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Theoretical and Experimental Analysis of Particle Damped Boring Bar

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ABSTRACT

Active and passive vibration mitigation techniques are commonly used in the different industrial fields of application. Many of the times, passive vibration technique will be preferred over the active vibration technique due to its simplicity and low cost. In past time, there were various types of passive vibration techniques developed by the researchers. These techniques differ from each other based on the type of mechanism and principle used. Particle impact Damping (PID) is one of the commonly used passive vibration technique and the constant improvement in this technique has been observed through literature survey. In this research work a particle impact damper has been developed with special reference to boring operation to alleviate the ill effects of vibration. Before conducting the experiments the significant factors are sorted out separately and ranked as per their importance, using the Analytic Hierarchic Process (AHP) technique. The proven DoE technique has been used to plan the number of experiments to be carried. L_{27} orthogonal array has been used to conduct the partial factorial experiments for 3^6 factor and level combination. The data obtained from the experiments have been analyzed using a reliable multi-criteria optimization technique called Grey Relational Analysis (GRA). An optimum combination of design parameters of PID are obtained through GRA which is validated by conducting confirmation tests. The mathematical models for predicting acceleration and surface roughness values are developed showing good R-Sq values. The contour plots for acceleration and surface roughness shows the interrelation of various design parameters and their significance in achieving the objectives.

***Keywords*— Analytic Hierarchic Process, Grey Relational Analysis, Particle Impact Damping**

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I. INTRODUCTION

Vibration and noise in metal cutting are most common problems in workshop or any manufacturing industry. It is important to limit vibrations of the machine tool structure as their presence results in poor surface finish, cutting-edge damage, and irritating noise. The causes and control of free and forced vibrations are generally well understood and the sources of vibration can be removed or avoided during operation of the machine. Boring is one of the metal removal processes that often exhibits vibration related problems. The vibrations occur because of the basic interaction between the cutting process and the machine tool structure.

Particle damping is a passive vibration control technique where multiple auxiliary masses are placed in a cavity attached to a vibrating structure. The behaviour of the particle damper is highly non-linear and energy dissipation or damping is derived from a combination of loss mechanisms. Steven E. Olson [9] presented a mathematical model that allows particle damper designs to be evaluated analytically. The model utilizes the particle dynamics method and captures the complex physics involved in particle damping, including frictional contact interactions and energy dissipation due to viscoelasticity of the particle material.

M. Saeki [10] analyzed the results of experimental and analytical studies of the performance of a multi-unit particle damper in a horizontally vibrating system. The principle behind particle damping is the removal of vibratory energy through losses that occur during impact of granular particles. An analytical solution based on the discrete element method is compared with the experimental results, which shows that the accurate estimates of the rms response of a primary system can be obtained. It is shown that the response of the primary system depends on the number of cavities and cavity dimensions.

Bryce L. Fowler et. al. [16] developed a design methodology for particle damping. They have presented a simulation technique that captures complex interactions of loss mechanisms in a particle damper.

Kun S. Marhadi et. al. [19] measured the effect of Particle impact damping (PID) on a cantilever beam with a particle-filled enclosure attached to its free end. The experimental results indicate that a more advanced model of PID must include the size and the number of particles as additional independent parameters, and remove the restriction of all particles moving as a single particle

M. Senthil kumar [14] investigate the use of particle damping method for vibration control in boring bar. A boring bar is treated with longitudinal holes filled with metal particles. The experimental investigations on the effectiveness of particle damping in vibration control of boring bar are carried out and found to be remarkably effective.

Show-Shyan Lin et. al. [15] investigated the optimization of computer numerical control (CNC) boring operation parameters for aluminum alloy 6061T6 using the grey relational analysis (GRA) method. Nine experimental runs based on an orthogonal array of Taguchi method were performed. The surface properties of roughness average and roughness maximum as well as the roundness were selected as the quality targets. An optimal parameter combination of the CNC boring operation was obtained via GRA.

II. DESIGN OF EXPERIMENTS

Success of any research work depends on the proper planning and execution of the experiments. To logically analyze the data obtained after conduction of experiments, it is necessary to scientifically plan the number of experiments required to be carried out.

Based on the various numerical analysis methods studied, total 10 numbers of parameters are finalized for conducting experiments to identify their role in minimizing the vibration level of boring bar using particle impact damping (PID).

Table 1: Factors under Consideration for AHP

No.	Parameter		No.	Parameter
1	Cutting Speed		6	Type of Insert
2	Cutting Feed		7	Particle Mass
3	Depth of Cut		8	Particle Size
4	Work piece Material		9	Particle Shape
5	Boring Bar L/D Ratio		10	Packing Ratio

As all these 10 parameters are not so effective, Analytic Hierarchic Process (AHP) approach is used to prioritize the parameters used for actual experimentation. The AHP provides a means of decomposing the problem into a hierarchy of sub-problems which can more easily be comprehended and subjectively evaluated. The subjective evaluations are converted into numerical values and processed to rank each alternative on a numerical scale.

Gradation scale for quantitative comparison of parameters is used for the gradation of each factor from pairwise comparison matrix of AHP. Normalised priority weights of each factor are determined. The percentage weight of each factor is calculated and based on the results, rank is decided for each individual factors. This rank will now help to prioritize the factors to be used for experimentation. 6 parameters are finalized according to their ranks for consideration for experimentation.

A well known Taguchi approach is used only to decide the number of experiments to be carried out. 6 parameters with their 3 levels are finalized.

Table 2: Factor and Level Combination

Factor		Level			Unit
		1	2	3	
A	Cutting Speed	60	120	180	rpm
B	Cutting Feed	0.02	0.03	0.04	mm/rev
C	Depth of Cut	0.5	1	1.5	mm
D	Boring Bar L/D Ratio	6	8	10	
E	Particle Size	2	4	6	mm
F	Packing Ratio	25	50	75	%

Above table shows the 6 factor and its 3 level i.e. 3^6 Full Factorial, which yields to total 729 numbers of experiments.

Taguchi technique helps to minimize this full factorial into fractional factorial number of experiments using the concept of orthogonal array. For 3^6factor and level combination L_{27} orthogonal array is suitable.

Table 3: L_{27} Orthogonal Array (OA)

Test No.	Natural and Coded Variables											
	A		B		C		D		E		F	
1	60	1	0.02	1	0.5	1	6	1	2	1	25	1
2	60	1	0.02	1	0.5	1	6	1	4	2	50	2
3	60	1	0.02	1	0.5	1	6	1	6	3	75	3
4	60	1	0.03	2	1	2	8	2	2	1	25	1
5	60	1	0.03	2	1	2	8	2	4	2	50	2
6	60	1	0.03	2	1	2	8	2	6	3	75	3
7	60	1	0.04	3	1.5	3	10	3	2	1	25	1

8	60	1	0.04	3	1.5	3	10	3	4	2	50	2
9	60	1	0.04	3	1.5	3	10	3	6	3	75	3
10	120	2	0.02	1	1	2	10	3	2	1	25	2
11	120	2	0.02	1	1	2	10	3	4	2	50	3
12	120	2	0.02	1	1	2	10	3	6	3	75	1
13	120	2	0.03	2	1.5	3	6	1	2	1	25	2
14	120	2	0.03	2	1.5	3	6	1	4	2	50	3
15	120	2	0.03	2	1.5	3	6	1	6	3	75	1
16	120	2	0.04	3	0.5	1	8	2	2	1	25	2
17	120	2	0.04	3	0.5	1	8	2	4	2	50	3
18	120	2	0.04	3	0.5	1	8	2	6	3	75	1
19	180	3	0.02	1	1.5	3	8	2	2	1	25	3
20	180	3	0.02	1	1.5	3	8	2	4	2	50	1
21	180	3	0.02	1	1.5	3	8	2	6	3	75	2
22	180	3	0.03	2	0.5	1	10	3	2	1	25	3
23	180	3	0.03	2	0.5	1	10	3	4	2	50	1
24	180	3	0.03	2	0.5	1	10	3	6	3	75	2
25	180	3	0.04	3	1	2	6	1	2	1	25	3
26	180	3	0.04	3	1	2	6	1	4	2	50	1
27	180	3	0.04	3	1	2	6	1	6	3	75	2

III. EXPERIMENTAL INVESTIGATIONS

1) *Boring Bar*

Two types of boring bars are used for the experiments,

(i) Conventional Boring Bar (as shown in fig.1) with a cross-section of 16×16 mm and an overall length of 250 mm. The boring bar is of WIDAX make and having model no. S20S SCLCR 09T3

(ii) To provide the damping against the vibrations developed during work piece and tool interaction, the conventional or standard boring bar is converted into Particle Impact damper. A hole of 8 mm diameter and 230 mm deep is drilled in a boring bar body. This cavity will accommodate the particles of different diameter with different packing ratios. A threaded plug is used to close this cavity so that the particles will freely move inside the cavity and collide with the walls.

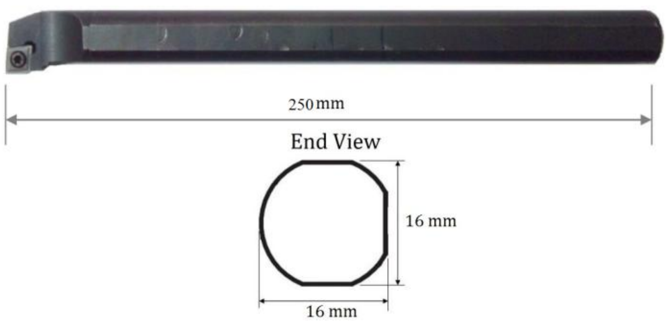

Fig.1 Conventional Boring Bar

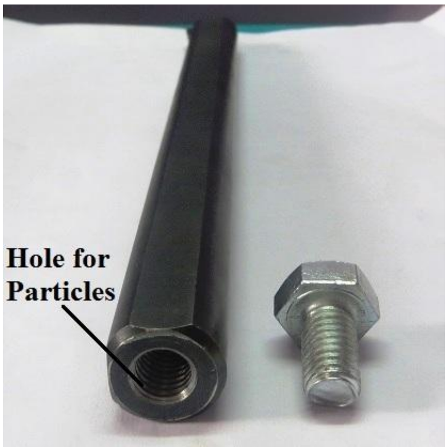

Fig.2 Boring bar with cavity

2) *Particles*

Steel particles of diameter 2mm, 4mm and 6mm are used to fill the cavity with the desired packing ratio (25%, 50% and 75%) made in the boring bar body.

3) *Experimental Setup*

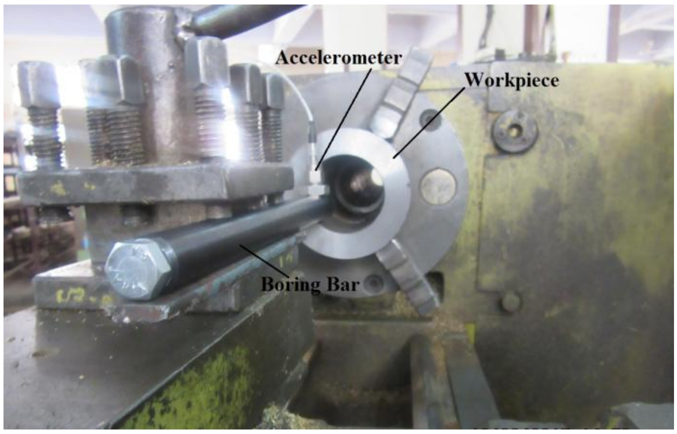

Fig.3 Actual Experimental Setup

Figure 3 shows actual arrangement of experimental setup for analyzing the configurations of Particle Impact damper. A FFT Analyzer is used to receive the frequency response (vibration acceleration) with the help of accelerometer placed on customized boring bar. The experiments were carried out as per the L_{27} orthogonal array as given in Table 3. Total 27 tests and each test 2 times (for minimizing the effects of error) were carried out. The results obtained through these tests are in terms of vibration acceleration and surface roughness. Accelerometer placed on boring bar gives vibration acceleration amplitude while surface roughness is measured using surface roughness testing machine. The surface roughness and acceleration amplitude are measured for all the 27 samples (repeated twice)

IV. ANALYSIS AND VALIDATION

A) *Taguchi Parameter Design*

Taguchi technique helps to optimize the design parameters to enhance the performance of the system or process. The signal to noise approach of Taguchi method for smaller the better criteria has been used for the analysis. Using results obtained in the form of acceleration and surface roughness the optimum design parameters are found independently for less vibration and less surface roughness. All $3^6 = 729$ tests results are predicted using Taguchi Predictions in MINITAB R-14 software.

The S/N ratios for acceleration and surface roughness are given in fig.4 and Fig.5 respectively.

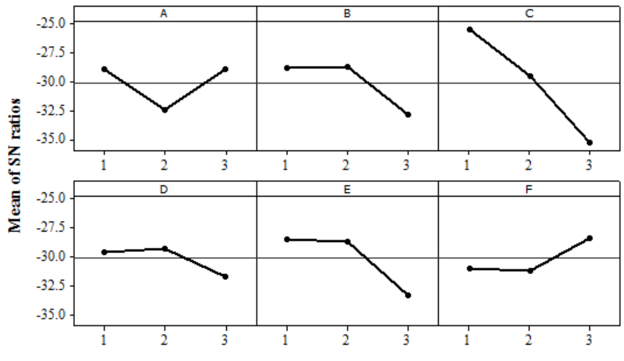

Fig.4 S/N Ratio for Acceleration

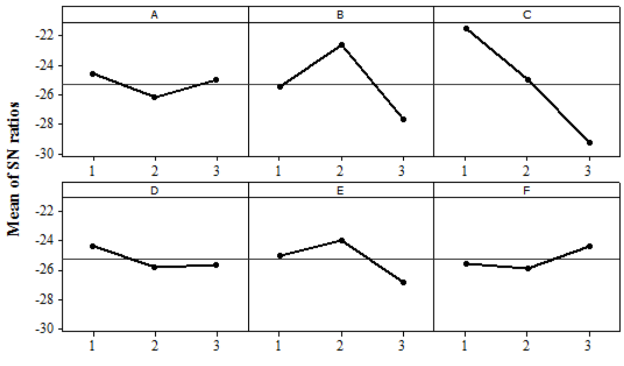

Fig. 5 S/N Ratio for Surface Roughness

From fig. 4 i.e. S/N ratio for acceleration and fig5 i.e. S/N ratio for surface roughness, it has been observed that there are more than one possibility of getting optimum design parameters which can yield lower vibration and surface roughness. For vibration, there are 12 numbers of optimum combinations and for surface roughness there are 02 numbers of optimum combinations available. Due to this, the choice or selection of optimum design parameters becomes difficult. To resolve such issues, one can use multi-criteria optimization techniques.

B) *Grey Relational Analysis*

In the case when experiments are ambiguous or when the experimental method cannot be carried out exactly, grey analysis helps to compensate for the shortcoming in statistical regression. Grey relation analysis is an effective means of analyzing the relationship between sequences with less data and can analyze many factors that can overcome the disadvantages of statistical method. Grey relational analysis is widely used for measuring the degree of relationship between sequences by grey relational grade.

In GRA, first step is to normalize the experimental results of each performance characteristics. As one can always expect minimum vibration and less surface roughness, therefore smaller the better criterion has been used.

For S/N ratio with Smaller-the-better condition

$$Z_{ij} = \frac{max(y_{ij}, i = 1,2..n) - y_{ij}}{max(y_{ij}, i = 1,2..n) - min(y_{ij}, i = 1,2..n)}$$

All the experimental results are normalized. Then, grey relational coefficient is calculated. It is expressed as

$$\gamma_{ij} = \frac{\Delta min + \xi \Delta max}{\Delta_{oi}(k) + \xi \Delta max}$$

The grey relational grade is calculated by the mean value of grey relational coefficient. It is expressed as

$$\bar{\gamma}_j = \frac{1}{k} \sum_{i=1}^{m} \gamma_{ij}$$

All these calculations are done for both acceleration as well as surface roughness.

C) *Multiple Linear Regression Analysis*

Regression Analysis is a conceptually simple method for investigating functional relationships among variables. The relationship is expressed in the form of an equation or a model connecting the response or dependant variable and one or more explanatory or predictor variables. A regression with two or more explanatory variables is called a multiple regression. Rather than modeling the mean response as a straight line, as in simple regression, it is now modeled as a function of several explanatory variables. The model creates a relationship in the form of a straight line (linear) that best approximates all the individual data points. The separate mathematical model in the form of equation was developed with the help of regression analysis technique using MINITAB R-17 software. Values of all grey relational grades are given as an input to the MINITAB software and regression analysis is carried out. The equations for acceleration and surface roughness along with their R-Square values are stated as follows

Regression equation for acceleration;

Acceleration = - 50.7 - 0.0517 S + 690 F + 39.5 D + 3.63 L/D + 4.94 d - 0.238 P

Regression equation for surface roughness;

Surface Roughness = - 15.8 + 0.00018 S+ 207 F + 17.3 D + 1.42 L/D + 1.03 d - 0.0521 P

Where,
S – Spindle Speed
F –Feed rate
D – Depth of Cut
d – Particle diameter

P – Packing ratio

R-Square (Coefficient of determination)

R-Square, also known as the *Coefficient of determination* is a commonly used statistic to evaluate model fit. *R-square* is 1 minus the *ratio of residual variability*. When the variability of the residual values around the regression line relative to the overall variability is small, the predictions from the regression equation are good. *R-square* value is an indicator of how well the model fits the data (e.g., an *R-square* close to 1.0 indicates that we have accounted for almost all of the variability with the variables specified in the model).
R-Sq for equation of acceleration is 78.2%
R-Sq for equation of surface roughness is 73.1%

D) *Validation*

From the calculations of all tests, it has been observed that the test number 572 out of 729 tests has higher grey relational grade i.e. 0.9454. It clearly states that the design parameters of this test will satisfy the requirement of multi-objective optimization i.e. less vibration and minimum surface roughness. The factors and level combination of this test is as follows

$\mathbf{A_3B_2C_1D_1E_2F_2}$
Where,
Spindle Speed = 180 rpm,
Feed rate = 0.03 mm/rev
Depth of Cut = 0.5 mm
L/D Ratio = 6
Particle Diameter = 4 mm
Packing Ratio = 50%

The validation or confirmation test with the given design parameters has been carried out with and without damper and the results are given in table

Table 4 Comparison of acceleration and surface roughness values for optimum design parameters

	Predicted Value (With Damper)	Experimental Value (With Damper)	Experimental Value (Without Damper)
Acceleration ($\mu m/sec^2$)	1.085	1.12	19.6
Surface Roughness (µm)	2.1611	2.89	23.4

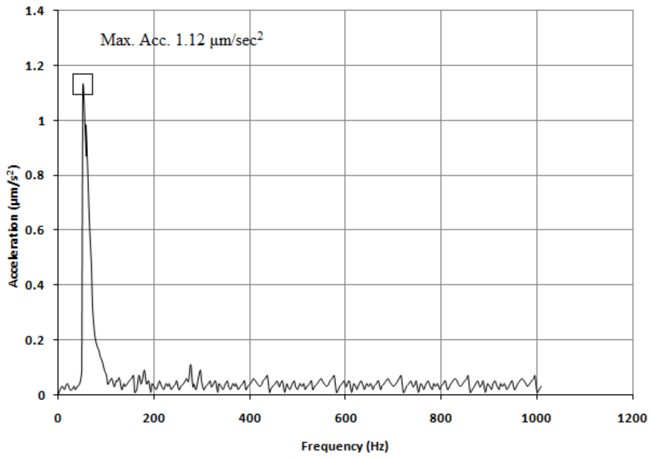

Fig.6 Frequency Response of confirmation test with damper

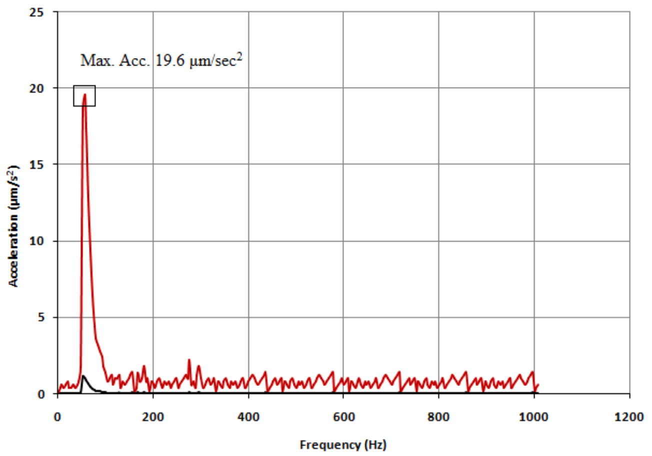

Fig.7 Frequency Response of confirmation test without damper

An individual grey relational grade has been calculated to see the significant factor and its level.

E) *Contour Plots*

In a contour plot the values for two variables are represented on the X and Y axes, while the values for a third variable are represented by shaded regions called contours. A contour plot is like a topographical map in which X, Y and Z values are plotted instead of longitude, latitude and altitude. In simple, it is a three dimensional plot shown on two dimension.

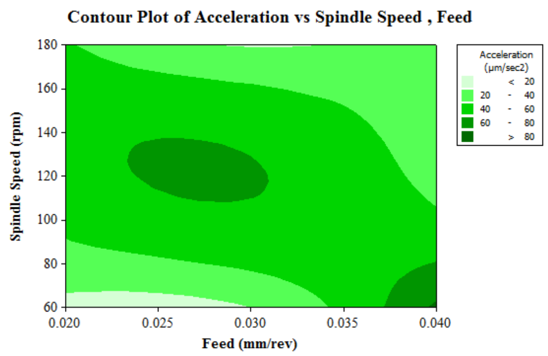

Fig.8 Contour Plot

For six factors, i.e. speed, feed rate, depth of cut, L/D ratio, particle diameter, packing ratio with two responses, total 30 contour plots have been identified.

IV. CONCLUSIONS

The performance of particle impact damper in an application of boring operation has been analyzed experimentally. The Design of Experiments (DoE) technique has been successfully applied for planning and conducting experiments. The Gray Relational Analysis (GRA) a multi-criteria optimization technique has been used to find the optimum combination of input parameters which will yield the better output in terms of low acceleration and improved surface finish.

The proposed mathematical models predict the effect of system and damping parameters on acceleration amplitude of boring tool and surface roughness of work piece with coefficient of determinant, R^2= 0.782 and 0.731 respectively.

Significant reduction in acceleration amplitude has been observed with L/D Ratio = 6, Particle Diameter = 4 mm and Packing Ratio = 50%

Ranking obtained from GRA clearly highlights the significance of particle diameter and subsequently followed by packing ratio over the other parameters. This fact also further confirmed through contour plots.

From contour plot of Acceleration amplitude it is seen that the lower level of vibration acceleration can be maintained by keeping L/D ratio 7, packing ratio 60 to 70%, and particle diameter 2 to 4 mm. The better surface finish also can be obtained through this damper configuration.

These contour plots also help to select the appropriate process parameters value e.g. cutting speed, feed depth of cut etc.

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