Experimental Investigation and Estimation of Spindle Bearing Vibration in Turning Process

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Abstract

Effective monitoring of a manufacturing process is essential for ensuring product quality. Excessive vibration is the major cause for premature bearing failure. A performance study of the spindle bearing has been studied in terms of vibration signals. Estimation of spindle bearing vibration was done by measuring bearing vibration in horizontal and vertical directions, flank wear of the tool, machining time and tool tip temperature. From the experimental investigation it was observed that the vibration velocity depends on the cutting conditions. For bearing vibration estimation methods like multiple Regression analysis and Group Method of Data Handling (GMDH) have been used. Multiple regression estimates gives better results for higher speeds. Three criterions were considered for GMDH. The comparison studies on the estimates of spindle bearing vibration by Multiple Regression Analysis and GMDH were made. It was observed that good correlation was observed for both multiple regression and GMDH. Among these, GMDH with regularity criterion gives better results.

1. Introduction

Vibration monitoring is one of the powerful methods commonly used in condition monitoring for predicting health of the machinery. The measurement of vibration signals involves installation of transducer as close as possible to the bearing being monitored so that clearest fault signal can be obtained. The ability of vibration based method to detect and diagnose a broad range of faults in a wide array of machine elements is one reason that it is often chosen as a preferred method. Monitoring and diagnostic systems are becoming increasingly necessary in improving the efficiency and reliability of the manufacturing systems. The main demand made of these monitoring and diagnostic systems is the estimation of vibration in machining process for on-line process optimization [1]. The present work involves an investigation regarding estimation of bearing vibration in turning process. For the estimation, the dependant variables are flank wear (maximum and average), machining time, tool tip temperature along with the cutting conditions. The experiments have been conducted on SG cast iron using multi-layer coated carbide tool. The emphasis is on the approaches that are capable of integrating information from multiple sensors. Hence, methods like Multiple Regression Analysis and Group Method of Data Handling (GMDH) have been applied for the estimation of bearing vibration. Finally, comparison studies of vibration estimates were made.

2. Estimation Methods

For the estimation of spindle bearing vibration, estimation methods like Multiple Regression Analysis (MRA) and Group Method of Data Handling (GMDH) have been used.

MRA is an appropriate method when the research problem includes one dependent variable that is related to more than one independent variable. The general purpose of MRA is to learn about the relationship between several independent variables and a dependent variable. The objective of this analysis is to use the independent variables whose value is known to predict the value of the unique dependent variable selected by the researcher. The MRA is used to construct a model that explains, as much as possible, the variability in a dependent variable, using several independent variables. The model fit is usually a linear model, though some times non-linear models such as log-linear models are also constructed. [2]

The GMDH was first developed by Ivakhnenko as a multivariate analysis method for complex system modeling and identification. It constructs high-order regression type models beginning with a few basic quadratic equations and generates gradually more complicated models based on the evaluation of model performances on a set of multi-input, single-output data pairs. The algorithm GMDH is ideal for complex, unstructured systems where the investigator is only interested in obtaining a high-order input-output relationship. The approach is to fit a high degree polynomial using a multilayered network like structure. Each element in the network is a partial polynomial (a quadratic function) of two inputs. The co-efficients of quadratic function are determined by data from the training set [3]. All possible combinations of inputs, taken two at a time, are evaluated. The combinations that are allowed to pass to next layer and self-organizing is terminated when optimum complexity is reached by evaluation of a criterion function from data in checking set. Three different criterions are considered like Regularity criterion, Unbiased criterion and Combined criterion. Regularity criterion has good predictive power but sensitive to noise. Unbiased criterion selects models that are insensitive to data from which it is built and hence gives good noise immunity but may not have good predictive power. Combined criterion is the combination of regularity and unbiased criterions.

Luke Huang and Joseph Chen [4] in their paper have discussed about the prediction of surface roughness in turning operation by using vibration signals. A multiple regression model was developed that was capable of predicting the in-process surface roughness of a machined work piece using turning operation. The multiple regression model uses machining parameters such as feed rate, spindle speed, depth of cut and vibration information as predictors. The prediction accuracy was above 90%.

Mandara Savage and Joseph Chen [5] have discussed about the multiple regression based multilevel in-process surface roughness recognition system in milling operations. A multiple regression analysis approach was used to develop surface roughness recognition system. To develop this system precisely, the variables chosen were feed rate, spindle speed, depth of cut, Vibration etc. It was concluded that the surface roughness recognition system demonstrated 82% accuracy of prediction average.

Ivakhnenko [6] have described the use of algorithms of Group Method of Data Handling (GMDH) in solving various problems of experimental data processing. They highlight that, the choice of an algorithm depends mainly on the accuracy & completeness of information presented in the sample of experimental data and on the type of the problem to be solved. Solving practical problems and developing theoretical questions of the GMDH produced a wide spectrum of computing algorithms. They infer that GMDH can be effectively used for various applications.

Ravindra, et. al., [7] in their paper have discussed about the multi-sensory approaches based on force, vibration and AE signals as potential methods for tool wear monitoring. In their work, steady-state components of force, dynamics of the main cutting force and vibration have been used for on-line tool wear estimation in a turning process. The GMDH, a heuristic self-organizing method of modeling, has been used to integrate information from different sensors to obtain estimates of tool wear. The results show that GMDH can be effectively used to integrate sensor information and obtain reliable estimates of tool wear.

Heung Suk Hwang [8] discussed about usage of GMDH and their application to forecasting of mobile communication systems. At present, the GMDH family of modeling algorithms discovers the structure of empirical models and it gives way to get most accurate identification and demand forecasts. Therefore, many types of nonlinear systems can be automatically modeled by using GMDH. A computer program is developed and successful applications are shown in the field of estimating problems of mobile communication with a number of factors considered.

3. Methodology

Experiments were carried out on an automatic precision lathe. The experimental work consisted of turning S.G. Cast iron using multi-layer coated carbide tool (HK 15). Spheroidal Graphite (SG) cast iron is used as work material because it has higher mechanical strength, ductility, excellent toughness and increased shock resistance. It is extensively used in automobile and machine tool industries. HK 15 coated carbide tool is used since it has got high wear resistant properties. Experiments were conducted by varying cutting speed and depth of cut with a constant feed of 0.208 mm/rev. Cutting conditions were selected as per the tool and work material combinations [9]. The turning operation was interrupted at regular intervals and the flank wear (maximum and average) was measured using Toolmaker’s Microscope. The tool tip temperature was measured using Heat spy digital infrared thermometer device. Vibration signals were recorded at front and rear spindle bearings housing along horizontal and vertical directions using the instrument Machine Condition Tester T-30. The experimental data obtained was used to estimate the bearing vibration by applying analysis methods like Multiple Regression Analysis and Group Method of Data Handling. GMDH estimates were obtained for various percentages of data viz., 50 %, 62.5 % & 75 % in the training set using Regularity, unbiased and combined criterions. Finally the estimates of bearing vibration obtained by MRA and GMDH were compared with the measured bearing vibration.

4. Results and Discussion

Experimental results are presented, so that a clear insight can be obtained about the signals involved. Functional relationship between the parameters obtained have been plotted to derive a basis for more detailed analysis.

Fig. 1 and Fig. 2 show the measured vibration in horizontal and vertical direction respectively at cutting speed of 377.142 m/min and depth of cut 0.5 mm.

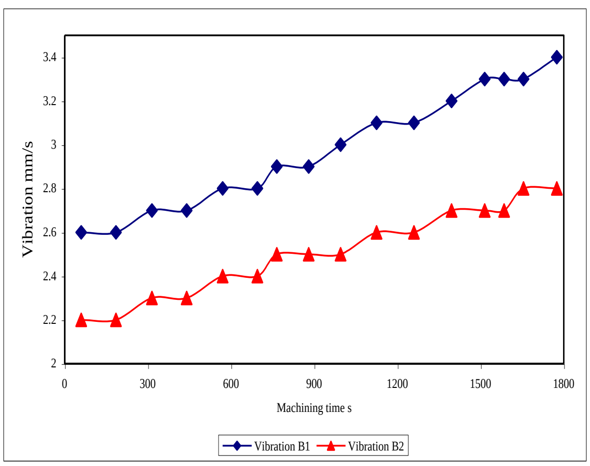

Fig. 1: Vibration in horizontal direction

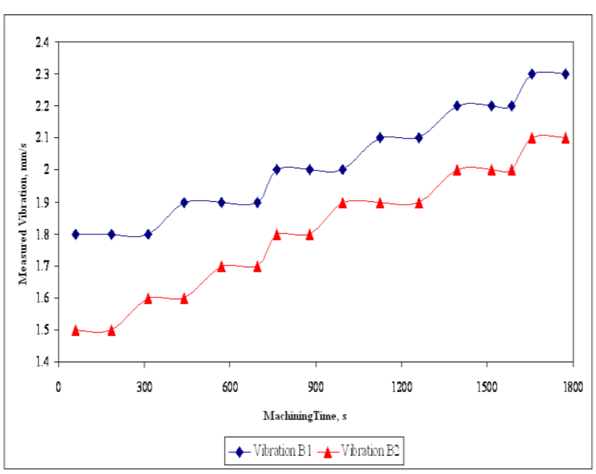

Fig. 2: Vibration in Vertical direction

From the plots, it was observed that vibration in front bearing housing (B1) is more compared to rear bearing housing (B2). This is due to higher order compliance of front end bearing assembly. The lathe structure is stiffer in the vertical direction. Hence, the vibration in horizontal direction is more when compared to vertical direction. The same trend follows for the vibration measurement experiments under various cutting conditions. Since the vibration at front bearing housing is more, front bearing is considered as the critical bearing and further studies has been concentrated on front bearing.

The signals from the cutting process have been recognized as stochastic due to the existence of inevitable material property variations and other uncertainties. Hence bearing condition diagnosis based on a machining signal was not found to be efficient and consistent. Hence an attempt was made to extract maximum possible information from multiple signals such as tool tip temperature, bearing vibration, and flank wear. To investigate the dependence of vibration, estimation of vibration and AE parameters was carried out using Multiple Regression Analysis (MRA) and Group Method of Data Handling (GMDH).

Fig. 3 and Fig. 4 give the estimates of bearing vibration in horizontal and vertical direction respectively by using Multiple Regression Analysis.

Referring to the figures, it was observed that most of these estimates closely represent the observed trend of bearing vibration especially at higher cutting speeds. Under these conditions, there will be a larger amount of load on the bearing which results in higher vibration. Hence it results in better correlation between cutting conditions and vibration. It was also observed that the estimates of bearing vibration in horizontal direction correlate well with the measured vibration when compared to estimates of bearing vibration in vertical direction.

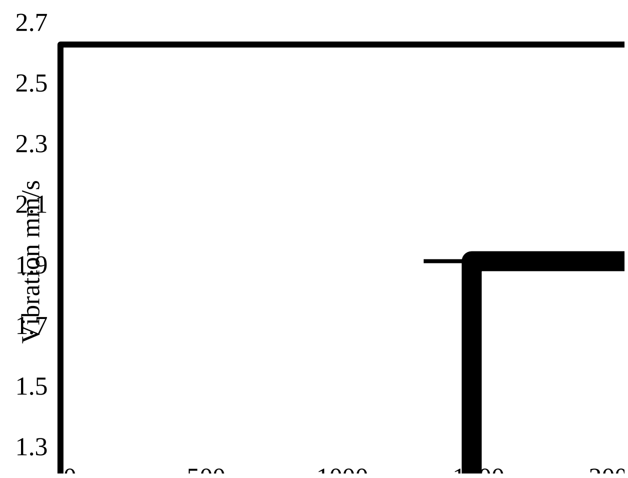

Fig. 3: MRA vibration estimates in horizontal direction

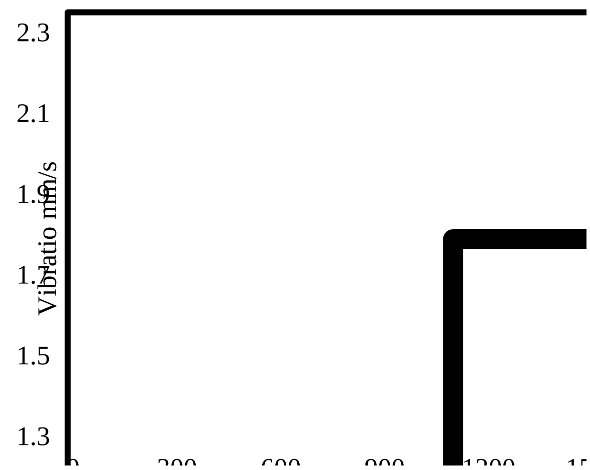

Fig. 4: MRA vibration estimates in vertical direction

Estimation of vibration was obtained by using GMDH for various cutting conditions. GMDH estimates were obtained for various percentages of total data in the training set viz., 50%, 62.5% & 75%. Different criteria viz., Regularity, Unbiased & Combined were used for guiding the self-organization procedure. The independent variables considered are cutting speed, feed, depth of cut, machining time, flank wear (avg.), tool tip temperature and vibration along horizontal and vertical directions.

Fig. 5 shows GMDH estimates of vibration in horizontal direction using different percentages of data in training set at a particular cutting condition considering flank wear (avg).

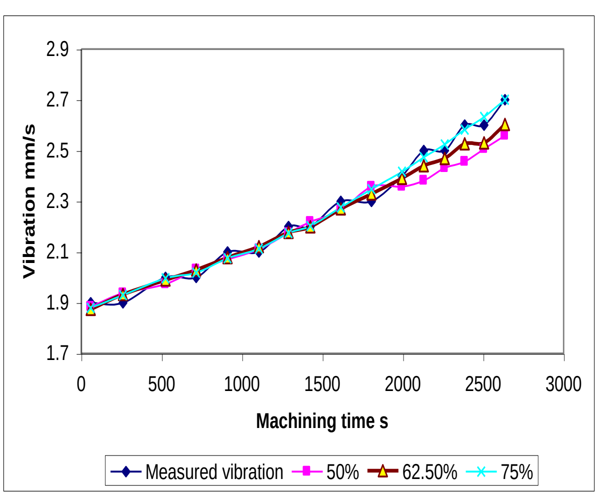

Fig. 5: GMDH estimates in horizontal direction for various % of data in training set

From the figure, it was observed that the vibration estimates obtained using 75% of data in training set correlates well with the measured vibration. This may be because, as the data in the training set is more, capability of the algorithm to learn and estimate will be more. From the analysis, it may be inferred that least error and best fit is found when 75% of data is used in the training set. Hence, for estimating vibration using GMDH 75% of data will be considered.

Fig. 6 and Fig. 7 shows GMDH estimates of vibration in horizontal and vertical direction using different criteria at a particular cutting condition considering 75% of data in the training set.

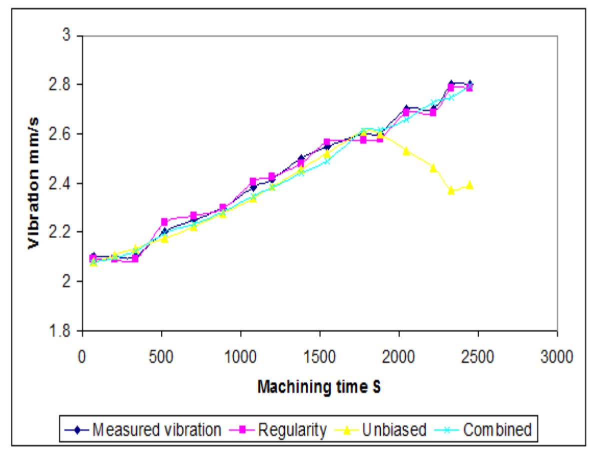

Fig. 6: GMDH Estimates in horizontal direction

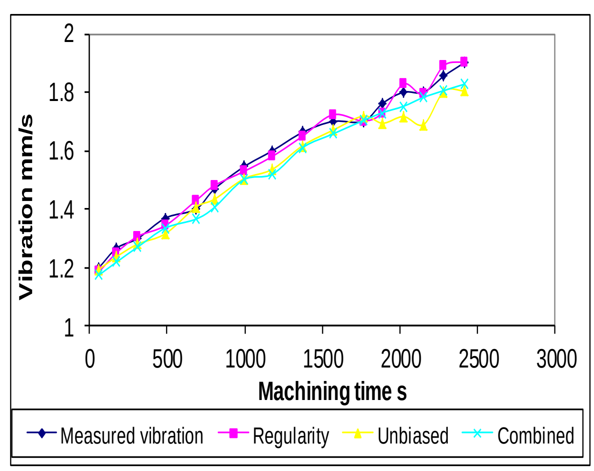

Fig. 7: GMDH Estimates in vertical direction

Referring to the figures, it was observed that the vibration estimates obtained using regularity criterion correlates well with the measured vibration. Unbiased criterion does not have good predictive power and usually tends to wrongly estimate the variations in the

dependent variable. Also, GMDH estimates in horizontal direction are found to be good compared to estimates in vertical direction.
Finally, the bearing vibration estimates from MRA and GMDH were compared. Fig. 8 shows the comparison of vibration estimation in horizontal direction at a particular cutting condition. For GMDH, estimates from regularity criterion with 75% data used in training set are considered for comparison. From the graphs, it was observed that good correlation is obtained for Regularity criterion.

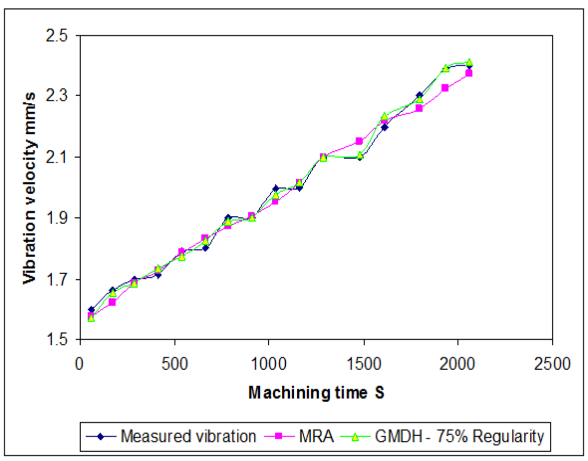

Fig. 8: Comparison of GMDH and MRA estimates of vibration in horizontal direction

5. Conclusion

Experiments were performed by turning S. G. Cast iron using multi-layer coated carbide tool (HK15). Performance of front & rear spindle bearing in terms of vibration signal has been studied under various cutting conditions. From the vibration analysis, it was observed that the as the load acting on the bearing increases, vibration shows an increasing trend. The value of vibration in front spindle bearing housing along horizontal direction was more compared to vertical direction. Thus front spindle bearing was found to be critical as it is nearer to the chuck and also experience frequent variation of load. Estimation of spindle bearing vibration was carried out using MRA and GMDH. In estimating vibration MRA, it was observed that the vibration estimates are correlating well with the measured vibration at higher cutting speeds. In estimating spindle bearing vibration through GMDH, least error and best fit was found when regularity criterion with 75% of data for training was used. Comparing MRA and GMDH, GMDH with regularity criteria proved to be the better method.

6. References

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