Modelling and Prediction Using Regression, ANN and Fuzzy Logic of Real Time Vibration Monitoring on Lathe Machine in Context of Machining Parameters

Saurin Sheth, Bhavin S. Modi, Dipal Patel and Ashish B. Chaudhari

Abstract--- *Machine tool vibration plays a dominant role in the surface finish, dimensional and geometrical tolerances of the machined work piece. Condition of the machines includes collected data, such as vibration analysis, oil and wears debris analysis, ultrasound, temperature and performance evaluation. Out of these the vibrations have been measured and its effect has been studied. The present paper deals with the measurement of acceleration during machining of Cast Iron on lathe machine.* 3^3 *full factorial design of experiments were selected, experiments are performed by varying machining parameters such as spindle speed, feed rate and depth of cut. ANOVA and Regression analysis has been carried out to know the significance of these parameters. Even Artificial Neural Network (ANN) and Fuzzy Logic based models have been developed to predict Acceleration in the context of these input parameters. The predicted results obtained from the developed models are compared with the experimental one. Results shows that the developed models having more than 95% accuracy, which leads the use of it in predicting the acceleration within the range of the specified input parameters for a given machine too.*

Keywords--- *Machining, Acceleration, ANOVA, Regression Model, ANN, Fuzzy Logic, Condition Monitoring*

I. Introduction

NEW generation of machine tools are capable of manufacturing the goods with higher accuracy, due to their inherent capabilities. But the old machine tools may not be able to fulfill the same functional requirements, due to many aspects. The major aspect is machine tool vibrations during condition monitoring. Turning, the most versatile machining process, covers around 70% share of the machining on lathe machine. DOE is an experimental strategy in which effects of multiple factors are studied simultaneously by running tests at various levels of the factors. The tool Design of Experiments (DOE) can be used to know the significance of machining parameters on the machine tool vibration and even it helps in deciding the most significant one.

II. Literature Review

D. Zhou et al., [1] introduced a systematic methodology for the design of an integrated condition monitoring and fault diagnosis expert system for modern manufacturing systems. This is an integrated and intelligent system with a modular and re-configurable structure, and it has the functions of condition monitoring, fault diagnosis and maintenance planning. The system has been implemented for FFS-1500-2 FMS and it can also be applied to other manufacturing systems. Aiwina Heng et al., [2] reviewed various state of art challenges and opportunities during rotary machine diagnostic system. Lin Ma [3] discusses new directions for the condition monitoring for sustainability. Vinay. V. N [4] was studying the effect of unbalanced mass of motor spindle assembly for lathe machine. S. Saravanan et al., [5] study about the causes of failure of critical components and subsystems of lathes using failure data. Faulty bearing in lathe can be identified by using online vibration monitoring and surface roughness monitoring. For defective bearing conditions, significant peaks at the bearing fault frequencies are observed. Pratik Patel et al., [6,7] analyzed the effect of machining parameters on MRR and Spread for flashing operation of ball bearing ball. They have performed ANOVA and regression analysis for the same. Pratihar [8] review that soft computing based expert systems like ANN, Fuzzy and ANFIS can be used to establish input output relationships of various manufacturing processes. The paper reveals that a reasonably good results were obtained using soft computing techniques.Aiwina Heng et al., [19] have suggested a use of artificial neural network for prediction of failure of machinery. The ability to forecast machinery failure helps in reducing maintenance costs, operation downtime and safety hazards. This implies the need of proper selection of speed, feed and depth of cut to reduce the level of vibration, which enhances the machine tool life.

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III. Experimentation

A. Material Selection

ASTM A48 Class 40 - Pearlite Gray Cast Iron is used to perform for the experimentation. It represents the same graphite distribution, however, in an essentially pearlite matrix, which yields better mechanical properties and better heat treatment response. Hardness is 198-285 BHN. It is widely used to manufacture pistons, valves, dies etc. The size of the work piece is 30 mm diameter and 150 mm length.

Table 1 shows the chemical composition of the work piece material.

Table 1: Chemical Composition

Material	C	SI	Mn	S	P
Percentage contribution (%)	2.80-3.70	2.30 - 2.70	0.40 - 0.80	0.20 max.	0.10 max.

B. Cutting Tool

High speed steel (HSS) is a high carbon ferrous alloy consisting of W, Mo, Cr, V, and Co. HSS is inexpensive compared to other tool materials. It has excellent fracture toughness and fatigue resistance. HSS is suitable for use only at limited cutting velocities of 30-70 m/min because of its limited wear resistance and chemical stability. Table 2 shows the composition of HSS tool[9].

Fig. 1: Signal Point HSS Tool

Table 2: Composition of HSS Tool Bit

Contents	C	W	Cr	V	Co
Percentage%	0.80	20	4	2	5 and 10

C. Experimental Setup

The Experiment setup developed at the workshop of CSPIT, CHANGA is shown in Fig. 2 [9]. For vibration monitoring the sensor was mounted to the tool post of the machine. The used DAQ system includes Physical input/output signals as shown in figure (3), DAQ hardware as shown in figure (4) and Driver software. DAQ hardware act as interface between computer and outside world. Machining parameters spindle speed, feed rate and depth of cut varied at 3 levels as shown in table 3. 3^3Full factorial design is selected to perform the reliable experiments. As per this total 27 experiments were performed and acceleration is measured [10].

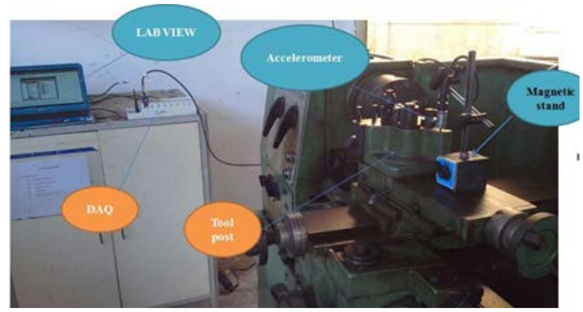


Fig. 2: Experimental Setup

Table 3: Factors with Levels

Factor	Level 1	Level 2	Level 3
Spindle speed(RPM)	125	250	350
Feed rate (mm/rev)	0.05	0.1	0.15
Depth of cut (mm)	1	2	3

Fig. 3: NI 9234 Physical Input/Output Signals Device

Fig. 4: DAQ Hardware

D. Measurement of Acceleration

The accurate measurement technique is required to develop reliable models. Acceleration measurement was done using NI 9234 module. Figure (5) shows the interfacing of DAQ system with sensor and Lab View. During turning operation, acceleration signal collected by piezo sensor goes to lab view software by using a DAQ device [11]. Figure (6) shows the sample signal collected by lab view, from which the interest is to find the max acceleration value. The outcomes of 27 experiments are shown in table 4.

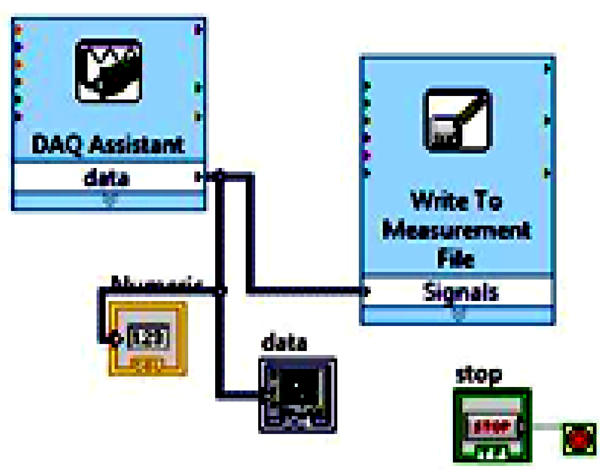


Fig. 5: Labview Diagram

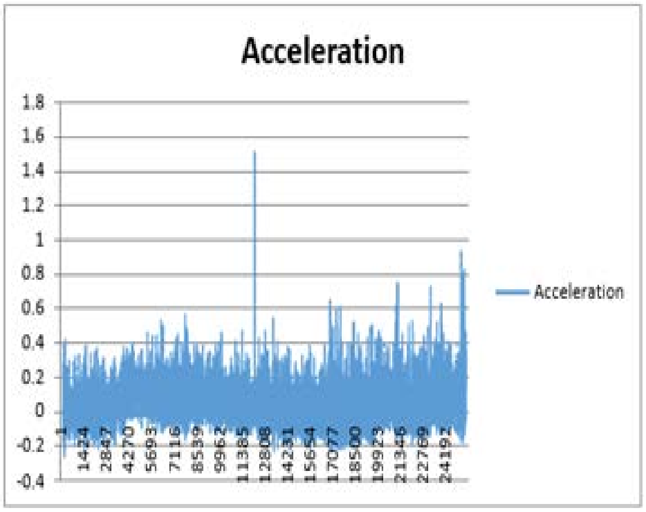


Fig. 6: Typical Acceleration Signal

Table 4: Experimental Results

Run order	Spindle Speed (RPM)	Feed rate (mm/rev)	Depth of cut (mm)	Acceleration (m/s^2)
1	125	0.05	1	1.009661
2	125	0.05	2	1.156552
3	125	0.05	3	1.592348
4	125	0.1	1	1.013119
5	125	0.1	2	1.329162
6	125	0.1	3	1.895578
7	125	0.15	1	1.304193
8	125	0.15	2	1.956258
9	125	0.15	3	2.398151
10	250	0.05	1	1.079311
11	250	0.05	2	1.297001
12	250	0.05	3	1.88997
13	250	0.1	1	1.308859
14	250	0.1	2	1.801105
15	250	0.1	3	1.996056
16	250	0.15	1	1.737262
17	250	0.15	2	2.013218
18	250	0.15	3	2.701215
19	350	0.05	1	1.124168
20	350	0.05	2	1.716078
21	350	0.05	3	2.112353
22	350	0.1	1	1.877681
23	350	0.1	2	2.126821
24	350	0.1	3	2.365218
25	350	0.15	1	1.993757
26	350	0.15	2	2.627641
27	350	0.15	3	3.115454

IV. Analysis of the Results

A. *Analysis of Variance (ANOVA)*

Table 5: ANOVA Table

Source	DF	SS	MS	F	P
Spindle Speed	2	1.6435	0.8218	41.29	0.000
Feed rate	2	2.6580	1.3290	66.77	0.000
D.O.C	2	3.2284	1.6182	81.10	0.000
Error	20	0.3981	0.0199		
Total	26	7.9280			
S = 0.141082		R-Sq = 94.98 %		R-Sq(adj) = 93.47%	

The ANOVA Table 4 shows that the speed, Feed rate and Depth of cut are significant parameters. The percentage contribution of spindle speed, feed rate and depth of cut are 20.73%, 33.52% and 40.72% respectively. Figure 7 and 8 shows the Main effect Plot and interaction plots for Spindle Speed, Feed and Depth of Cut. Itseems that acceleration increases with increases of spindle speed, feed and Depth of Cut. Figure 8 Shows that interaction plot for Spindle Speed, Feed, and depth of cut. It seems that there is no interaction effect present between the input variables.

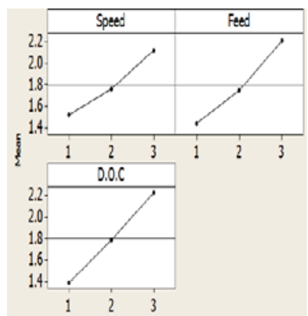


Fig. 7: Main Effect Plot

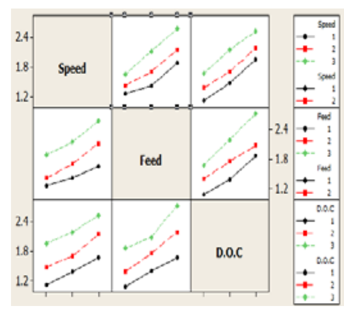


Fig. 8: Interaction Plot

B. *Regression Model*

Regression analysis is a statistical tool for the investigation of relationships between variables. Here second order regression model is developed using Minitab 16 software which is show in equation 1. The R-Sq value is the variability in the data accounted by the model in percentage. The R-Sq value for acceleration model is close to 1, which shows the high correlation that exists between the experimental and predicted values [10, 18].

Acceleration=1.0814 - 0.279337* spindle speed - 0.398142* feed - 0.00874461*depth of cut +0.0592333* spindle speed2 +0.168124* spindle speed* feed +0.0776329* feed2+ 0.160946* feed* depth of cut + 0.097632* depth of cut * spindle speed +0.0259268* depth of cut2 - 0.0472199* spindle speed *feed * depth of cut (R-Sq = 96.70%) (1)

C. Artificial Neural Network

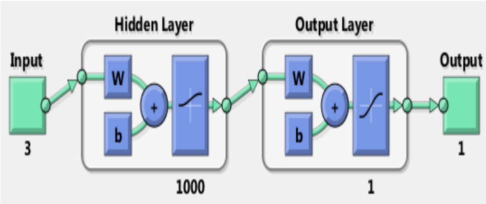


Fig. 9: ANN Model in MATLAB 2012a

ANN is the soft computing technique in which experimental data are used to train the neurons at its learing stage. Fig 9 indicates the architecture used between input and output parameter. Here spindle speed, feed rate, depth of cut is three input variable and acceleration is the response. Total 1000 iterations are performed for modelling using ANN technique. Here back propagation algorithm is used to develop a model using MATLAB tool box [12, 13]. The predicted values obtained from the model are shown in table 6.

D. Development of Fuzzy Logic based Model to Predict Acceleration

Fuzzy logic (FL) is a common element of Expert System with an increasing rate of interest and widely used over the past few years due to its successful applications in many control and prediction systems. It suits very well in defining the relationship between inputs and desired outputs of a system, where its extra ordinary controlling and reasoning capability made its way to the application of many complex industrial systems. Fuzzy system consist few inputs, output(s), set of predefined rules and a defuzzification method with respect to the selected fuzzy inference system. [14, 15, 16].

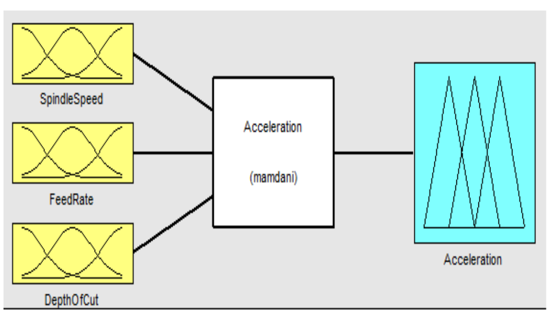


Fig. 10: Fuzzy Logic System

MATLAB 12 Fuzzy Logic Tool Box is used to developed Fuzzy model. Figure 10indicates the structure of fuzzy system having three input variables viz. spindle speed, feed rate and depth of cut and response is acceleration. Fuzzy modeling basically involves three main processes viz. fuzzification, fuzzy inference and defuzzification.

i. Membership Functions for Inputs and Output Fuzzy Variables

In choosing the membership functions for fuzzyfication, the event and type of membership functions are mainly dependent upon the relevant event. Triangular shape of membership function is employed to describe the fuzzy sets for input and output variables. Triangular membership function is generally used and possesses gradually increasing and decreasing characteristics with only one definite value.

Figure 11 shows membership functions for each input variable and figure 12 shows membership functions for response [15, 16]

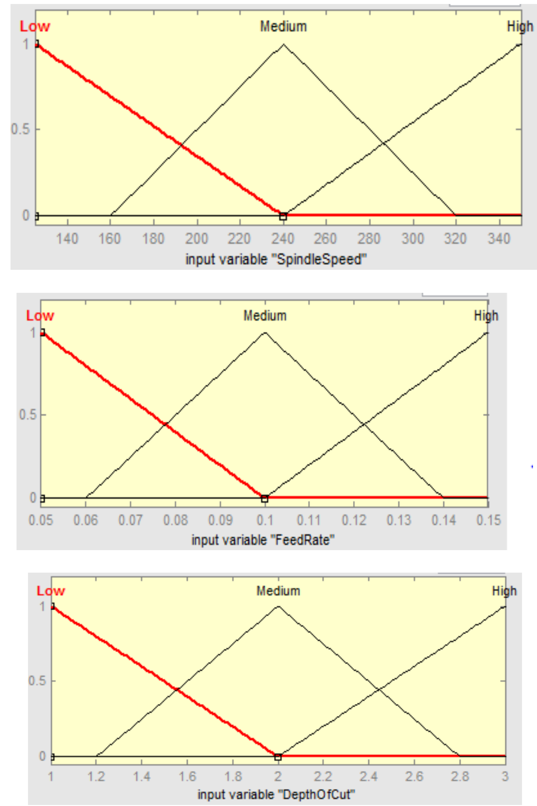


Fig. 11: Membership Functions for Spindle Speed, Feed, Depth of Cut

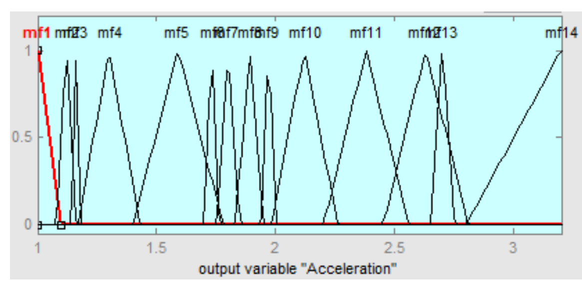


Fig. 12: Membership Function for Acceleration

1. If (SpindleSpeed is Low) and (FeedRate is Low) and (DepthOfCut is Low) then (Acceleration is mf1) (1)
2. If (SpindleSpeed is Low) and (FeedRate is Low) and (DepthOfCut is Medium) then (Acceleration is mf3) (1)
3. If (SpindleSpeed is Low) and (FeedRate is Low) and (DepthOfCut is High) then (Acceleration is mf5) (1)
4. If (SpindleSpeed is Low) and (FeedRate is Medium) and (DepthOfCut is Low) then (Acceleration is mf1) (1)
5. If (SpindleSpeed is Low) and (FeedRate is Medium) and (DepthOfCut is Medium) then (Acceleration is mf4) (1)
6. If (SpindleSpeed is Low) and (FeedRate is Medium) and (DepthOfCut is High) then (Acceleration is mf8) (1)
7. If (SpindleSpeed is Low) and (FeedRate is High) and (DepthOfCut is Low) then (Acceleration is mf4) (1)
8. If (SpindleSpeed is Low) and (FeedRate is High) and (DepthOfCut is Medium) then (Acceleration is mf9) (1)
9. If (SpindleSpeed is Low) and (FeedRate is High) and (DepthOfCut is High) then (Acceleration is mf11) (1)
10. If (SpindleSpeed is Medium) and (FeedRate is Low) and (DepthOfCut is Low) then (Acceleration is mf2) (1)
11. If (SpindleSpeed is Medium) and (FeedRate is Low) and (DepthOfCut is Medium) then (Acceleration is mf4) (1)
12. If (SpindleSpeed is Medium) and (FeedRate is Low) and (DepthOfCut is High) then (Acceleration is mf8) (1)
13. If (SpindleSpeed is Medium) and (FeedRate is Medium) and (DepthOfCut is Low) then (Acceleration is mf4) (1)
14. If (SpindleSpeed is Medium) and (FeedRate is Medium) and (DepthOfCut is Medium) then (Acceleration is mf7) (1)
15. If (SpindleSpeed is Medium) and (FeedRate is Medium) and (DepthOfCut is High) then (Acceleration is mf9) (1)
16. If (SpindleSpeed is Medium) and (FeedRate is High) and (DepthOfCut is Low) then (Acceleration is mf6) (1)
17. If (SpindleSpeed is Medium) and (FeedRate is High) and (DepthOfCut is Medium) then (Acceleration is mf9) (1)
18. If (SpindleSpeed is Medium) and (FeedRate is High) and (DepthOfCut is High) then (Acceleration is mf13) (1)
19. If (SpindleSpeed is High) and (FeedRate is Low) and (DepthOfCut is Low) then (Acceleration is mf2) (1)
20. If (SpindleSpeed is High) and (FeedRate is Low) and (DepthOfCut is Medium) then (Acceleration is mf6) (1)
21. If (SpindleSpeed is High) and (FeedRate is Low) and (DepthOfCut is High) then (Acceleration is mf10) (1)
22. If (SpindleSpeed is High) and (FeedRate is Medium) and (DepthOfCut is Low) then (Acceleration is mf8) (1)
23. If (SpindleSpeed is High) and (FeedRate is Medium) and (DepthOfCut is Medium) then (Acceleration is mf10) (1)
24. If (SpindleSpeed is High) and (FeedRate is Medium) and (DepthOfCut is High) then (Acceleration is mf11) (1)
25. If (SpindleSpeed is High) and (FeedRate is High) and (DepthOfCut is Low) then (Acceleration is mf9) (1)
26. If (SpindleSpeed is High) and (FeedRate is High) and (DepthOfCut is Medium) then (Acceleration is mf12) (1)
27. If (SpindleSpeed is High) and (FeedRate is High) and (DepthOfCut is High) then (Acceleration is mf14) (1)

Fig. 13: Fuzzy Rules

ii. Fuzzy Rules

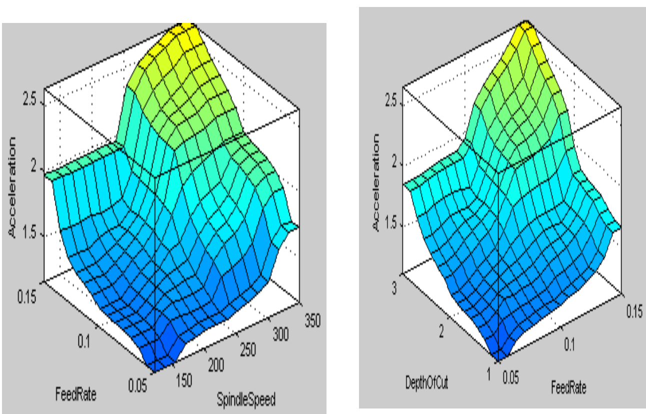
Based on three input variable and their three membership values a set of 27 rules have been constructed based on the actual experimental Acceleration. Figure 13 shows the set of rules.

iii. Defuzzyfication

Defuzzyfication is the conversion of the fuzzy quantity to real value. The selection of the method is important as it greatly influences the speed and accuracy of the model. In this model, centroid of area (COA) defuzzyfication method is used due to its wide acceptance and capability in giving more accurate result compared to other methods [15]. Figure 14 shows fuzzy surfaces between the Spindle Speed, Feed Rate, Depth of Cut and Acceleration.

iv. Prediction of Acceleration using developed Fuzzy Logic Model

Figure 15 shows an example of prediction of Acceleration using developed Fuzzy logic model.



The values of Spindle speed, Feed and Depth of cut are taken 125RPM, 0.05 mm/rev and 1mm respectively and the predicted value of Acceleration obtained by model is 1.03 m/s^2 which is shown in Figure 15.Rest of the prediction for each treatment combinations are shown in table 6.

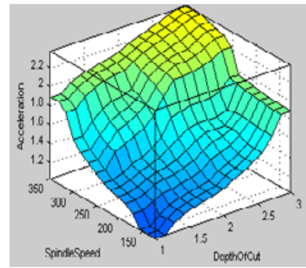


Fig. 14: Fuzzy Surface Plots between Spindle Speed, Feed Rate, Depth of Cut and Acceleration

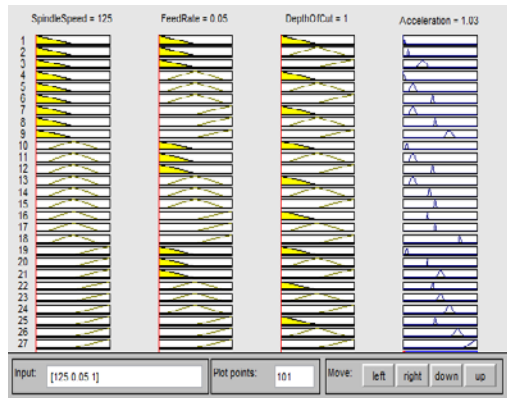


Fig. 15: Predicted Value of Acceleration Using Fuzzy Model

Table 6: Acceleration Values

Run order	Spindle Speed	Feed rate	Depth of cut	Experimental results	ANN predicted	Regression predicted	Fuzzy predicted
1	125	0.05	1	1.009661	1.0522	0.93745219	1.03
2	125	0.05	2	1.156552	1.1524	1.21784678	1.16
3	125	0.05	3	1.592348	1.5676	1.55009497	1.59
4	125	0.1	1	1.013119	1.0333	1.05405899	1.03
5	125	0.1	2	1.329162	1.3834	1.44817968	1.3
6	125	0.1	3	1.895578	1.9376	1.89415397	1.89
7	125	0.15	1	1.304193	1.2949	1.32593159	1.3
8	125	0.15	2	1.956258	1.9949	1.83377838	1.97
9	125	0.15	3	2.398151	2.365	2.39347877	2.38
10	250	0.05	1	1.079311	1.0678	1.05435189	1.12
11	250	0.05	2	1.297001	1.1806	1.38515928	1.32
12	250	0.05	3	1.88997	1.8651	1.76782027	1.96
13	250	0.1	1	1.308859	1.3191	1.29186279	1.35
14	250	0.1	2	1.801105	1.7487	1.68917638	1.91
15	250	0.1	3	1.996056	1.8828	2.13834357	2.18
16	250	0.15	1	1.737262	1.7279	1.68463949	1.77
17	250	0.15	2	2.013218	1.9501	2.14845928	2.3
18	250	0.15	3	2.701215	2.774	2.66413267	2.83
19	350	0.05	1	1.124168	1.1551	1.28971819	1.12
20	350	0.05	2	1.716078	1.6675	1.67093838	1.73
21	350	0.05	3	2.112353	1.8051	2.10401217	2.12
22	350	0.1	1	1.877681	1.8501	1.64813319	1.89
23	350	0.1	2	2.126821	2.0305	2.04863968	2.12
24	350	0.1	3	2.365218	2.6203	2.50099977	2.38
25	350	0.15	1	1.993757	1.9738	2.16181399	1.97
26	350	0.15	2	2.627641	3.0832	2.58160678	2.63
27	350	0.15	3	3.115454	3.0832	3.05325317	3.07

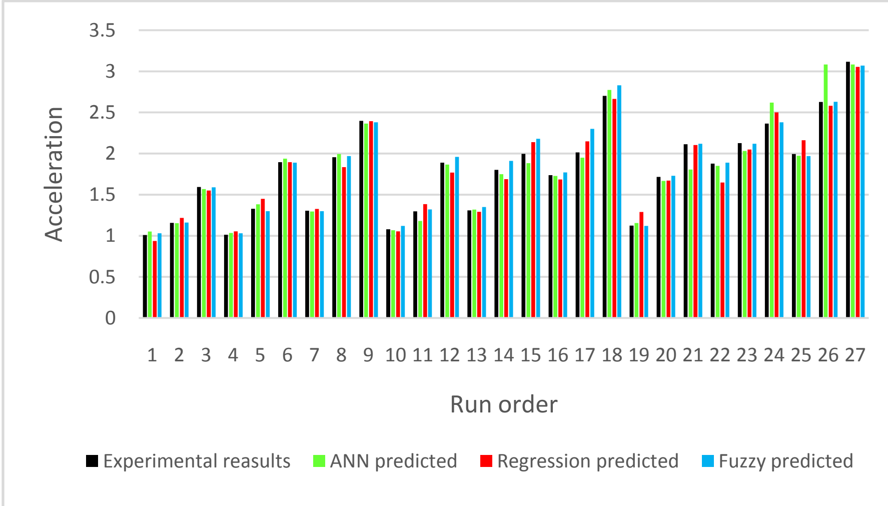


Fig. 16: Comparison of Acceleration Results with Different Model

V. Conclusion

- ANOVA shows that spindle speed, feed rate, and depth of cut are the most significant parameters. Their contributions are 20.73%, 33.52% and 40.72% respectively.
- For achieving minimum acceleration we have to keep spindle speed, feed, and depth of cut at low level.
- It is found that the average error related to Regression model, ANN model and fuzzy logic model are 3.7726%, 4.7852% and 2.32% respectively.
- The predicted and measured values are fairly close as shown in figure 16, which indicates that the developed models can be effectively used to predict the Acceleration in vibration monitoring with more than 95% confidence intervals.
- The work can be extended by measuring the surface roughness and geometrical tolerances viz. cylindricity, circularity, run out to know the impact of vibrations on it. Later on multi objective optimization can be carried out [17].

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