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Suppression of Machine Tool Vibration Using Passive Damping

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ABSTRACT

Vibration in machine components is a common phenomenon and reducing the amplitude of vibrations is one of the critical tasks. So, Passive damping is now the major means of suppressing unwanted vibrations. Passive damping for any structure is usually based on one of four damping mechanisms: Viscoelastic materials, viscous fluids, magnetic or passive piezoelectric. Approximately 85 percent of the passive damping treatments in actual applications are based on viscoelastic materials. In the present work, attempt is made to predict and reduce the vibration level of cutting tool in CNC lathe using passive damping pad of viscoelastic material called Silicon. In this work, the effects of cutting parameters on machine tool vibration were experimentally investigated. The experimentation is carried out on CNC lathe for dry turning of SS304 work piece material using single point carbide tool inserts of varying tool nose radius. Three levels for spindle speed, depth of cut, feed rate and tool nose radius were chosen as cutting variables. Design of Experiment approach is selected for investigating the effect of varying controllable parameters on tangential acceleration. The Taguchi method L_{27} orthogonal array was applied to design of experiment. The amplitude of vibration is measured with the help of tri-axial accelerometer for with and without damping condition. This work highlights about the effect of cutting parameters on the tool vibration during machining using and optimizes the multi response parameters on turning operation using optimization techniques like Taguchi Method, Regression Analysis etc.

Keywords— **ANOVA, Cutting Parameters, Passive Damping, Taguchi Method.**

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I. INTRODUCTION

In all the cutting operations like turning, boring and milling, vibration is a common problem. Vibration in machine tool affects the performance of a machine, tool life and surface finish of the work material in turning process. Today, the standard procedure adopted to avoid vibration during machining is by careful planning of the cutting parameters and damping of cutting tool.

There have been many investigations on vibration prediction and controlling based on periodic measurements of various machining conditions using accelerometer and active vibration controller .Y. Altintas et.al. [1] presented the integrated vibration avoidance and contouring error compensation algorithm for multi-axis machine tools. They developed an integrated method which shapes the trajectory commands in such a way that they do not excite the structural modes. B. Chen et.al. [2] proposes a reliability estimation approach to cutting tools based on a logistic regression model by using vibration signals. The results show the effectiveness of the proposed model that facilitates machine performance and reliability estimation. A I Sette et.al. [3] described a cutting-force-based vibration analysis to ascertain the effect of the tool entering angle on tool vibration and tool life in a titanium alloy milling operation. It shows that a tool with a higher entering angle and round inserts associates radial load to higher frequencies, at which the tool does not behave as a rigid body. This led to cutting edge breakage that shortened the tool life. Therefore, a productive milling operation on Ti–6Al–4V alloy and a long tool life requires reduced tool vibration. Lower vibration will prevent cutting edge breakage caused by fatigue, after which the problem of reducing tool wear can be tackled. H. Wang et.al. [4] Presented a theoretical and experimental investigation of the influence of tool-tip vibration on surface generation in single point diamond turning (SPDT). Thus, results shows that the tool-tip vibration and the process damping effect are regarded as the prime influences on surface roughness. D.E. Dimla Sr. and P.M. Lister [5] suggested that ASPS(Automated Sensory and Signal Processing Selection System) approach can be implemented to reduce the cost and complexity of the condition monitoring system and the number of sensors required for fault identification of milling cutters without compromising the system's ability to detect cutter faults. A.H. El-Sinawi, Reza Kashani [6] a new Kalman estimator-based feed-forward control scheme was developed and employed to reduce the vibration transmitted to the tool through the machine-tool structure. The transmitted force enables the successful isolation of the tool from the vibration of the machine-tool structure improving the surface finish of turned workpiece. Marcus A. Louroza et.al [7] investigated the possibility of using the Coulomb damping to reduce the vibrations of structures submitted to human loadings. A computational–theoretical model was developed to represent a structural system with Coulomb damping having two degrees of freedom.

From the literature review of machine tool vibration, passive damping is the major means of suppressing unwanted vibrations. In the present work attempt has been made to predict and suppressing the transverse vibration level of cutting tool in CNC lathe for dry turning of SS304, by using passive damping pad of viscoelastic material called Silicon. These vibrations are minimized by controlling the cause parameter and suppressing peak acceleration by using damping method.

II. EXPERIMENTATION

The experimental setup consists of lathe machine and FFT analyzer. The experimental setup is shown in Fig.1.

Main objective of the research work is to monitor the vibration level of cutting tool. So it is assumed that the condition of the machine and its components is good in all other aspects such as foundation of the machine, rigidity of the machine components like bed, spindle, tail stock etc. The simplest vibration analysis is conducted through collecting the overall vibration amplitude Root Mean Square (RMS) value and plotting the vibration data in time domain and frequency domain.

For the experiment purpose three inserts of triangular shape having tool nose radius 0.4mm, 0.8mm and 1.2mm is used, manufactured by SANDVIK Company. Stainless Steel 304 of diameter 30 mm is selected as a workpiece material in the experiment. The chemical composition and mechanical properties of SS304 is shown in Table II and Table III. Silicon is used as a damper material. Detailed properties of damping material are given below in tabulated form as shown in Table IV.

TABLE IV
PROPERTIES OF DAMPING MATERIAL

Sr. No.	Materials Properties	Silicon
1	Hardness	50-55 BHN
2	Temperature	-62 to 216 degree
3	Thermal Conductivity	0.2 to 0.21 W/m-k
4	Tensile Strength	11 N/mm^2
5	Tear Strength	9.8 KN/mm^2

Design of Experiment (DOE) approach is selected for investigating the effect of varying controllable parameter on tangential acceleration, since Taguchi design of 27 runs is efficient to study the effect of two or more factors. These three levels of factor are referred as low level, intermediate level & high level. For the present work the amplitude of vibration in tangential direction is measured for with and without damping condition. Tool without damper and with damper is shown in Fig 2. The experimental observations obtained are shown in Table V.

III. METHODOLOGY

Design of Experiment (DOE) approach is selected for investigating the effect of varying controllable parameters on tangential acceleration. Numbers of experiments to be performing are decided with the help of Taguchi Method & MINITAB 15 software. It is assumed that inherent vibration, tool wear and L/D are constant throughout experimentation and Tool Nose Radius, Cutting Speed, Depth of cut, & feed rate are varied at different levels. This research work highlights the influence of cutting parameters on the transverse tool vibration during machining using and optimizes the multi response parameters on turning operation using optimization techniques like Taguchi Method, Regression Analysis, and ANOVA etc.

After pre-experimentation, the number of levels for each factor considered in this DoE is as shown in Table-I.

TABLE I
MACHINING PARAMETERS AND THEIR LEVELS

Parameters	**Level 1**	**Level 2**	**Level 3**
Spindle speed (rpm) X1	420	520	620
Depth of cut (mm) X2	0.4	0.5	0.6
Feed rate(mm/rev) X3	0.15	0.2	0.25
Nose Radius(mm) X4	0.4	0.8	1.2

As the number of experiments were too many in full factorial design which involves more machining time and cost, DoE was applied using Taguchi design to get an optimal number of experiments thereby reducing the machining time and cost involved. Taguchi method uses a special set of array called orthogonal array. The Taguchi method L_{27} orthogonal array for four factors with three levels was applied to design of experiment.

IV. RESULTS AND DISCUSSION

Fig.3 shows the comparison of with damper and without damper based on Tangential Acceleration. It is observed that by using Silicon damper tangential acceleration is reduced to a great extent as compared to undamped condition. Silicon damper absorbed 41.75% of Tangential acceleration.

Regression Analysis: Based on the experimental results, the statistical analysis software system MINITAB 15 is used for linear regression analysis of damped and undamped condition. A regression equation was developed for each desired output. The regression coefficients are estimated by regression analysis.

Fig.1. Experimental Setup

TABLE II
CHEMICAL COMPOSITION OF SS 304 [8]

Grade	**C (%)**	**Mn (%)**	**Si (%)**	**P (%)**	**S (%)**	**Cr (%)**	**Ni (%)**	**N (%)**
SS 304	0.08max	2.0	0.75	0.045	0.030	18-20	8-10.5	0.1

TABLE III
MECHANICAL PROPERTIES OF SS304 [8]

Grade	Tensile strength (Mpa)	Yield Strength 0.2% Proof (Mpa) min	Elongation (%in50mm)min	Rockwell B (HR B) max	Brinell (HB) max
SS 304	515	205	40	92	201

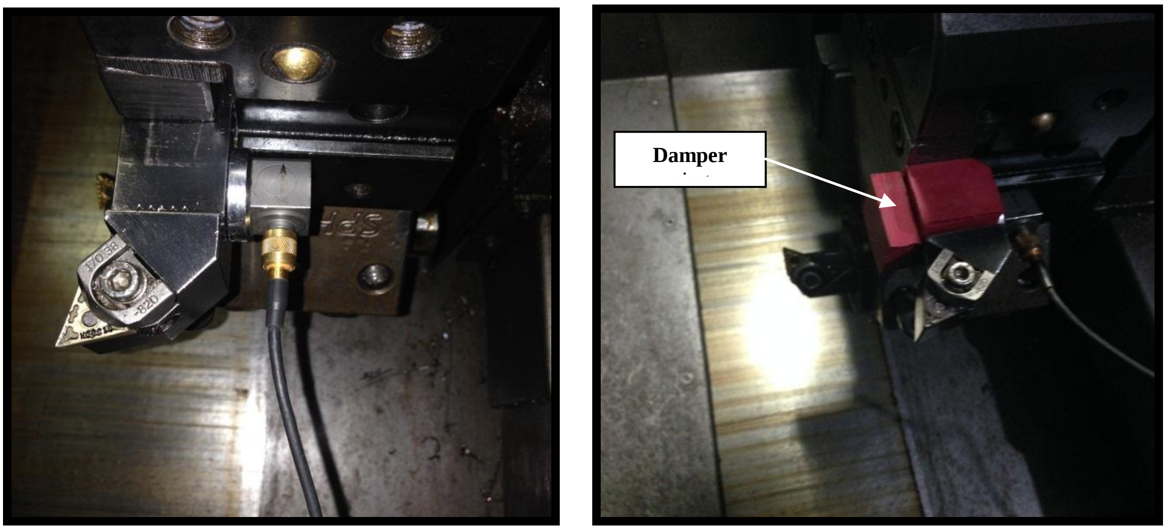
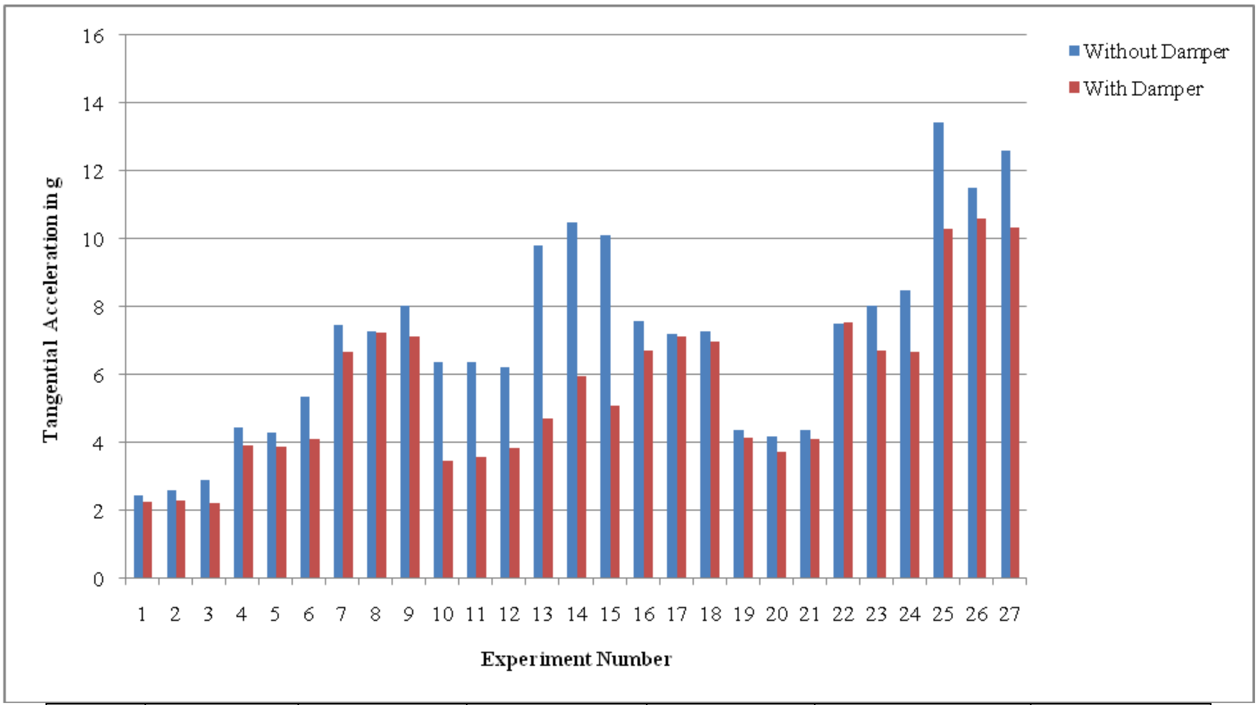


Fig.2 Machine-tool without damper and with damper

TABLE V
OBSERVATIONS FOR SILICON DAMPER

SR. NO.	Nose Radius (mm)	Spindle Speed (rpm)	Depth of Cut (mm)	Feed Rate (mm/rev)	Amplitude of Acceleration of cutting tool in g — Tangential Direction (RMS)	
					Without Damper	With Damper
1	0.4	420	0.4	0.15	2.44	2.27
2	0.4	420	0.4	0.15	2.62	2.31
3	0.4	420	0.4	0.15	2.89	2.22
4	0.4	520	0.5	0.2	4.45	3.92
5	0.4	520	0.5	0.2	4.29	3.90
6	0.4	520	0.5	0.2	5.36	4.13
7	0.4	620	0.6	0.25	7.47	6.69
8	0.4	620	0.6	0.25	7.30	7.24
9	0.4	620	0.6	0.25	8.05	7.14
10	0.8	420	0.5	0.25	6.36	3.47
11	0.8	420	0.5	0.25	6.37	3.58
12	0.8	420	0.5	0.25	6.21	3.85
13	0.8	520	0.6	0.15	9.80	4.70



14	0.8	520	0.6	0.15	10.50	5.95
15	0.8	520	0.6	0.15	10.10	5.09
16	0.8	620	0.4	0.2	7.60	6.73
17	0.8	620	0.4	0.2	7.22	7.12
18	0.8	620	0.4	0.2	7.27	6.98
19	1.2	420	0.6	0.2	4.39	4.14
20	1.2	420	0.6	0.2	4.20	3.72
21	1.2	420	0.6	0.2	4.37	4.10
22	1.2	520	0.4	0.25	7.51	7.55
23	1.2	520	0.4	0.25	8.02	6.71
24	1.2	520	0.4	0.25	8.50	6.69
25	1.2	620	0.5	0.15	13.45	10.3
26	1.2	620	0.5	0.15	11.5	10.6
27	1.2	620	0.5	0.15	12.6	10.35

Fig.3. Comparison of with and without Damper Based on Tangential Acceleration

The regression equation for tangential acceleration with Silicon damper is obtained as follows:
Tangential Acceleration =3.38 N R + 0.0241 SS +0.105 DoC - 0.967 FR -9.51……………………….. (i)

TABLE VI

REGRESSION FOR TANGENTIAL ACCELERATION WITH SILICON DAMPER

Regression Statistics				
Multiple R	**R Square**	**Adjusted**	**Standard**	**Observations**

		R Square	Error	
0.9605	0.9226	0.9085	0.7254	27

Table VI shows the regression analysis for tangential acceleration. The value of adjusted R square is 90.85% and is a decrease of 1.41 % R square value indicate that the degree of closeness of variable with best fit line. The value of R square which is 0.9226 indicates that the degree of closeness of the parameters with the best fitted line is 92.26 %. It shows that the parameters are strongly correlated with each other.

ANOVA Analysis: Vibration data values were analyzed using Analysis of Variance (ANOVA) method to understand the influences of the cutting parameters on transverse vibration. Cutting parameters such as depth of cut, feed rate, and spindle speed were considered as input and transverse vibration is considered as output parameter during this ANOVA analysis.

In the ANOVA results, F-test values were used at 95% confidence level to decide the significant factors affecting the machine tool vibration. As per ANOVA analysis, for a particular cutting parameter the P value less than 0.05 (5%) and larger F value indicates the statistically significant effects on the machine tool vibration in tangential direction.

The ANOVA results of machine tool vibration for Taguchi design are as shown in Table VII and VIII:

TABLE VII
ANOVA OF TANGENTIAL ACCELERATION FOR SILICON DAMPER

	df	SS	MS	F	Significance F
Regression	4	138.034	34.508	65.565	6.65291E-12
Residual	22	11.579	0.526		
Total	26	149.613			

TABLE VIII
ANOVA OF TANGENTIAL ACCELERATION FOR SILICON DAMPER

Predictor	Coeff.	Standard Error	t Stat	P-value	Significance
Intercept	-9.518	1.458	-6.528	1.446E-06	Significant
X Variable 1	3.380	0.427	7.907	7.152E-08	Significant
X Variable 2	0.024	0.001	14.129	1.626E-12	Significant
X Variable 3	0.105	1.709	0.061	0.951	Not Significant
X Variable 4	-0.967	3.419	-0.282	0.780	Not Significant

The Table VII of ANOVA shows the degrees of freedom (df), sum of squares (SS), mean squares (MS), F-value (F) and P values. As the F value is 65.565, this indicates that the obtained models are considered to be statistically significant, which is desirable. It demonstrates that the cutting parameters used for the model have a significant effect on the tangential acceleration.

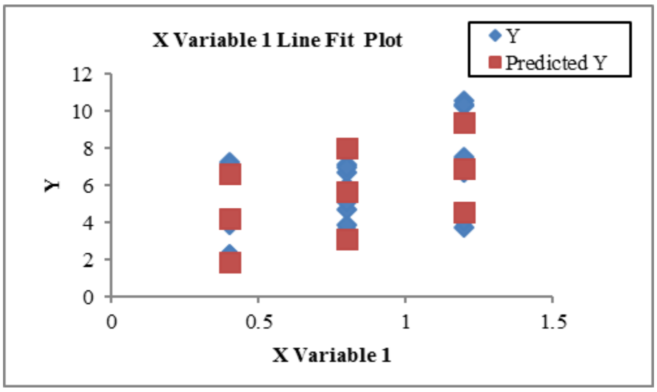
A low P-value (≤0.05) indicates statistical significance for the source on the corresponding response that is $\alpha = 0.05$, or 95% confidence level. From table VIII, it is concluded that the tool nose radius and spindle speed are the most significant parameters for machine tool vibration in tangential direction. Feed and depth of cut are insignificant parameters which does not contribute the machine tool vibration.

The results obtained for predicted acceleration and residual outputs are shown in Table IX.

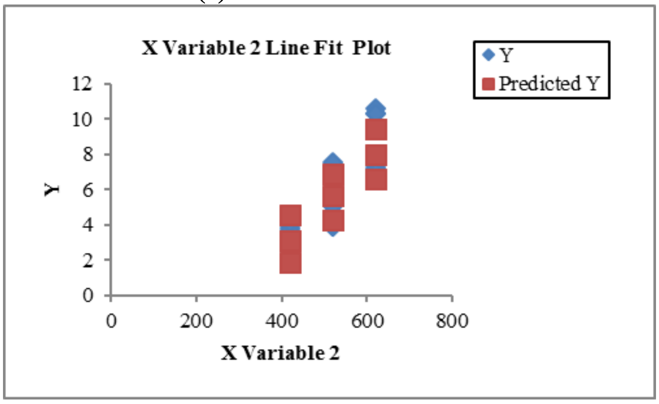
TABLE IX
PREDICTED RESULTS OF TANGENTIAL ACCELERATION FOR SILICON DAMPING

Observation	Predicted Y	Residuals
1	1.878703704	0.391296296
2	1.878703704	0.431296296
3	1.878703704	0.341296296
4	4.257037037	-0.337037037
5	4.257037037	-0.357037037
6	4.257037037	-0.127037037
7	6.63537037	0.05462963
8	6.63537037	0.60462963
9	6.63537037	0.50462963
10	3.144814815	0.325185185
11	3.144814815	0.435185185
12	3.144814815	0.705185185
13	5.668148148	-0.968148148
14	5.668148148	0.281851852
15	5.668148148	-0.578148148
16	8.014814815	-1.284814815
17	8.014814815	-0.894814815
18	8.014814815	-1.034814815
19	4.555925926	-0.415925926
20	4.555925926	-0.835925926
21	4.555925926	-0.455925926
22	6.902592593	0.647407407
23	6.902592593	-0.192592593
24	6.902592593	-0.212592593
25	9.425925926	0.874074074
26	9.425925926	1.174074074
27	9.425925926	0.924074074

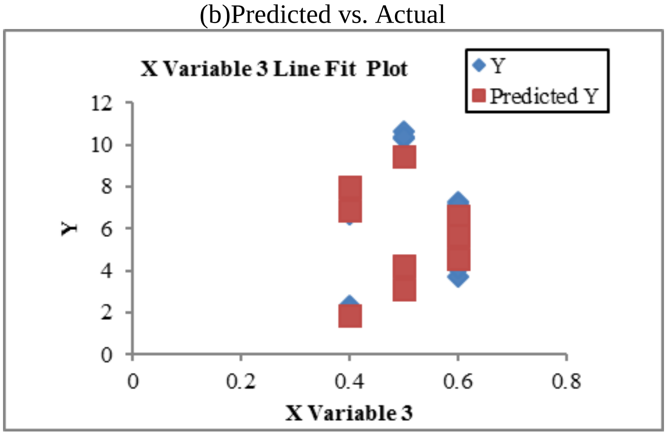
Fig.4 (a), (b), (c) and (d) show the line fit plot for actual acceleration and predicted acceleration. From this it is observed that the predicted and actual values are close to each other. Hence the model obtained is statistically significant.



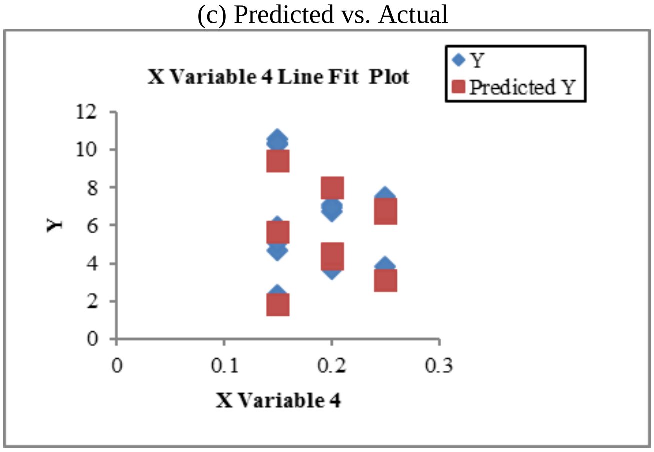
(a) Predicted vs. Actual



(b)Predicted vs. Actual



(c) Predicted vs. Actual



(d) Predicted vs. Actual

Fig.4 (a), (b), (c) and (d) shows the Comparison of Measured and Predicted values for (*NS, SS, DoC* and *FR*) with silicon damping

The regression equation for tangential acceleration without damper is obtained as follows:
Tangential Acceleration =4.120833 NR + 0.023672SS +6.727778 DoC - 11.2333 FR - 9.6553……………… (ii)

TABLE X
REGRESSION FOR TANGENTIAL ACCELERATION WITHOUT SILICON DAMPER

Regression Statistics				
Multiple R	**R Square**	**Adjusted R Square**	**Standard Error**	**Observations**
0.853392	0.7283	0.6789	1.665	27

Table X shows the regression analysis for tangential acceleration without silicon damper. The value of adjusted R square is 67.89% and is a decrease of 4.94 % R square value indicate that the degree of closeness of variable with best fit line. The value of R square which is 0.7283 indicates that the degree of closeness of the parameters with the best fitted line is 72.83 %. It shows that the parameters are correlated with each other.

TABLE XI
ANOVA OF TANGENTIAL ACCELERATION WITHOUT SILICON DAMPER

	df	**SS**	**MS**	**F**	**Significance F**
Regression	4	163.599	40.899	14.741	5.37E-06
Residual	22	61.039	2.774		
Total	26	224.638			

TABLE XII
ANOVA OF TANGENTIAL ACCELERATION WITHOUT SILICON DAMPER

Predictor	**Coeff.**	**Standard Error**	**t Stat**	**P-value**	**Significance**
Intercept	-9.655	3.347	-2.884	0.0086	Significant
X Variable1	4.121	0.981	4.198	0.0003	Significant
X Variable 2	0.023	0.003	6.029	4.55E-06	Significant
X Variable 3	6.727	3.926	1.713	0.1006	Not Significant
X Variable 4	-11.233	7.852	-1.430	0.1665	Not Significant

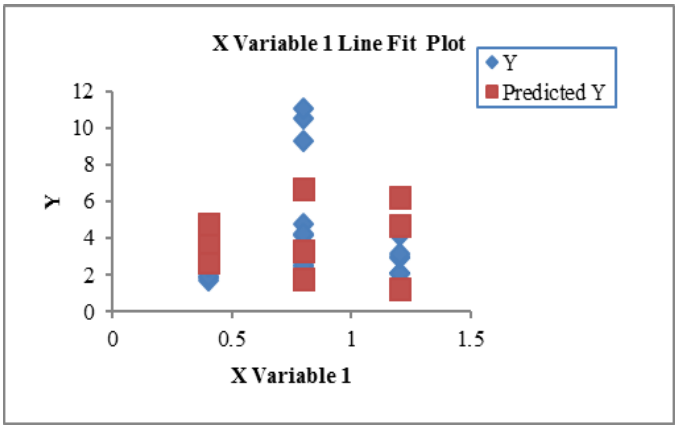
The Table XI and XII of ANOVA show that the F value is 14.74131; this indicates that the obtained models are considered to be statistically significant. It demonstrates that the cutting parameters used for the model have a significant effect on the tangential acceleration. It is

concluded that the tool nose radius and spindle speed are the most significant parameters for machine tool vibration in tangential direction. Feed and depth of cut are insignificant parameters which do not contribute to the machine tool vibration.
The results obtained for predicted acceleration and residual outputs are shown in Table XIII.

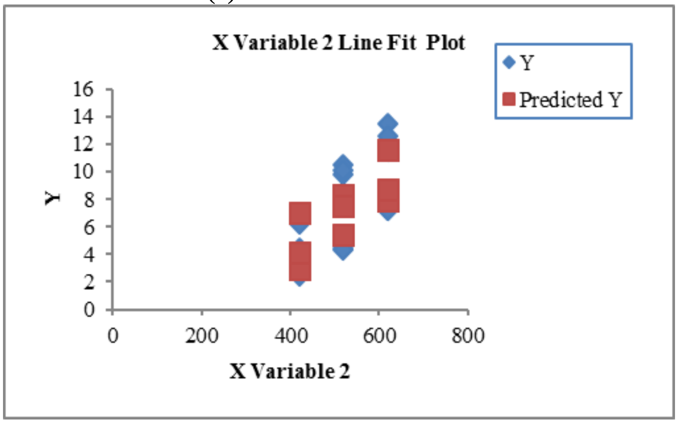
TABLE XIII
PREDICTED RESULTS OF TANGENTIAL ACCELERATION FOR WITHOUT SILICON DAMPING

Observation	Predicted Y	Residuals
1	2.941481	-0.501481481
2	2.941481	-0.321481481
3	2.941481	-0.051481481
4	5.419815	-0.969814815
5	5.419815	-1.129814815
6	5.419815	-0.059814815
7	7.898148	-0.428148148
8	7.898148	-0.598148148
9	7.898148	0.151851852
10	4.139259	2.220740741
11	4.139259	2.230740741
12	4.139259	2.070740741
13	8.302593	1.497407407
14	8.302593	2.197407407
15	8.302593	1.797407407
16	8.762593	-1.162592593
17	8.762593	-1.542592593
18	8.762593	-1.492592593
19	7.022037	-2.632037037
20	7.022037	-2.822037037
21	7.022037	-2.652037037
22	7.482037	0.027962963
23	7.482037	0.537962963
24	7.482037	1.017962963
25	11.64537	1.80462963
26	11.64537	-0.14537037
27	11.64537	0.95462963

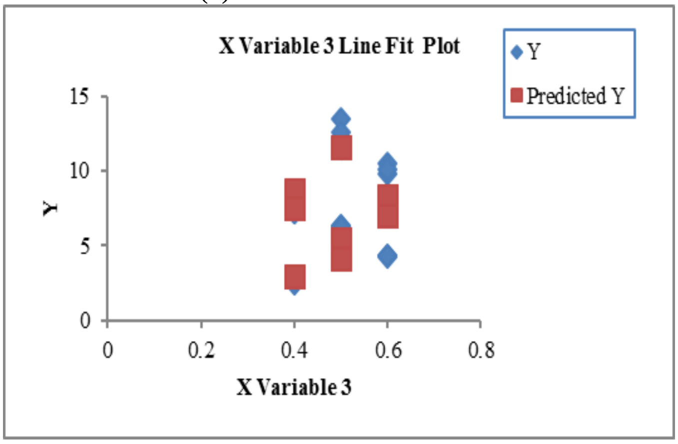
Fig.5 (a), (b), (c) and (d) show the line fit plot for actual acceleration and predicted acceleration without damper. It is observed that the predicted and actual values are close to each other. Hence the model obtained is statistically significant.



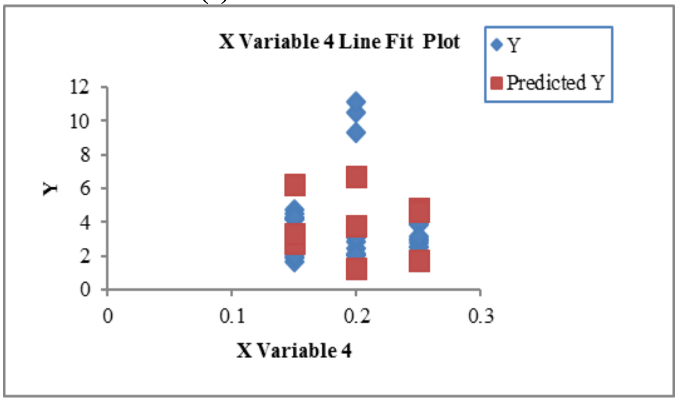
(a)Predicted vs. Actual



(b)Predicted vs. Actual



(c)Predicted vs. Actual



(d)Predicted vs. Actual

Fig.5 (a), (b), (c) and (d) Comparison of measured and predicted value for (*NS*, *SS*, *DoC* and *FR*) without damping

V. CONCLUSION

The effect of cutting parameters such as nose radius of cutting tool, spindle speed, depth of cut and feed rate on machine tool vibration is evaluated. The test results show that the developed method was successful. Based on the current study, the following conclusions can be drawn:

- Silicon damper absorbed 41.75% of tangential acceleration and vibration is reduced to great extent.
- Passive damping can provide substantial performance benefits in many kinds of structures and machines, often without significant weight or cost penalties. In all aspects of the studies performed, a significant reduction in tool vibration during machining was achieved for a CNC machining operations.
- From ANOVA shows that tool nose radius and spindle speed are the most influencing parameters for tangential acceleration.
- Tool nose radius, Spindle speed, depth of cut and feed rate are closely correlated to tangential acceleration.

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