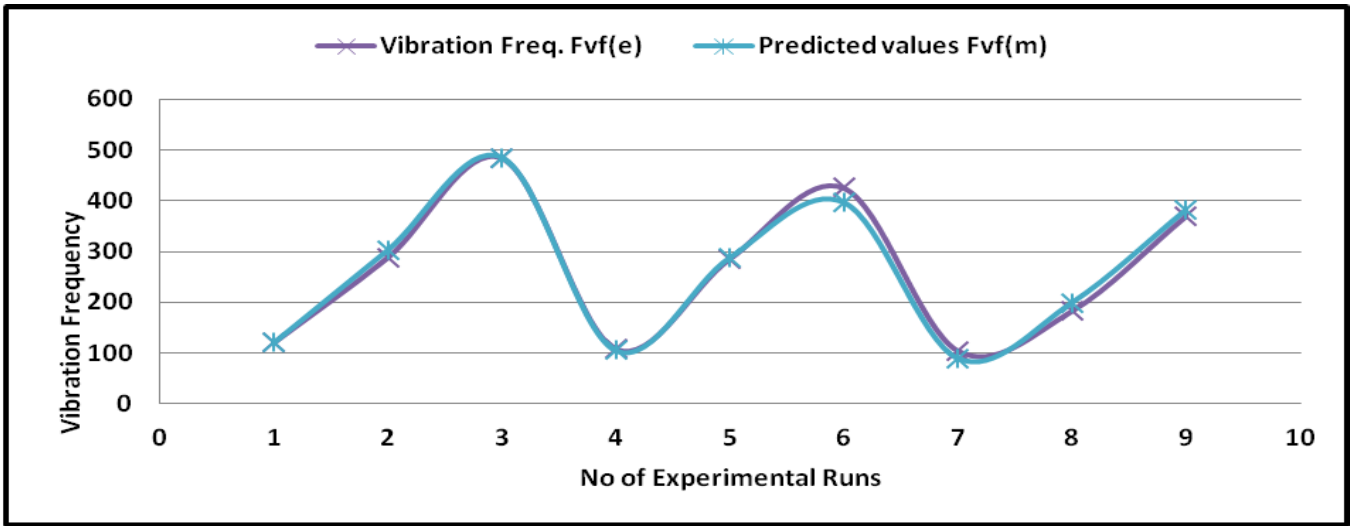

Fig. II: Actual and Predicted values of vibration frequency

The actual values gotten from the experiment and the predicted values obtained from the developed mathematical models are depicted in Fig. II is clearly observed that they have good agreement quantitatively.
To determine the correctness of the mathematical model developed, percentage deviation φ_i and average percentage deviation $\bar{\varphi}$ were used. The percentage deviation φ_i is stated as [18].

$$\varphi_i = \left(\frac{F_{vf\,(m)} - F_{vf\,(e)}}{F_{vf\,(e)}}\right) \times 100\,\% \qquad (8)$$

Where, φ_i = percentage deviation of single sample data, $F_{vf\,(e)}$=experimental values, $F_{vf\,(m)}$= predicted values from the multiple regression equation (model).

Similarly, the average percentage deviation $\bar{\varphi}$ is stated as [18];

$$\bar{\varphi} = \frac{\sum_{i=1}^{n} \varphi_i}{n} \qquad (9)$$

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

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

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

A. Evaluation of the signal to noise ratio with the process parameters

The main effect of the signal-to-noise ratio characteristics with process parameters which are cutting speed (v), feed rate (f), and depth of cut (d) on vibration frequency for the turning experiments are shown in Fig. III - V. The relative impact of each parameter on vibration frequency for the test materials can be deduced from the respective graph.

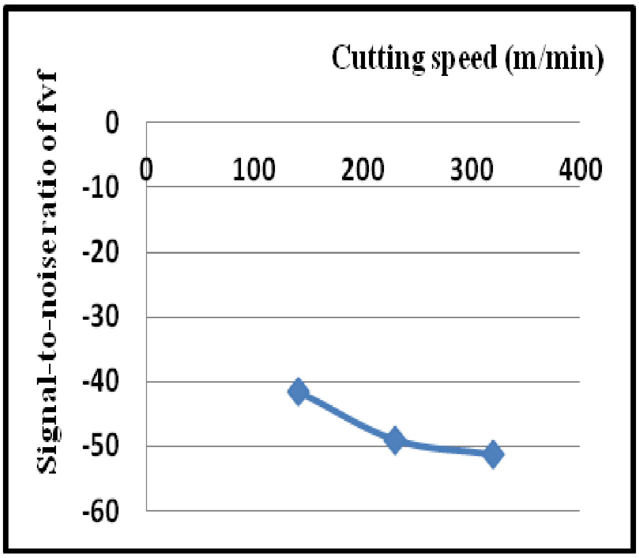

Fig. III: Signal-to-noise ratio variation with cutting speed

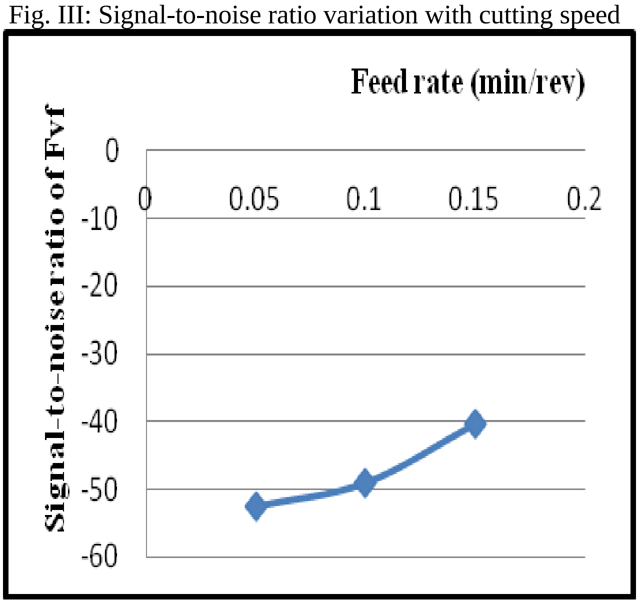

Fig. IV: Signal-to-noise ratio variation with Feed rate

ISBN: 978-988-14048-9-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

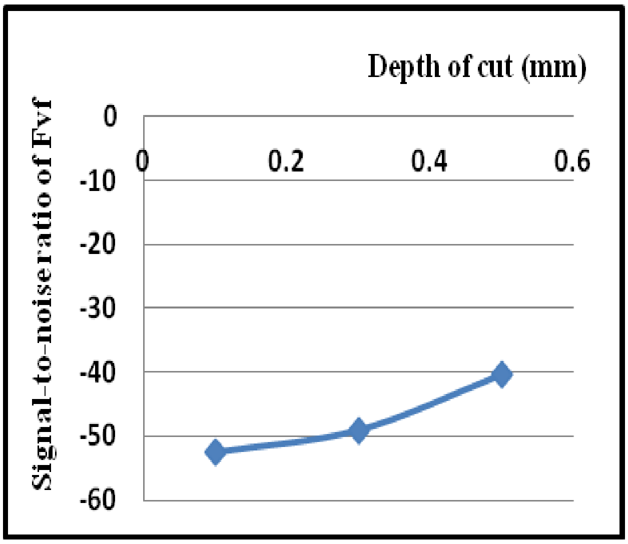

Fig. V: Signal-to-noise ratio variation with Depth of cut

Fig. III-V shows the influence of each level of the process parameters on the signal-to-noise ratio with maximum value taken as the optimum value. In Fig. III as the cutting speed increases, the signal-to-noise ratio decreases. This explains the negative trend of the Signal-to-noise ratio and in the predictive mathematical models. Increases in feed rate and depth of cut leads to increase in signal-to-noise ratio as portrayed in the positive sign of the coefficients of feed rate (f) and depth of cut (d). As the signal-to-noise ratio increases it result in increasing the vibration frequency

B. Effect of process parameters on the vibration frequency

Fig. VI-VIII shows the contour plots for the vibration frequency and the process parameters which are the cutting speed (v), feed rate (f) and depth of cut (d) respectively. The contour plot shows graphically the influence of each control parameters on vibration frequency. These plots reveal that as cutting speed increases, vibration frequency decreases, increasing the cutting speed will increases the cutting force and eradicates the built-up edge (BUE) inclination there by producing good surface finish. At low cutting speed, the unstable larger BUE is developed and also the chips rupture eagerly creating the vibration and heat generation. As the cutting speed increases, the BUE vanishes, chip fracture decreases, and hence, the vibration frequency decreases. This result is in line with observation made by Ezugwu et al [3], Nwoke et al. [19] and Seguy [20], which indicated that the increase in cutting speed reduces vibration frequencies.

Increase in feed rate and depth of cut leads to increase in vibration frequency, surface roughness and tool wear. This correspond to the observation made by Okokpujie et al. [21] and [22] - [27] Which indicate that 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 and heat generations, which lead to increase in surface roughness and tool substitution.

Fig. VI show that as the feed rate in the vertical axis increased from 20 mm/rev to 30 mm/rev, the vibration frequency increases and attained 300Hz. This is described with the colour changing from light blue to deep orange. As the cutting speed increases from 200 to 300 m/min, the vibration frequency reduces to 104 Hz; at this stage, the colour changes from light blue to blue colour which shows that with more increase in cutting speed it will continue to reduce the vibration frequency.

Fig. VII shows that due to the great influence of the feed rate as it increases, the vibration frequency also increases, irrespective of changes in the depth of cut.

V. CONCLUSION

Through experimentation, the model developed for perpex round bars material investigated during turning operations, proved its capability of predicting the vibration frequency with about 99.5% accuracy

The important conclusions drawn from the present study are as follows:

- The quadratic second order models developed to predict the vibration frequency value for the turning operation could provide very close predictive values for vibration frequency to the actual values by applying the values of the control parameter on the model.
- In the order of influence, feed rate has the most significant effect on the vibration frequency, followed by cutting speed. However, depth of cut has little effect on the vibration frequency.
- From the investigation the minimum vibration frequency of 104.8 Hz during turning operation occurs at a cutting speed of 320 m/min, feed rate of 0.05 min/rev and depth of cut 0.5 mm respectively.

ACKNOWLEDGMENT

The authors wish to acknowledge the management of Covenant University for their financial assistants and contribution made towards the accomplishment of this study.

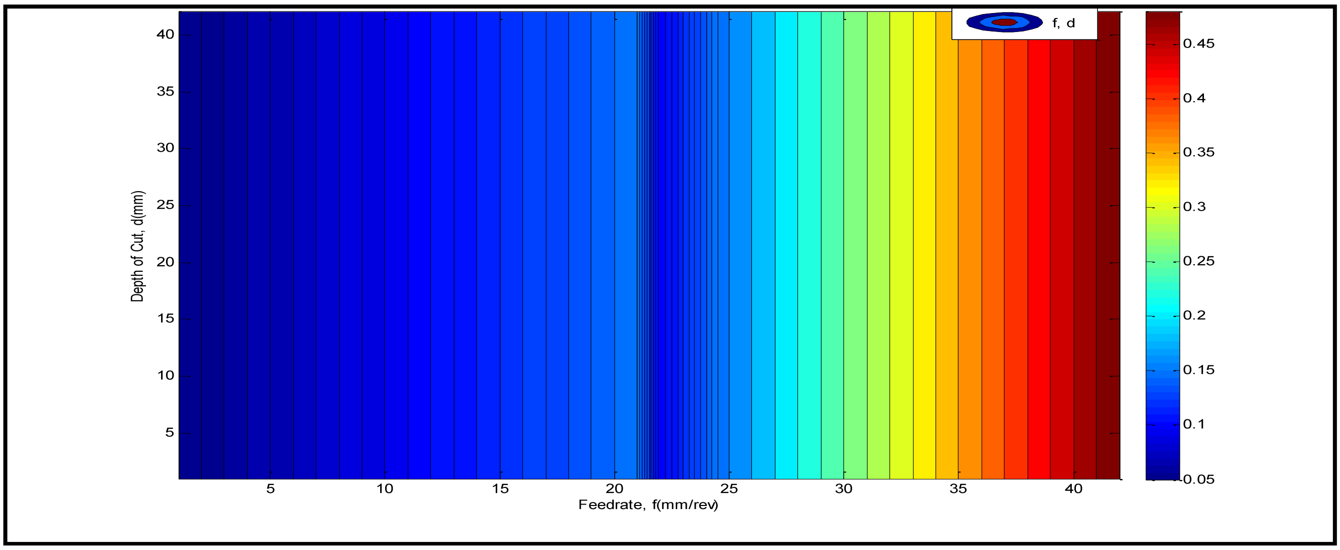

Fig. VI: Vibration frequency contour plot for feed Rate vs. depth of cut

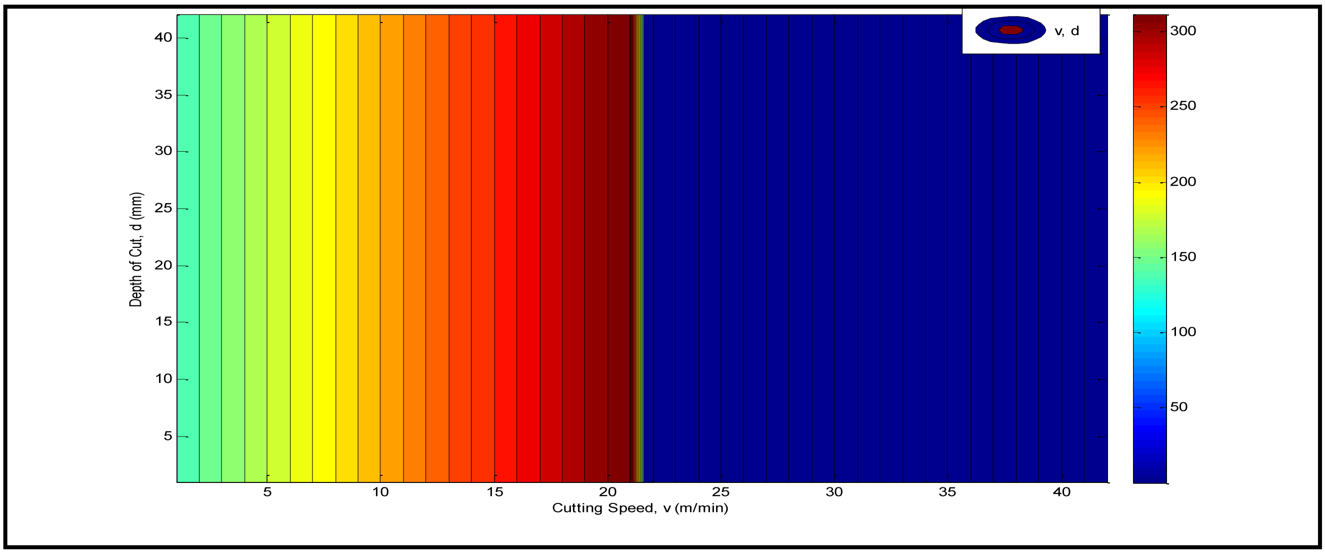

Fig. VII: Vibration frequency contour plot for cutting speed vs. depth of cut

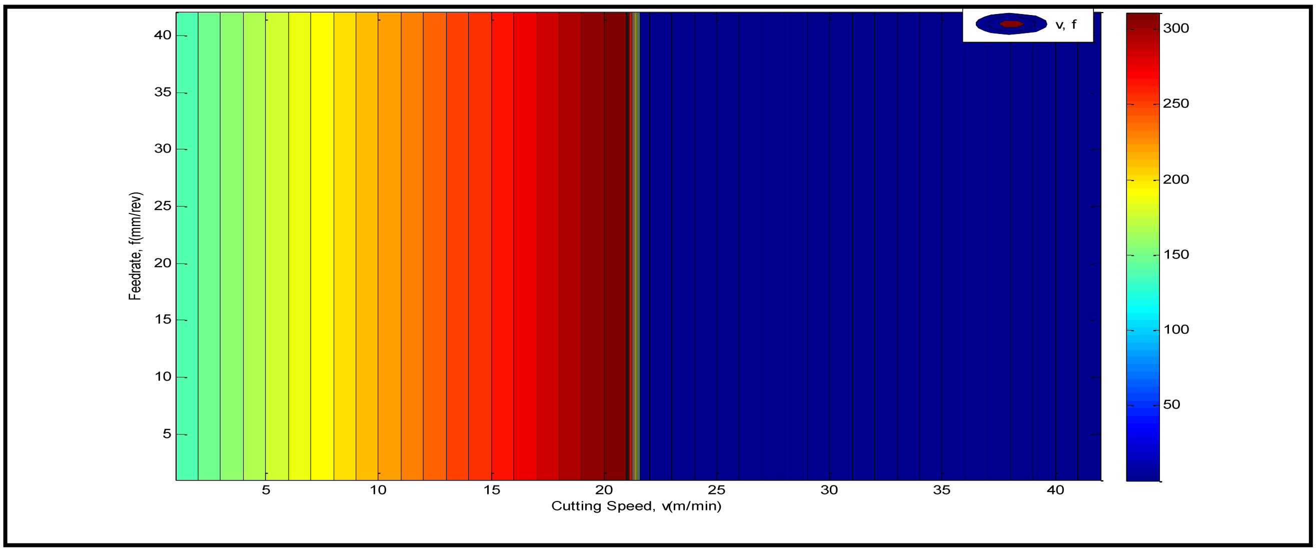

Fig. VIII: Vibration frequency contour plot for cutting Speed vs. feed Rate.

ISBN: 978-988-14048-9-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

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ISBN: 978-988-14048-9-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)