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Experimental Investigation to Minimize Resultant Vibration Signal in CNC Turing Operation of Hard AISI M2 Tool Steel

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Abstract : ***In the present research work, the effect of machining factors including cutting speed, feed rate and depth of cut on resultant vibration signal in a dry turning environment for hard (62-64HRC)AISI M2 are studied using the Taguchi method and analysis of variance (ANOVA).The design of experiment is done by Taguchi method. PCBN CNMG insert (Kennametal Company) of 0.8m is utilized for turning operation.The results are validated by taking confirmation experiments.The present study indicates that the feed rate is most influencing factors for resultant vibration while turning hard AISI M2 material.***
Keywords: ***CNC Turning, Resultant Vibration Signal, Taguchi Method, AISI M2, PCBN Insert***

I. INTRODUCTION

In the present days, there is very much importance for vibration signal study in various machining process such as drilling, milling, and turning etc. Because due to minimizing resultant vibration signal, we gets the various benefits such as minimum possible tool wear, better surface finish, tool life increases, and productivity is also increased due to minimum setting time for machine therefore, it is very important to study and optimize the resultant vibration signals in machining process.

Dimla et al. [1], studied the experimental and analytical method for online tool condition monitoring system. They used three mutually perpendicular components of cutting forces (static and dynamic) and vibration signature measurements. They employed the Kistler mini accelerometers (type 8730A) for acceleration signal measurement in three mutually perpendicular directions and Kistler tool post dynamometer platform (type 9263A) for cutting force measurement again in three planes. They investigated that vertical components (z-direction) of both cutting forces and the vibration signatures were the most sensitive to tool wear, with nose wear being the most useful indicator of eminent tool failure. In the second part, studied the multilayer neural network and input is given to distinguish and classify the tool wear state. Abouelatta, O. B. et al. [2], employed FFT analyser to measure tool vibration in radial direction and feed direction and for measurement of surface roughness the Surtronic 3+ measuring instrument used and correlation between surface roughness and cutting vibration during turning established.They developed mathematical model to the predicted roughness parameter based on the cutting parameter and machine tool vibration for better understanding of the relation. Finally the measured results were analysed by commercial software MATALAB, BC++, SPSS. Bhuiyan. M. S. H. et al. [3], investigated various sensor used to monitor tool condition using different signal like optical, electrical and magnetic. They studied transient elastic wave generarated during machining known as acoustic emission (AE).In this study, they proposed use of acoustic emission sensor and tri-axial accelerometer placed on shank of cutting tool holder was capable to monitor tool condition. Acoustic emission sensor assessed the internal change whereas vibration sensor asses external information of tool state. They illustrated use of RMS signal and fast Fourier transform as output of sensor. They proved that vibration components, Vx, Vy and Vz change with feed rate, depth of cut and cutting speed respectively.

The amplitude of vibration components decreases with the increase of cutting speed, and increases with the increase of feed rate and depth of cut. Alonso, F. J. and Salgado, D. R. [4], developed a reliable tool condition monitoring system (TCMS) for industrial application. They employed singular spectrum analysis (SSA) and cluster analysis for analysis of the tool vibration signals.SSA was non-parametric technique, of time series analysis that decomposes the acquired tool vibration signals and Cluster analysis was used to group the SSA decomposition in order to obtain several independent components in the frequency domain and that are apply to feed forward back-propagation (FFBP) neural network to determine the tool flank wear. Aliustaoglu, C. et al. [5], studied tool wear condition monitoring using a sensor fusion model based on fuzzy inference system.They mainly concentrated on the drilling and milling operation. They used two stage fuzzy logic schemes for developing the advanced tool condition monitoring system. They acquired signal from various sensors and processed to make a decision about status of tool. In first stage, they derived statistical parameters from thrust force, machine sound (acquired via a very sensitive microphone) and vibration signals were used as inputs to fuzzy process; and the crisp output values of this process were then taken as the input parameters of the second stage. Conclusively, outputs of this stage were taken into a threshold function, the output of which was used to assess the condition of the tool. Bhuiyan, M. S. H. et al. [6], studied the tool wear, chip formation and surface roughness of work piece under different cutting conditions in machining using acoustic emission (AE) and vibration signature in turning. The investigation concluded that the acoustic emission and vibration components can effectively respond to different occurrences in turning including tool wear and surface roughness.The acoustic emission has shown a very significant response to tool wear progression whereas resultant vibration (V) represented surface roughness in turning. Vibration components Vx, Vy and Vz described the chip formation type and increase with increase of feed rate, depth of cut and cutting speed respectively. A KISTLER 8152B AE-piezoelectric sensor with sensitivity of 57 dB ref 1 V/(m/s) and a KISTLER 8762A50 tri-axial accelerometer with sensitivity of 100 ± 5% mV/g was used. They captured raw acoustic emission and vibration sensors analysed to determine the different occurrences, including the tool wear and surface roughness of work piece.The data from direct measurement of flank wear and surface roughness, and chip formation occurrences utilized to justify the signals response, and thus to investigate the tool condition even more accurately. The output signals from the acoustic emission and vibration sensors were essentially complex and stochastic in nature. The acoustic emission and vibration signature performed exceptionally well to investigate tool state as well as the different occurrences in turning.

The combined application of acoustic emission and vibration sensors described the tool wear, tool breakage, chip formation, chip breakage, machine tool vibration, machine vibration, work piece surface roughness. Kilundu, B. et al. [7], presented the singular spectrum analysis (SSA) for analysis of vibration signal from tool holder. They explored the use of data mining technique for tool condition monitoring in metal cutting. They also performed Pseudo-local singular spectrum analysis (SSA) on vibration signals measured on tool holder. Then this coupled to a band-pass filter to allow definition and extraction of features which are sensitive to tool wear. These features defined in some frequency bands, from sums of Fourier coefficients of reconstructed and residual signals obtained by SSA.

They also studied two important aspects as strong relevance of information in high frequency vibration components and benefits of the combination of SSA and band-pass filtering to get rid of useless components (noise). Abuthakeer, S. S. et al. [8], used damping pad made from neoprene to control the cutting tool vibration. The experiment was carried out fewer than two cases with use of damping pad and without damping pad on CNC LATHE machine. They developed empirical model using analysis of variance (ANOVA).They also used multilayer perception neural network model constructed with feed forward back-propagation algorithm using the acquired data. On the completion of the experimental test ANN was used to validate the results obtained and also to predict behaviour of system under any cutting condition within the operating range.

On the strength of the evaluation of research work done by former researchers, it is found that a huge amount of research work has been carried out on development of tool condition monitoring system based on vibration signal during turning operation.However no work is found for optimizing the resultant vibration for hard (62-64 HRC) AISI M2 while using PCBN CNMG 0.8 mm (Kennametal Company) nose radius insert in the dry turning environment.This investigation demonstrates details of Taguchi optimization technique to optimize the resultant vibration signal during hard turning. The main objective of present study is to find out set machining parameters which results in minimum resultant vibration signal in Hertz while turning hard AISI M2 on a CNC machine.

II. EXPERIMENTATION

For the conducting experimental trials, the ACE make CNC model Simple Turn-5075 Siemens 802C is employed (see Figure 4). First of all, it is very important to select process with process parameters and their levels.

In the research work, machining parameters such as cutting speed, feed rate, and depth of cut are selected for optimization of resultant vibration.The three parameter with three level are fixed with the help of insert manual and machining hand book (see Table.I).In the present research work, we are going to utilize the Taguchi method for experiment design.The design of experiment is done with help of MINITAB 17 software and for this condition suited orthogonal array such as L27 is selected from the series of array.

TABLE I
Control Factors with Levels

Levels	Control Parameters		
	Cutting Speed (mm/min)	Feed Rate (mm/rev)	Depth of Cut (mm)
L1	100	0.1	0.4
L2	140	0.15	0.5
L3	180	0.2	0.6

The AISI M2 material rods with 60 mm diameter and 350 mm length are selected for experimental trials.The chemical analysis of AISI M2 material C-0.86/0.96, Cr-3.8/4.5, Mo-4.9/5.5, W-6.0/6.75, V-1.7/2.2[11] and the properties of AISI M2 are density-8.028×10-3g/mm3, melting point-46800, hardness-62-65 HRC, compressive yield strength-3250 Mpa, Poisson's ratio-0.27-0.30, elastic modulus-190-210 Gpa [11].In present work, rectangular shape PCBN CNMG 160408 insert(Kennametal company) is used as cutting tool used for turning hard AISI M2 specimen.The clearance angle of the selected insert is zero.The inscribed circle size is 9.5mm and thickness is 5mm.The tool holder such as PCLNR 2525M12 is employed to hold the insert. After designing experiment the experiment, it important to conduct all trials as per design of experiment.The RT-Pro photon software is first installed in the laptop to support FFT analyser. The vibration signal frequency in three direction (Vx, Vy, and Vz) are measured using FFT analyser with three axis accelerometer (see Figure 1, Figure 2, and Figure 3) and after measuring signals,the resultant vibration signals are calculated by Equation (1) .

$$Vr = \sqrt{(Vx)^2} + \sqrt{(Vy)^2} + \sqrt{(Vz)^2} \qquad (1)$$

The values of resultant vibrations are inserted in the already design of experiment table in MINITAB 17 software.After inserting resultant vibration signals in the MINITAB 17 software, the signal to noise ratios for each trial is calculated by applying the smaller is better condition.

$$S/N = -10 \times log(\Sigma(Y^2)/n)) \qquad (2)$$

Where, S/N-Signal to Noise Ratio, Yi – ith observed value of the response, n - Number of observations in a trial, Y - Average of observed responses values.

Figure 1 3-Axis Accelerometer

Figure 2 FFT Analyser

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Figure 3 Computer System with RT-Pro Photon Software and FFT Analyser

Figure 4 Experimental Unit (VIIT, Pune)

The calculation of signal to noise ratios with help of MINITAB17 software is shown in following Table II.

TABLE II
Conduction Of Experiment For Collection Of Vibration Signals And S/N Ratios

Expt. No.	Cutting Speed	Feed Rate	Depth of Cut	Vx (Hz)	Vy (Hz)	Vz(Hz)	Vr (Hz)	S/N Ratio (dB)
1	100	0.1	0.4	1999	0519	1956	2844.52	-69.08
2	100	0.1	0.5	1996	1996	1973	3443.94	-70.74
3	100	0.1	0.6	1951	1968	1961	2766.56	-68.84
4	100	0.15	0.4	1977	1979	1977	3425.41	-70.69
5	100	0.15	0.5	1975	1987	1929	3401.44	-70.63
6	100	0.15	0.6	1989	1996	1989	3449.09	-70.75
7	100	0.2	0.4	1991	1995	1916	3408.10	-70.65
8	100	0.2	0.5	1966	1966	1966	3405.21	-70.64
9	100	0.2	0.6	1970	1893	1921	3339.84	-70.47
10	140	0.1	0.4	1990	1990	1971	3435.84	-70.72
11	140	0.1	0.5	1949	1952	1930	3366.57	-70.54
12	140	0.1	0.6	1946	1946	1936	3364.80	-70.54
13	140	0.15	0.4	1994	1994	1951	3429.06	-70.70
14	140	0.15	0.5	1996	1985	1955	3427.28	-70.70
15	140	0.15	0.6	1987	1999	1943	3423.36	-70.69
16	140	0.2	0.4	1996	1993	0513	2866.92	-69.15
17	140	0.2	0.5	1995	1987	1952	3426.14	-70.70
18	140	0.2	0.6	1995	1993	1959	3433.62	-70.72
19	180	0.1	0.4	582	1938	1708	2647.98	-68.46
20	180	0.1	0.5	1738	1966	1939	3262.74	-70.27
21	180	0.1	0.6	0577	1980	1910	2810.94	-68.98
22	180	0.15	0.4	1980	1989	1989	3439.86	-70.73
23	180	0.15	0.5	0501	1990	1959	2827.03	-69.03
24	180	0.15	0.6	1998	1997	1930	3421.24	-70.68
25	180	0.2	0.4	1997	1990	1990	3450.82	-70.76
26	180	0.2	0.5	1942	1993	1936	3389.91	-70.60
27	180	0.2	0.6	1961	1962	1942	3386.19	-70.59

III. OPTIMIZATION AND ANALYSIS FOR RESULTANT VIBRATION SIGNAL

A. Optimum Predicted Resultant Vibration Signal

The optimum value of resultant vibration can be calculated by manually hand calculation as well as using MINITAB 17 software. Let V'= average results for 27 runs of resultant vibration value = 3270.17Hz.

$$Vr\ (optimum) = V' + (An1 - V') + (Bn2 - V') + (Cn3 - V') + (Dn4 - V') \quad (3)$$

Where An1, Bn2, Cn3 and Dn4 are corresponding mean values of optimum points indicated in S/N graph.

Now putting all values in equation (2), we get following step

$$= 3270.17 + (3182 - 3270.17) + (3105 - 3270.17) + (3217 - 3270.17)$$
$$= 2963.66$$

Optimum surface roughness (Ra) by manual hand calculation = 2963.66 Hz

Now,calculating optimum resultant vibration (Vr) by using MINITAB17software.

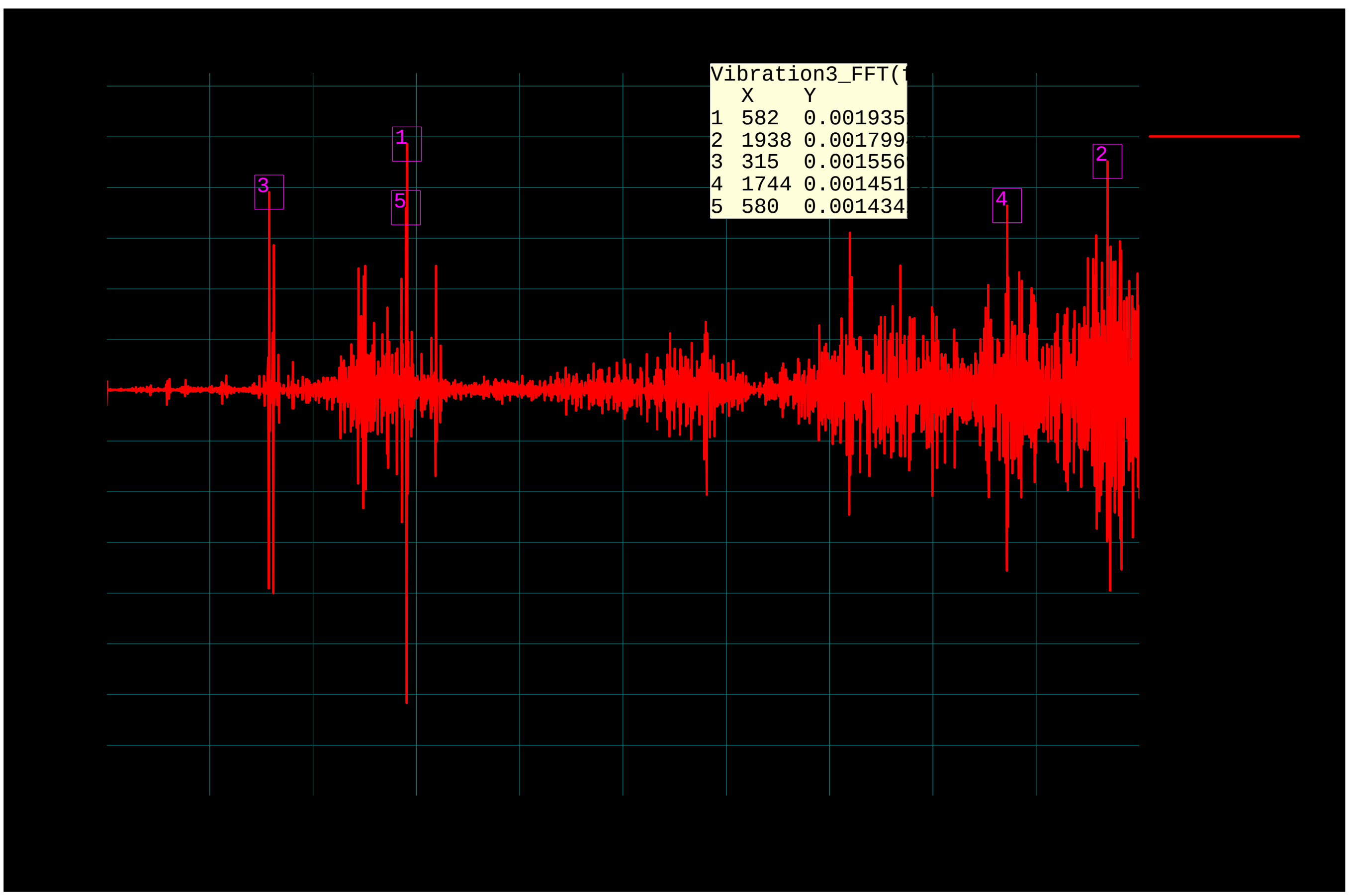
So, optimum resultant vibration (Vr) predicted by MINITAB 17 software = 2829.82Hz.

From the above calculation, the conclusion can be drawn that there is a minor error (133.84Hz) between manually and software predicted optimum resultant vibration value and therefore it is proved that the optimum resultant vibration value is accurately calculated.

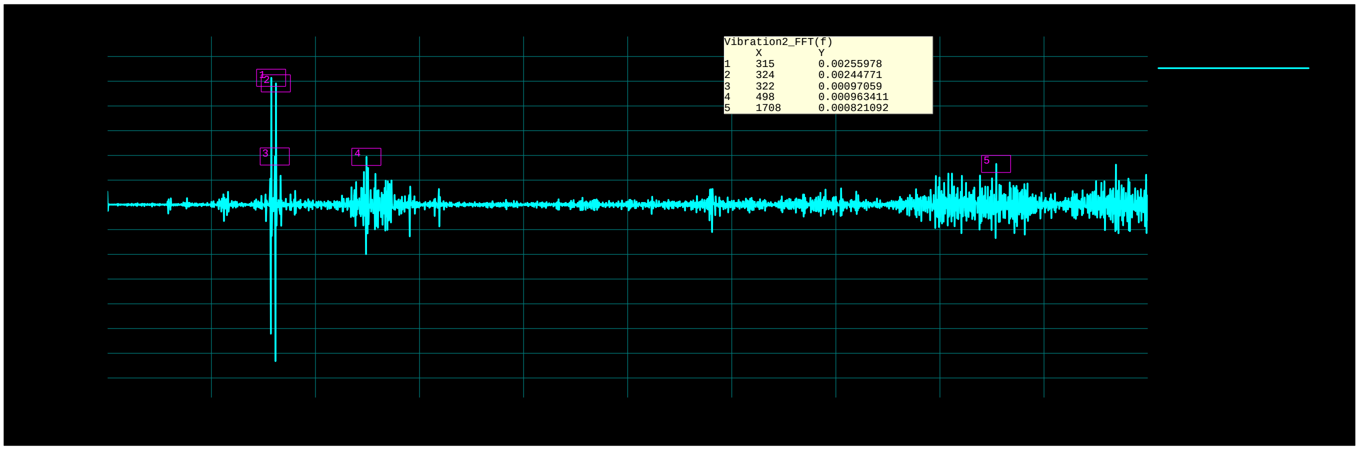
TABLE III
RESPONSE TABLE FOR MEANS

Level	Cutting Speed	Feed Rate	Depth of Cut
1	3276(A1)	3105(B1)	3217(C1)
2	3353(A2)	3360(B2)	3328(C2)
3	3182(A3)	3345(B3)	3266(C3)
Delta	171	256	111
Rank	2	1	3

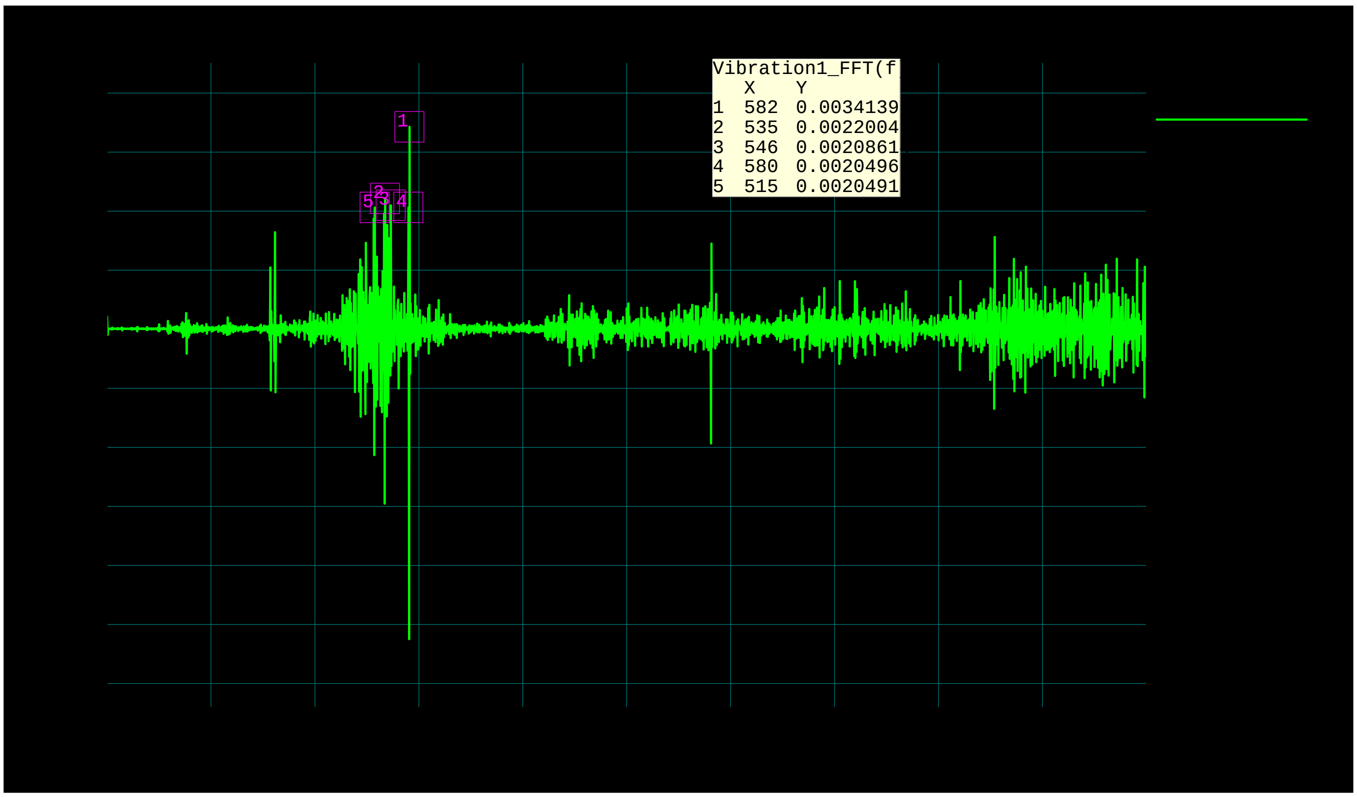
The mean value Table III shows that cutting speed of level A3, feed rate of B1 , and depth of cut C1 gives the minimum possible resultant vibration (optimum value of resultant vibration). The feed rate (rank1) is most affecting machining parameter on resultant vibration.The Figure 5 shows the typical time and frequency domain vibration signal obtained at optimum setting of machining parameters.This set of parameters gives minimum resultant vibration signals which results in better tool life, better surface finish and less setting time so better productivity can be achieved.



(a) Typical Frequency Domain Vibration Signal ‘Y’ Direction (Vy) in Hertz



(b) Typical Frequency Domain Vibration Signal 'Z' Direction (Vz) in Hertz



(c) Typical Frequency Domain Vibration Signal 'X' Direction (Vx) in Hertz

Figure 5 Typical frequency domain vibration signals obtained at optimum level i.e. cutting speed =180 mm/min, feed rate = 0.1mm/rev, and depth of cut = 0.4 mm in Vx, Vy, and Vz directions.

B. Analysis of Variance for Resultant Vibration Signal

As there are a large number of variables regulating the process, some mathematical models are mandatory to represent the process. However, these models are to be established using only the significant parameters influencing the process rather than including all the parameters. In order to achieve this, statistical analysis of the experimental results will have to be processed using the analysis of variance (ANOVA).ANOVA is a statistical technique that enables the estimation of the relative contributions of each of the control factors to the overall measured response. From Table IV, it can be concluded that feed rate is most significant factors which affect the resultant vibration.

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Table iv
Application of anova for s/n ratios

Source	DOF	Seq.SS	Adj.SS	Adj.MS	F	P
Cutting Speed	2	1.0552	1.0552	0.5276	1.26	0.334
Feed Rate	2	2.9258	2.9258	1.4629	3.50	0.059
Depth of Cut	2	0.4729	0.4729	0.2365	0.57	0.589
Cutting Speed* Feed Rate	4	2.9931	2.9931	0.7483	1.79	0.224
Cutting Speed * Depth of Cut	4	0.6863	0.6863	0.1716	0.41	0.797
Feed Rate * Depth of Cut	4	2.9537	2.9537	0.7384	1.77	0.229
Residual Error	8	2.9537	3.3434	0.4179		
Total	26	3.3434				
S = 0.6465 R-Sq. = 76.8% R-Sq.(adj.) = 24.7%						

IV. RESULTS AND DISCUSSIONS

A. Effect of Cutting Speed on Resultant Vibration Signal

Figure 7 indicates the evolution of resultant vibration signal according to the cutting speed. Figure 7 shows that the resultant vibration signal initially increases with increase in cutting speed up to 140 mm/min and then decreases sharply with increase in cutting speed up to 180 mm/min.Figure 6 shows that at 180 mm/min, the resultant vibration signal is at an optimum level means we will get the smooth operation with minimum resultant vibration at 180 mm/min.The feed rate is a most influencing factor for the resultant vibration signal.

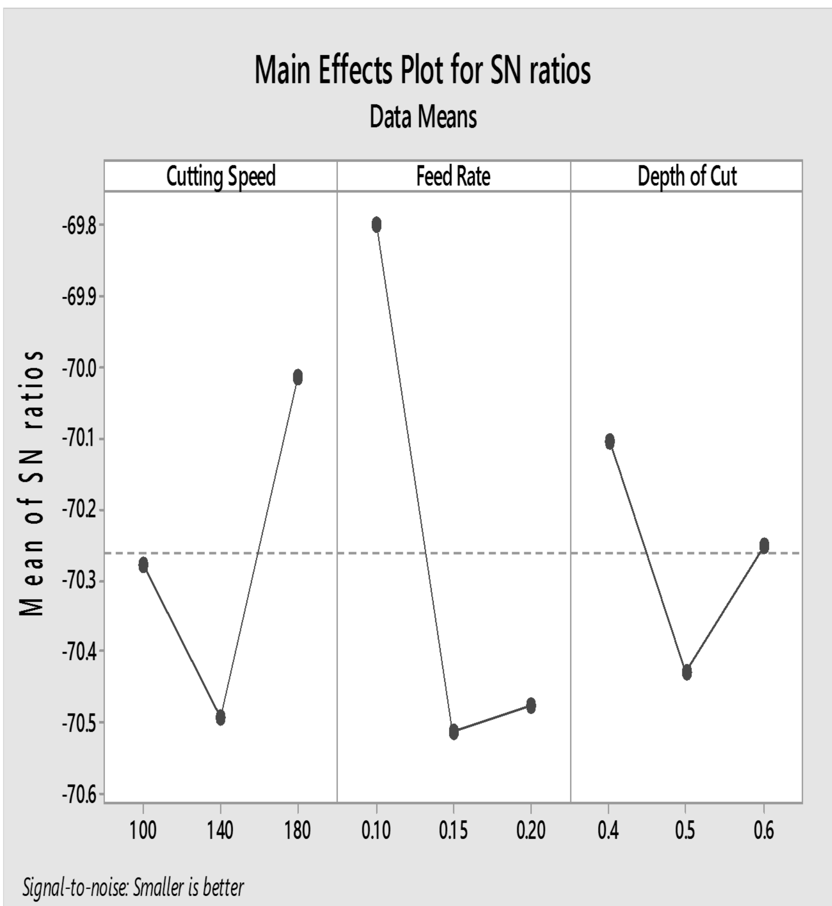

Figure 6 Main Effects Plot for SN Ratios

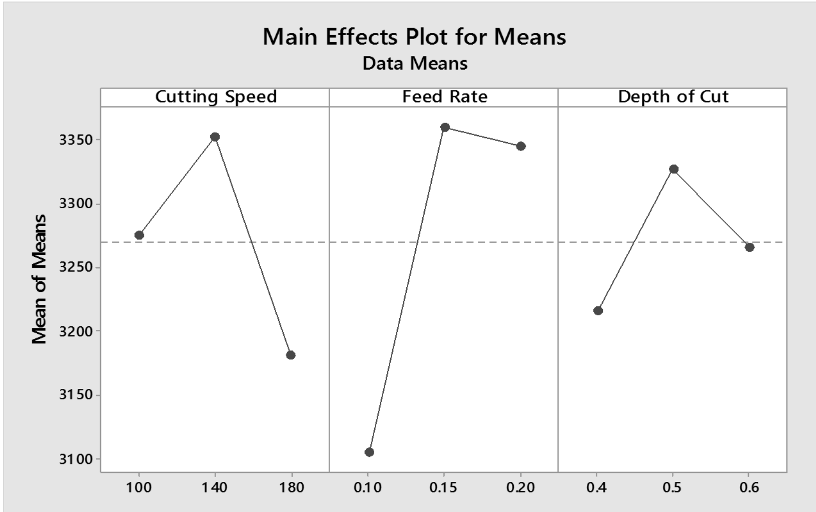

Figure 7 Main Effects Plot for Means

B. Effect of Feed Rate on Resultant Vibration Signal

Figure 7 illustrates the evolution of resultant vibration signal according to the feed rate. Figure 7 shows that the resultant vibration signal initially increases sharply with increase in feed rate up to 0.15 mm/rev and then decreases sharply with increase in feed rate up to 0.2 mm/rev. Figure 6 shows that at 0.1 mm/rev feed rate, the resultant vibration signal is at an optimum level means it gives minimum vibrational signal at 0.1 mm/rev feed rate.

C. Effect of Depth of Cut on Resultant Vibration Signal

Figure 7 shows the evolution of resultant vibration according to the depth of cut. Figure 7 shows that the resultant vibration signal initially increases sharply with the increase in the depth of cut up to 0.5 mm and then decreases sharply with increase in depth of cut up to 0.6 mm. Figure 6 shows that at 0.4 mm depth of cut, the resultant vibration signal is at an optimum level means it gives minimum vibration signal at 0.4 mm depth of cut.

D. Interaction Plots for Signal to Noise Ratios of Resultant Vibration Signals

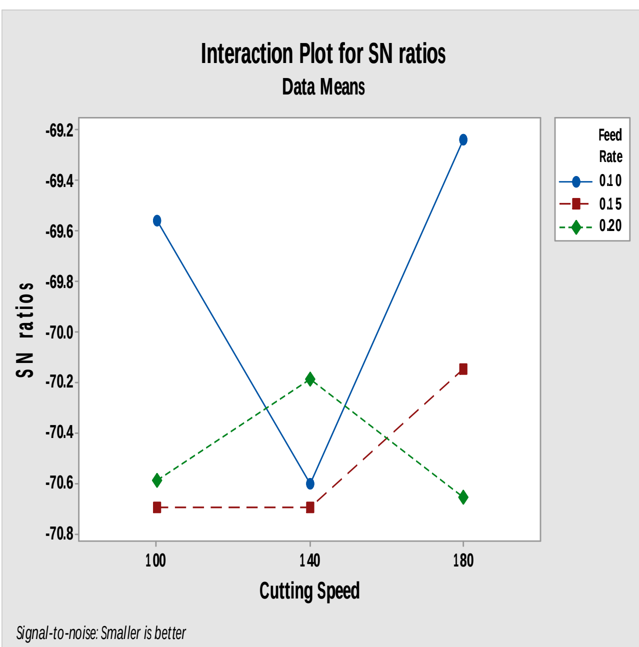

Figure 8 (a) Interaction Plot for S/N ratios Considering Feed Rates and Cutting Speeds

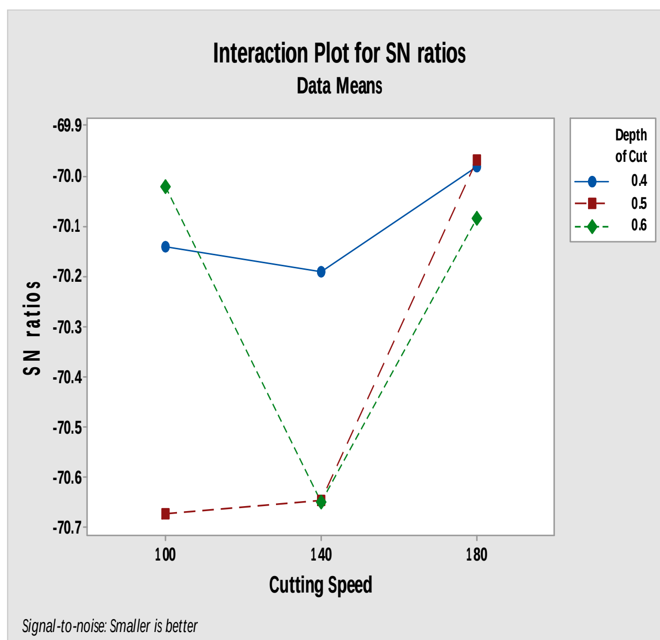

Figure 8. (b) Interaction Plot for S/N ratios Considering Depth of Cuts and Cutting Speeds

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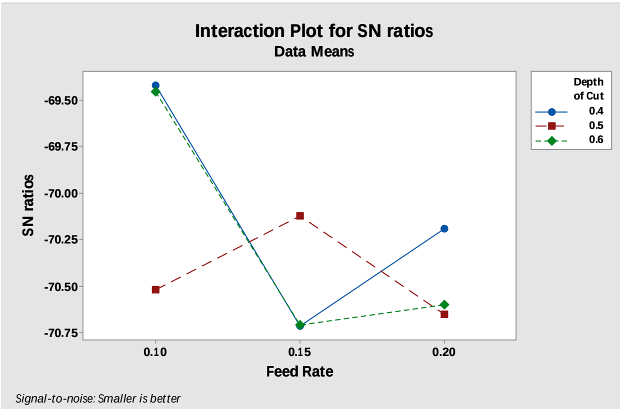


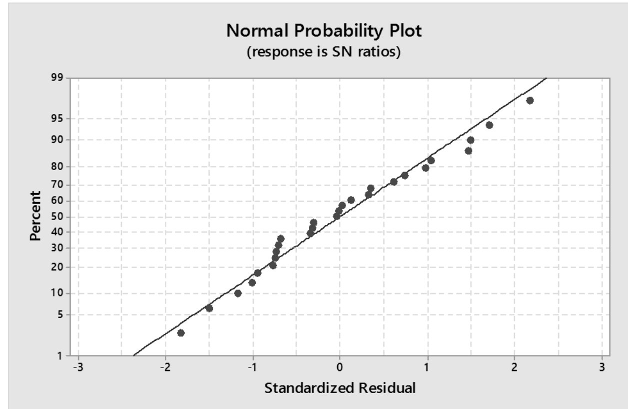
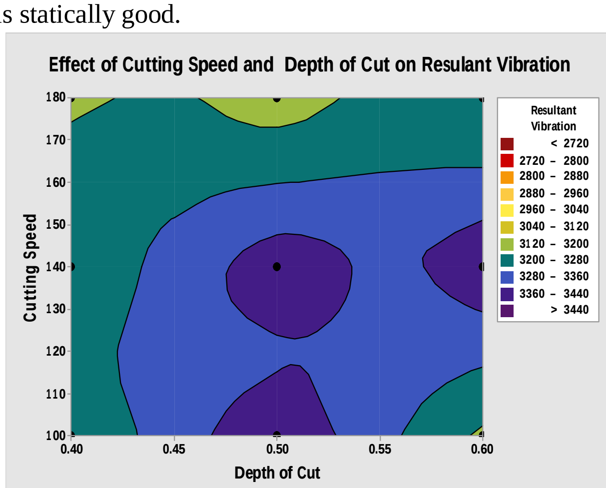


Figure 8.(c) Interaction Plot for S/N ratios Considering Feed Rates and Depth of Cuts

Figure 8. (d) Normal Probability Plot for Single to Noise Ratios

Figure 8 shows the interaction plots for the signal to noise ratios of resultant vibration signal with normal probability plot. In Figure 8 (a) the green dotted line shows 0.20 mm/rev feed rate, the blue continuous line shows 0.10 mm/rev feed rate, and the red dotted line shows 0.15 mm/rev feed rate.The feed rate 0.10 mm/rev gives the maximum value of the signal to noise ratio at cutting speed of 180 mm/min means interaction of these two factors gives optimum resultant vibration signal value.In Figure 8 (b) the green dotted line shows 0.6 mm depth of cut, the blue continuous line shows 0.4 mm depth of cut and red dotted line shows 0.5 mm depth of cut.The depth of cut of 0.4 mm gives the maximum value of the signal to noise ratio at cutting speed of 180 mm/min means interaction of these two factors gives optimum resultant vibration signal value.In Figure 8 (c) the green dotted line shows 0.6 mm depth of cut, the blue continuous line shows 0.4 mm depth of cut and the red dotted line shows 0.5 mm depth of cut.The depth of cut of 0.4 mm gives the maximum value of the signal to noise ratio at a feed rate of 0.10 mm/rev means interaction of these two factors gives optimum resultant vibration signal value.Figure 8 (d) shows the probability plot for the response which is the signal to noise ratio of resultant vibration signal.It shows that all signal to noise ratio values follows the straight line means our model is statically good.



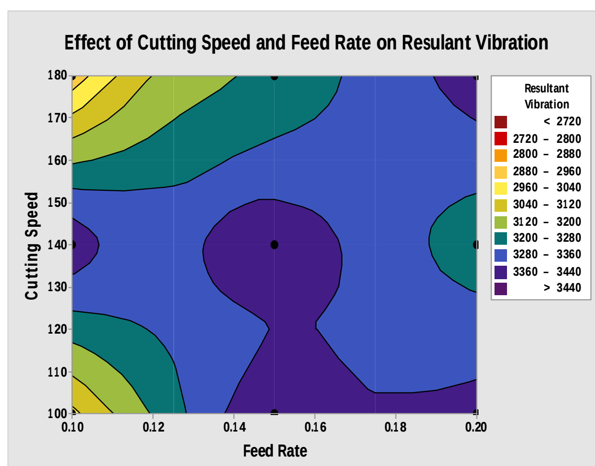


Figure 9 (a) Counter Plot to Study Influence of Cutting Speed and Depth of Cut on a Resultant Vibration Signal

Figure 9. (b) Counter Plot to Study Influence of Cutting Speed and Feed Rate on a Resultant Vibration Signal

Figure 9 (a) shows the counter plot to investigate the influence of cutting speed and depth of cut on a resultant vibration signal. It shows that the resultant vibration signal is minimum in the area of cutting speed range from 170 mm/min to 180 mm/min and depth of cut range from 0.40 mm and Figure 9 (b) shows that shows the counter plot to investigate the influence of cutting speed and feed rate on a resultant vibration signal .It shows that the resultant vibration signal is minimum in the cutting speed range from 175 mm/min to 180 mm/min and feed rate range from 0.10 mm/rev to 0.12 mm/rev.

V. VALIDATION OF RESULT

In order to validate the results obtained six confirmation trials are conducted for the resultant vibration signal at optimal levels of the process variables.The average values of the characteristic are obtained and compared with the predicted values.The results are given in Table V. The value of resultant vibration signal obtained through confirmation experiments is within the 95% of CI of respective response characteristic.It is to be pointed out that these optimal values are within the specified range of process variables.

Table v
Confirmation test for resultant vibration signal

Sr. No.	Optimum Value of Parameters	Optimum Level of Parameters	Optimum Predicted Resultant Vibration (Hz)	Optimum Experimental Resultant Vibration (Hz)	Error (Hz)
1.	Cutting Speed = 180 mm/min Feed Rate = 0.1 mm/rev Depth of Cut = 0.4 mm	A3	2830	3032	202
2.		B1	2830	3156	326
3.		C1	2830	3278	448
4.			2830	3345	515
5.			2830	3245	415
6.			2830	3436	606
		Average	2830	3249	419

The diagnosis test performs with help of MINITAB17 software to find confidence interval for the resultant vibration signal and it shows that the value of resultant vibration signal obtained through confirmation experiments are within the 95% of CI of respective response characteristic.i.e.$3183 \leq 3249 \leq 3357$.

VI. CONCLUSIONS

The turning trials are conducted on the hard AISI M2 specimens using the PCBN insert with 0.8 mm nose radius.The influences of cutting speed, feed rate, and depth of cut are investigated by Taguchi and ANOVA on the resultant vibration signals.Based on the results obtained, the following conclusions are drawn:

A. It is observed that the feed rate is most significant machining parameter which affects the resultant vibration signal most as p the analysis of variance (ANOVA) while hard turning of AISI M2 on a CNC machine.

B. The optimum level of process parameters is A3, B1, and C1 with a 0.8 mm nose radius of the PCBN insert (i.e. cutting speed= 180 mm/min, feed rate= 0.1 mm/rev, and depth of cut = 0.4 mm) for the hard turning of AISI M2 on a CNC machine.

C. The optimum value of resultant vibration signal at optimum level of machining parameters is 3249 Hz (Experimentally Value of Resultant Vibration Signal).

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