Vibration Suppression of a Boring Tool by Particle Impact Damper
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***Abstract*— Particle impact damping is a passive vibration control technique in which metal particles of small size are placed within the enclosure attached to a vibrating structure. Particle-to-particle and particle-to-wall collisions arise under the vibrating motion of the structure. As a result particles and structure will exchange momentum and thus dissipate kinetic energy due to frictional inelastic losses.**

In the present study particle impact damping is used to suppress the vibrations of a boring tool in which a longitudinal hole is drilled and partially filled with metal particles. The effect of input parameters, tool overhang length, spindle speed, particle material and packing ratio on acceleration amplitude of the boring tool is studied. An attempt has been made to develop an elementary mathematical model which predicts the effect of system and damping parameters on vibration level of the tool tip by using dimensional analysis approach along with multiple regression method. The proposed mathematical model predicts effect of system and damping parameters on acceleration amplitude of boring tool with coefficient of determinant, R^2 = 0.962.

***Index Terms*—Particle damping, boring bar, vibration control, dimensional analysis, multiple regression method.**

I. Introduction

A boring tool can usually be characterized as a slender beam and is generally the weakest link in a machine tool system, and is thereby more sensitive to excitation forces. Many practical vibration isolation systems for machinery and tools and for floor and building have been developed. However, when these complicated isolation systems are applied to machine tools, machining costs may be increased. If the damping capacity of the machine structure can be improved without any additional apparatus or cost, it is more practical for machine tool operation.

Particle Impact Damping is a damping technique in which the energy dissipation takes place due to impact between particles and vibrating structure. The damping performance in a particle impact damper system depends on several parameters such as geometry of structure, damper parameters, vibration amplitude, material of particle, and packing ratio [1].

Several studies have been conducted to study the effectiveness of a particle impact damping system. S. Ema et.al, [2] presented fundamentals of impact dampers. Performance of impact dampers was investigated from free damped vibration generated when a step function input was supplied to a leaf spring with a free mass. Yasunori et.al, [3] experimentally analyzed the damping characteristics of a tubular structure for different packing configuration using various size balls. M. Saeki [4] experimentally investigated performance of a multi-unit particle damper in a horizontally vibrating system.

In the present work, the damping behavior of boring tool with particle damper under different cutting conditions is studied. An elementary mathematical model is developed which determines the damping behavior of boring tool under different operating cutting conditions and system parameters by using dimensional analysis along with multiple regression method.

II. Experimental Analysis

To assess the dynamic behaviour of boring tool while performing boring operations two boring tools are selected. Vibrations levels are measured for conventional solid boring tool and a hollow boring tool filled with particles. A 2-level full factorial design is used to evaluate the effect of four (4) independent variables (spindle speed, tool overhang length, particle material and packing ratio).

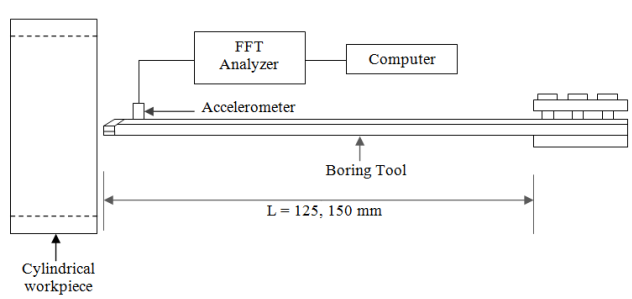

Fig. 1. Schematic of experimental apparatus.

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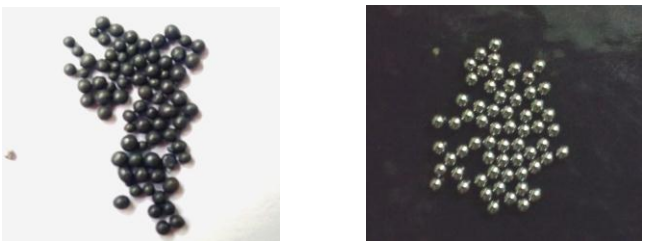
The experimental setup consists (Fig. 1) of a CNC lathe, Boring tool, Workpiece, Particles, Accelerometer and FFT analyzer. Mild steel sleeves of outer diameter 95mm and inner diameter 77mm and the length of the sleeve was 60mm are selected for experimentation. Pre-machining was done and work piece was finished for an inner diameter 77mm.

A. *Particles*

Particles of different materials as shown in Fig. 2 are chosen based on their material property and their availability in the market. Particles of 2mm diameter and material steel and lead are chosen for experimental analysis.



(a) (b)

Fig. 2 Particle materials

(a) Lead (b) Steel

B. *Experimental Conditions*

Impact tests have been carried out by exciting the boring tool for different configurations to get natural frequency of the system, where as cutting tests are carried out by machining a cylindrical workpiece on the CNC lathe. Table. I shows the experimental conditions of the cutting test performed in the present study. Where, WOD - without damper, WD - with damper configuration.

TABLE I
EXPERIMENTAL CONDITIONS WITH DAMPER CONFIGURATIONS

S.No	Damper configuration	Overhang length (mm)	Spindle speed (rpm)	Particle material	Packing ratio
1	WOD 1	125	60	-	-
2	WOD 2	125	80	-	-
3	WOD 3	150	60	-	-
4	WOD 4	150	80	-	-
5	WD 1	125	60	Steel	50%
6	WD 2	125	80	Steel	50%
7	WD 3	150	60	Steel	50%
8	WD 4	150	80	Steel	50%
9	WD 5	125	60	Steel	90%
10	WD 6	125	80	Steel	90%
11	WD 7	150	60	Steel	90%
12	WD 8	150	80	Steel	90%
13	WD 9	125	60	Lead	50%
14	WD 10	125	80	Lead	50%
15	WD 11	150	60	Lead	50%
16	WD 12	150	80	Lead	50%
17	WD 13	125	60	Lead	90%
18	WD 14	125	80	Lead	90%
19	WD 15	150	60	Lead	90%
20	WD 16	150	80	Lead	90%

Using a full factorial design 20 runs of experiments are carried out of which 4 are for acceleration response of the boring tool without damper and remaining 16 are for the boring tool with particle damper. Characteristics of the system with various parameters like effect of cutting forces, tool overhang length, particle mass and particle material is studied and verified with standard results. Feed rate of 0.02mm/rev and depth of cut of 0.3mm were maintained constant throughout the experimentation.

C. *Impact Test Results*

Impact tests are conducted to obtain the vibratory characteristics of the boring tool with and without particle damper. Natural frequency of the system obtained by Impact tests are verified with the results from Cutting tests. Table. II shows results of impact test.

TABLE II
VIBRATORY CHARACTERISTICS OF BORING TOOL FOR DIFFERENT CONFIGURATIONS

S.No	Damper configuration	Overhang length (mm)	Mass (Kg)	Stiffness (KN/m)	fn (Hz)
1	WOD 1, WOD 2	125	0.0864	2183	800
2	WOD 3, WOD 4	150	0.1017	1215	550
3	WD1 , WD 2	125	0.0954	2119	750
4	WD 3, WD 4	150	0.1083	1294	550
5	WD 5, WD 6	125	0.1097	2353	750
6	WD 7, WD 8	150	0.1227	1744	600
7	WD 9, WD 10	125	0.1026	2593	800
8	WD 11, WD 12	150	0.1156	1396	550
9	WD 13, WD 14	125	0.1227	3100	800
10	WD 15, WD 16	150	0.1357	1621	550

D. *Cutting Test Results*

Cutting tests have been carried out to study the behavior of the system by measuring acceleration amplitude of the tool for various parameters as tool overhang length, spindle speed, particle material and packing ratio. It is observed that natural frequency of the system obtained from cutting test matches well with the results of impact test. Maximum reduction in acceleration amplitude of 54.62% is achieved with particle damper containing steel particles with a packing ratio of 50% at spindle speed 60 rpm and tool overhang length of 125 mm. Fig. 6.2 shows comparison of acceleration response of the boring tool with and without particle damper. From the figure is observed that acceleration amplitude of the tool is minimized to a great extent (54.62%) by employing a particle

impact damper.

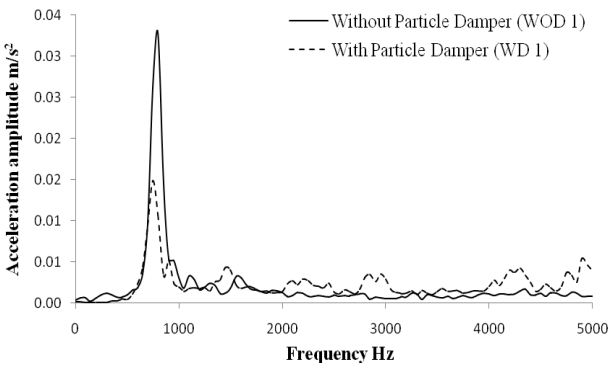


Fig. 3. Comparison of acceleration response for damper configuration with and without particles

E. Effect of Spindle Speed on Acceleration Amplitude

Fig. 4 and Fig. 5 show the effect of spindle speed on the acceleration amplitude of the tool with overhang length of 125mm and 150mm with particle damper containing steel and lead particles of packing ratio 50% and 90%. It is observed that acceleration amplitude of the boring tool is inversely proportional to the spindle speed during metal cutting operation.

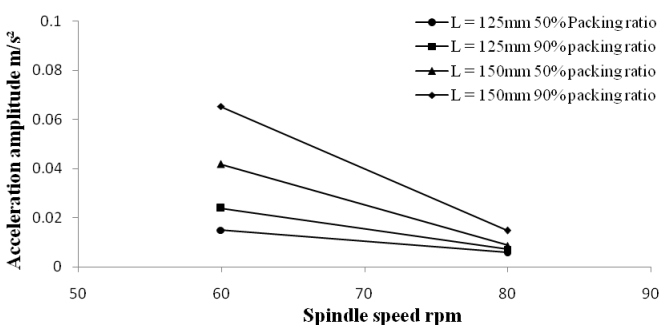


Fig. 4. Effect of spindle speed on acceleration amplitude for steel particles

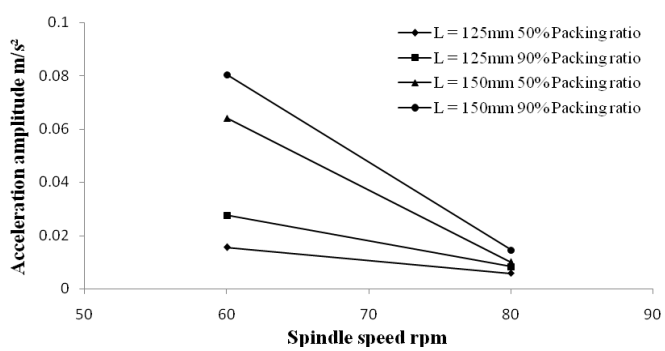


Fig. 5. Effect of spindle speed on acceleration amplitude for lead particles

F. Effect of Tool Overhang Length on Acceleration Amplitude

The effect of tool overhang length on the acceleration amplitude with a particle damper containing particles of steel and lead is presented in Fig. 6 and Fig. 7. It is observed that acceleration amplitude of the boring tool is directly proportional to the tool overhang length.

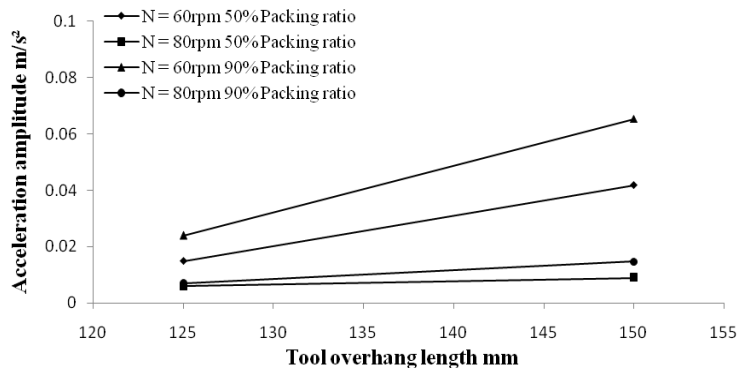


Fig. 6. Effect of tool overhang length on acceleration amplitude for steel particles

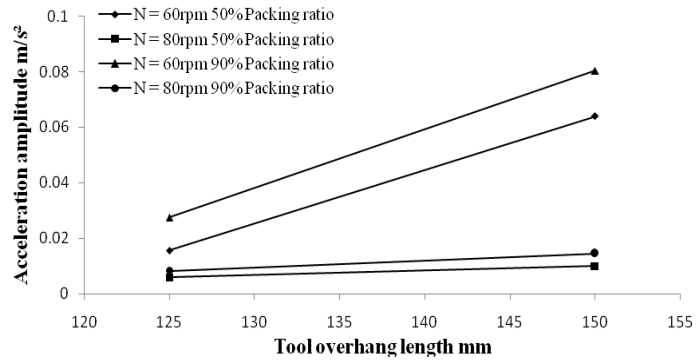


Fig. 7. Effect of tool overhang length on acceleration amplitude for lead particles

G. Effect of Packing Ratio on Acceleration Amplitude

Fig. 8 and Fig. 9 show the effect of packing ratio on the acceleration amplitude of the tool with particle damper containing particles of steel and lead. From figures it is observed that acceleration amplitude of the boring tool is directly proportional to the packing ratio.

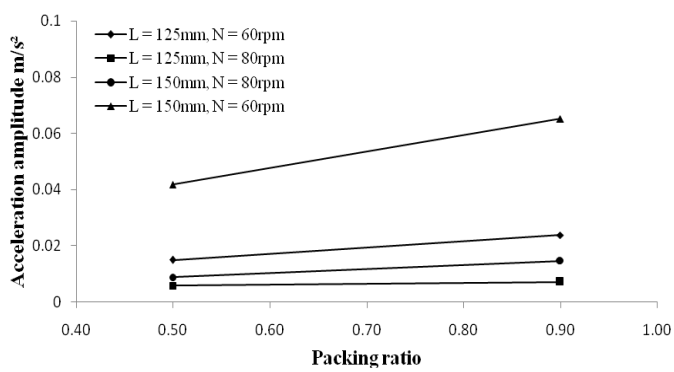


Fig. 8. Effect of packing ratio on acceleration amplitude for steel particles

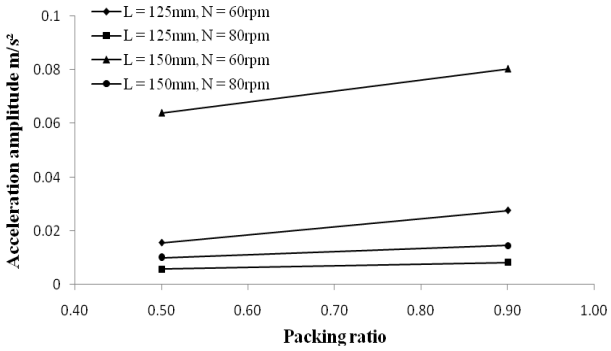


Fig. 9. Effect of packing ratio on acceleration amplitude for lead particles

H. *Effect of Particle Material on Acceleration Amplitude*

Fig. 10 and Fig. 11 show the effect of particle material density on the acceleration amplitude of the tool for packing ratio 90 and 50% respectively. From figures it is observed that influence of particle material density on acceleration amplitude of the boring tool is very less.

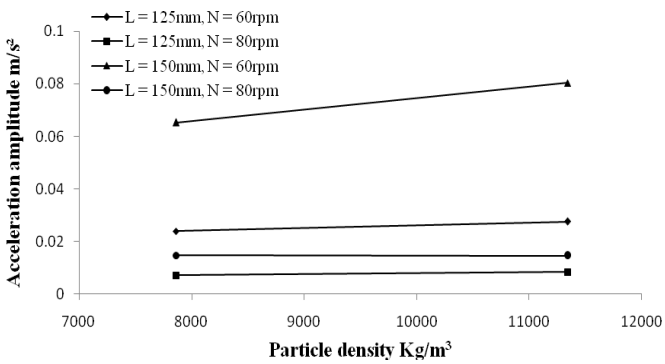


Fig. 10. Effect of particle material on acceleration amplitude with 90% packing ratio

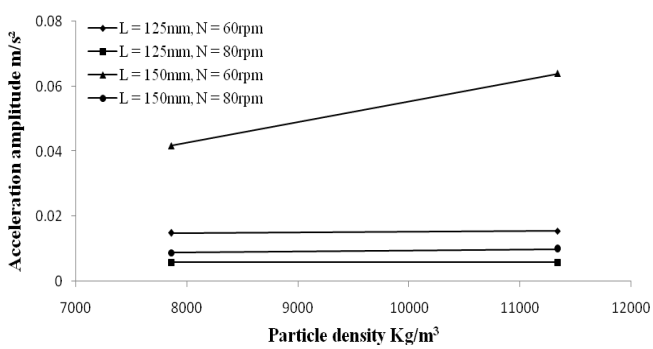


Fig. 11. Effect of particle material on acceleration amplitude with 50% packing ratio

III. DIMENSIONAL MODEL OF BORING TOOL WITH PARTICLE DAMPER

Dimensional Analysis is a well-known methodology used in physics and traditional engineering areas in order to empower the model formulation and to cut efforts in the empirical assessment phases. The highest achievement of DA is the Buckingham theorem (or pi-theorem or P-theorem), which states that any equation modeling a physical problem can be rearranged and simplified using a set of dimensionless variables (or numbers, or ratios) so that the number of variables originally used to describe the problem can be reduced by the number of independent fundamental physical quantities used in the original equation [5].

Parameters affecting acceleration amplitude of the boring tool with particle damper selected are equivalent mass (M_s), stiffness (k_s) and damping coefficient (c_s)of the system, cutting forces(F_c), excitation frequency(ω), particle material density (ρ) and packing ratio (β). Table III shows different parameters their units and dimensionality. Functional relationship between the above mentioned variables is written as

$$a = f\,(M_s, k_s, c_s, F_c\,, \omega, \rho, \beta)$$

Since the parameter packing ratio itself is dimensionless hence dimensional analysis of the system is carried out for the remaining seven parameters (Table III) with acceleration amplitude as the dependent parameter and the remaining as independent parameters.

TABLE III
PARAMETERS AFFECTING ACCELERATION AMPLITUDE OF THE BORING TOOL WITH PARTICLE DAMPER

S.No	Parameter	Symbol	Units	Dimensionality
1	Acceleration amplitude	a	m/s^2	$[LT^{-2}]$
2	Cutting forces	F_c	N	$[MLT^{-2}]$
3	Excitation frequency	ω	sec^{-1}	$[T^{-1}]$
4	Equivalent mass of the system	M_s	Kg	$[ML^0T^0]$
5	Stiffness of the system	k_s	N/m	$[MT^{-2}]$
6	Damping coefficient	c_s	N s/m	$[MT^{-1}]$
7	Particle density	ρ_p	kg/m^3	$[LT^{-3}]$
8	Packing ratio	β	-	$[M^0L^0T^0]$

Applying Buckingham theorem non dimensional parameters of the system are

$$\pi_1 = \frac{a}{(F_c/M_s)},$$ dimensionless acceleration of the boring tool

$$\pi_2 = \omega.\sqrt{\frac{M_s}{k_s}} = \frac{\omega}{\omega_n}$$, frequency ratio

$$\pi_3 = \frac{c_s}{\sqrt{M_s.k_s}} = 2.\frac{c_s}{2.\sqrt{M_s.k_s}} = 2.\varsigma$$, damping ratio of the system

$$\pi_4 = \frac{F_c^3.\rho_p}{M_s.k_s^3} = \frac{\rho_p/M_s}{k_s^3/F_c^3} = (\delta_{st})^3.(\rho_p/M_s)$$, static deflection of the system and

$$\pi_5 = \beta$$, = Packing ratio (1)

The dimensional model for the acceleration amplitude of a boring tool with particle damping is

$$\pi_1 = f(\pi_2, \pi_3, \pi_4, \pi_5) \quad (2)$$

From Eqn. (1) functional relationship between the dimensionless terms is given by

$$\frac{a}{F_c/M_s} = f\left(r, (2\varsigma), \left((\delta_{st})^3.(\rho_p/M_s)\right), \beta\right) \quad (3)$$

The values of non dimensional parameters corresponding to experimental results are presented in Table IV

.

TABLE IV
MAGNITUDES OF DIMENSIONLESS TERMS

S.No	π_1	π_2	π_3	π_4	π_5
1	3.14×10^{-05}	1	0.387	7.53×10^{-10}	0.50
2	1.27×10^{-05}	1	1.308	7.03×10^{-10}	0.50
3	9.89×10^{-05}	1	0.271	3.84×10^{-09}	0.50
4	2.14×10^{-05}	1	1.072	3.58×10^{-09}	0.50
5	5.65×10^{-05}	1	0.355	5.14×10^{-10}	0.90
6	1.76×10^{-05}	1	1.308	4.80×10^{-10}	0.90
7	1.75×10^{-04}	1	0.158	2.18×10^{-09}	0.90
8	4.04×10^{-05}	1	0.458	2.03×10^{-09}	0.90
9	3.52×10^{-05}	1	0.355	5.92×10^{-10}	0.50
10	1.35×10^{-05}	1	1.695	5.53×10^{-10}	0.50
11	1.62×10^{-04}	1	0.192	3.46×10^{-09}	0.50
12	2.57×10^{-05}	1	0.645	3.23×10^{-09}	0.50
13	7.45×10^{-05}	1	0.278	3.88×10^{-10}	0.90
14	2.30×10^{-05}	1	1.227	3.62×10^{-10}	0.90
15	2.38×10^{-04}	1	0.099	1.88×10^{-09}	0.90
16	4.40×10^{-05}	1	0.530	1.76×10^{-09}	0.90

A. Development of Correlation between Dimensionless Parameters by Regression Analysis

The dimensionless terms obtained (Eqn. (1)) by matrix method are correlated using multiple regression method.

The π terms are correlated using power law as;

$$\pi_1 = k.\pi_2^{c_1}.\pi_3^{c_2}.\pi_4^{c_3}.\pi_5^{c_4}, \quad (4)$$

Eqn. (4) can be written in log form,

$$\log(\pi_1) = \log(k) + c_1.\log(\pi_2) + c_2.\log(\pi_3) + c_3.\log(\pi_4) + c_4.\log(\pi_5), \quad (5)$$

$$Y = k_1 + c_2.A + c_3.B + c_4.C \quad (6)$$

where $\log(\pi_1)$ = Y, $\log(k) = k_1$, $\log(\pi_3)$ = A, $\log(\pi_4)$ = B and $\log(\pi_5)$ = C

Eqn. (6) is the regression equation of Y on A, B and C. To determine regression equation of 'Y', constants k_1, c_2, c_3 and c_4 should be calculated using following matrix.

$$Y.\begin{bmatrix} 1 \\ A \\ B \\ C \end{bmatrix} = \begin{bmatrix} n & A & B & C \\ A & A^2 & A.B & A.C \\ B & B..C & B^2 & B.C \\ C & C.A & C.B & C^2 \end{bmatrix}.\begin{bmatrix} k_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix}$$

or

$$\begin{aligned} \sum Y &= k_1.n + c_2.\sum A + c_3.\sum B + c_4.\sum C \\ \sum Y.A &= k_1.\sum A + c_2.\sum A^2 + c_3.\sum A.B + c_4.\sum A.C \\ \sum Y.B &= k_1.\sum B + c_2.\sum B.C + c_3.\sum B^2 + c_4.\sum B.C \\ \sum Y.C &= k_1.\sum C + c_2.\sum C.A + c_3.\sum C.B + c_4.\sum C^2 \end{aligned} \quad (7)$$

Where n = number of regression parameters = 4.

Solving Eqn (7) and substituting the values of dimension-less π terms in Eqn (4) gives

$$\pi_1 = \frac{1.02.\pi_4^{0.498}.\pi_5^{0.904}}{\pi_3^{0.762}}, \quad (8)$$

Substituting parameters of π_1, π_3, π_4 and π_5 in Eqn. (8) gives

$$a = \frac{0.61.F_c^{2.5}.\rho_p^{0.498}.\beta^{0.904}}{\varsigma^{0.762}.M_s^{1.498}.k_s^{1.494}}, \quad (9)$$

Above equation is the proposed model which relates acceleration amplitude with cutting and damper parameters.

B. Coefficient of Determination (R^2)

After fitting the model to a given data set, an assessment is made of the adequacy of fit. The quality of the fit is assessed by the coefficient of determination (R^2). R^2 is equal to the square of the correlation coefficient between the response variable and the predictor variable (multiple predictors in case of multiple regression analysis). Coefficient of determination can never be negative and lies between zero and one. Higher is the value of R^2 better is the quality of fit obtained by regression analysis. Mathematically R^2 is expressed by Eqn. (10)[6].

$$R^2 = \frac{SS_{tot} - SS_{err}}{SS_{tot}}, \quad (10)$$

where SS_{tot} = Deviation from mean = $[\text{Mean}(\pi_{exp})-(\pi_{cal})]^2$
SS_{err} = Residual error = $[(\pi_{exp})-(\pi_{cal})]^2$

π_{exp} = dimensionless acceleration amplitude from experimental results

π_{cal} = dimensionless acceleration amplitude of the system calculated by the developed mathematical model

Table V shows calculations for R^2 with dimensionless amplitude (π_1) of the system as response variable.

TABLE V
CALCULATIONS FOR R^2

S.No	(π_1)Exp	(π_1)Cal	[Mean((π_1)Exp)-(π_1)Cal]^2	[(π_1)Exp-(π_1)Cal]^2
1	$3.135x10^{-05}$	$3.215x10^{-05}$	$1.204x10^{-09}$	$6.313x10^{-13}$
2	$1.265x10^{-05}$	$1.228x10^{-05}$	$1.509x10^{-10}$	$1.337x10^{-13}$
3	$9.892x10^{-05}$	$9.490x10^{-05}$	$9.006x10^{-09}$	$1.614x10^{-11}$
4	$2.144x10^{-05}$	$3.216x10^{-05}$	$1.034x10^{-09}$	$1.147x10^{-10}$
5	$5.653x10^{-05}$	$4.831x10^{-05}$	$2.334x10^{-09}$	$6.751x10^{-11}$
6	$1.761x10^{-05}$	$1.727x10^{-05}$	$2.984x10^{-10}$	$1.156x10^{-13}$
7	$1.749x10^{-04}$	$1.839x10^{-04}$	$3.380x10^{-08}$	$7.951x10^{-11}$
8	$4.042x10^{-05}$	$7.891x10^{-05}$	$6.226x10^{-09}$	$1.481x10^{-09}$
9	$3.519x10^{-05}$	$3.046x10^{-05}$	$9.279x10^{-10}$	$2.233x10^{-11}$
10	$1.345x10^{-05}$	$8.945x10^{-06}$	$8.002x10^{-11}$	$2.033x10^{-11}$
11	$1.616x10^{-04}$	$1.173x10^{-04}$	$1.376x10^{-08}$	$1.960x10^{-09}$
12	$2.56x10^{-05}$	$4.502x10^{-05}$	$2.027x10^{-09}$	$3.750x10^{-10}$
13	$7.453x10^{-05}$	$5.056x10^{-05}$	$2.556x10^{-09}$	$5.747x10^{-10}$
14	$2.299x10^{-05}$	$1.577x10^{-05}$	$2.486x10^{-10}$	$5.225x10^{-11}$
15	$2.383x10^{-04}$	$2.441x10^{-04}$	$5.957x10^{-08}$	$3.346x10^{-11}$
16	$4.403x10^{-05}$	$6.571x10^{-05}$	$4.317x10^{-09}$	$4.697x10^{-10}$

(Mean(π_1)Exp)=$6.686x10^{-05}$

$SS_{tot} = 1.3755x10^{-07}$

$SS_{err} = 5.26784x10^{-09}$

The mathematical model developed i.e., Eqn. (10) is highly significant with coefficient of determinant, R2 = 0.962. The value R2 = 0.962 indicates that nearly 97% of the total variability in the response variable (dimensionless acceleration) is accounted for by the predictor variables.

IV. CONCLUSION

The damping characteristics of boring tool are analyzed experimentally. The experimental results are used to develop a mathematical model which relates the acceleration amplitude of the boring tool as well as damper parameters. The effect of input parameters, tool overhang length, spindle speed, particle material and packing ratio on acceleration amplitude of the boring tool is studied and verified.

- The proposed mathematical model predicts effect of system and damping parameters on acceleration amplitude of boring tool with coefficient of determinant, R2 = 0.962.
- Reduction in acceleration amplitude of 54.62% is achieved with steel particles for 50% packing ratio.
- Influence of particle material density on acceleration amplitude is very less compared to other parameters.
- Packing ratio is directly proportional to the acceleration amplitude.
- Results of impact test for vibratory characteristics as natural frequency of the boring tool matches well with results from cutting test.
- Acceleration amplitude of the boring tool is directly proportional to tool overhang length.
- Spindle speed is inversely proportional to the acceleration amplitude.
- Dimensional analysis and multiple regression method can be used to develop a mathematical model for vibration problems.

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