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A systematic solution methodology for inferential multivariate modelling of industrial grinding process

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ABSTRACT

The need for precision components and parts in manufacturing industries has bought an increase in the need for finishing operations that can satisfy this demand. In addition, there is a continuous demand for hard and tough materials that can withstand varying stress conditions to ensure prolonged service life of components and parts. The need to process these materials economically so as to meet stringent product quality requirements (generally expressed as composite of a family of properties, so-called multiple response characteristics) has become a real challenge for researchers and practitioners in manufacturing industries. Grinding has the potential to meet these critical needs for accurate and economic means of finishing parts, and generate the required surface topography. Despite this importance and popularity, grinding still remains one of the most difficult and least-understood processes due to lack of adequate inferential mechanistic and analytical multivariate models, for varied industrial situations. In this context, data-driven inferential linear or nonlinear multiple statistical regression, and artificial neural network modelling have become increasingly popular techniques for complex industrial grinding processes. Unfortunately, these techniques are either proposed and implemented in isolation or presented as a comparative evaluation grinding case study. A systematic solution methodology for inferential multivariate modelling, which addresses the different phases, starting from preliminary linear random *x*-case multivariate regression model, hypothesis testing of influence of addition of higher-order nonlinear terms to the adequate linear model (or presence of nonlinearity), and subsequent selection of a suitable nonlinear artificial neural network-based multivariate model, is lacking. In view of the above-mentioned conditional requirements, this paper attempts to provide a systematic methodology to develop a multivariate linear regression model, hypothesis testing for the influence of nonlinear terms to linear model, and accordingly selection of a suitable artificial neural network-based inferential model with improved prediction accuracy and control of grinding behaviour. The methodology suggests the use of various statistical techniques, such as Q–Q (quantile–quantile) plotting, data transformation, data standardization, outlier detection test, model adequacy test, model cross-validation and generalization. The suitability of the recommended methodology is illustrated with the help of an engine cylinder liner grinding (honing) case example, in a leading automotive manufacturing unit in India.

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1. Introduction

The technology of grinding has grown substantially over time owing to the contribution from different branches of engineering with a common goal of achieving higher machining process efficiency. As the complexity and dynamics of industrial scale grinding processes increased substantially, researchers and practitioners focused on data-driven inferential mathematical modelling techniques (Warne et al., 2004; Mukherjee and Ray, 2006a), such as statistical regression (Rencher, 1995; Montgomery and Peck, 1992), artificial neural network (Fu, 2003) and fuzzy set theory (Zadeh, 1965; Zadeh, 1973a,b) for process behaviour prediction and control. A significant improvement in process efficiency may be obtained by inferential modelling that identifies and determines the critical process variables leading to desired outputs or responses with acceptable variation, ensuring a lower cost of manufacturing.

Inferential modelling remains as a challenging problem in industry scale grinding, mainly because of the following reasons:

(a) Unlike in many other conventional machining processes where cutting is performed by a defined cutting edge, grinding is performed by a number of abrasive particles which are randomly oriented in a grinding stone with varied controlled kinematic motions of the wheel and the work piece to generate the desired surface topography. Therefore, it is not possible to maintain close surface finish or control dimensional accuracy of hard particles which affect the cutting process (Chen and Kumara, 1998).
(b) Grinding processes involve a high operational cost due to slow material removal rate which makes it necessary to maintain grinding processes near target process conditions.
(c) Systematic designed experiments for response surface design are usually costly and time consuming, and off-line. The products manufacturer during experimentation will often be scrapped, and experimentation conditions may be biased and substantially differ from actual production environments (Coit et al., 1998).
(d) Despite the extensive development in process control theory, conventional process control techniques still fall short of providing effective control means for complex grinding processes (Shin and Vishnupad, 1996).
(e) No comprehensive inferential mechanistic model exists, relating input variables, in-process parameters, and multiple responses to varied grinding process conditions (Lee and Shin, 2000).

In view of the above-mentioned conditional requirements, inferential models for industrial grinding processes are often based on direct production observations, which do not incur any addition data gathering cost, includes the effect of actual production environments, and ensure fidelity with operational conditions (Coit et al., 1998). In addition, for multiple response surface design, the multivariate response function may be multi-modal in nature.

Several inferential mathematical modelling techniques in grinding operation have been reported in the literatures. Back propagation algorithm-based artificial neural network (BPNN), proposed by Rumelhart et al. (1986), have been successfully applied for modelling (a) a typical creep feed super alloy-grinding (Sathyanarayanan et al., 1992), (b) prediction of material removal rate and surface finish parameter of a typical abrasive flow machining (Jain et al., 1999), and (c) a honing operation of engine cylinder liners (Feng et al., 2002). Shin and Vishnupad (1996) provide an intelligent grinding process control scheme based on neuro-fuzzy optimization approach. Chen and Kumara (1998) use a hybrid approach of fuzzy set theory and artificial neural network-based technique (ANN) for modelling a grinding process. Petri et al. (1998) develop and propose a back propagation neural network model for predicting surface finish and dimensional changes in a grinding process. Lee and Shin (2000) use fuzzy set theory for modelling grinding processes. Kwak (2005) propose a second order response surface model for determining the setting of process parameters for minimization of output part quality characteristics. In this context, Mukherjee and Ray (2006a) critical appraise different inferential empirical modelling techniques for metal-cutting processes, such as grinding, turning, and milling.

Although, various tools and techniques have been proposed in literatures, a systematic methodology for inferential multivariate response surface modelling, using preliminary linear random *x*-case multivariate regression, hypothesis testing of the influence of addition of higher-order non-linear terms (if the linear model is found to be satisfactory), and subsequent selection of an appropriate nonlinear multivariate regression model to improve the grinding model predictive performance, is lacking. Fuzzy set theory-based techniques suffer from few shortcomings, such as rules development is usually based on process expert(s) knowledge, and their prior experiences and opinion(s), which are not easily amenable to dynamic changes of underlying grinding process. It also does not provide any means of utilizing analytical models of metal cutting processes (Shin and Vishnupad, 1996). In this context, artificial intelligence-based neural network (ANN) techniques may provide an adequate static or dynamic inferential model, which is independent of any prior assumptions or knowledge on the functional form of the input-output relationship(s). However, open literatures only demonstrate the potential of ANN technique, either in isolation or as a comparative evaluation study (Govindhasamy et al., 2005; Mitra and Ghivari, 2006; Mukherjee and Ray, 2006b), with little emphasis on preliminary data analysis, critical steps involved for fitting and selection of a suitable linear multivariate and ANN model.

It is in this context, a systematic solution methodology for data-driven inferential linear multivariate random *x*-case and nonlinear artificial intelligence-based neural modelling is proposed in this research work. The application of the proposed methodology is illustrated based on data analysis of grinding (honing) case examples of a typical 6-cylinder diesel engine in a leading automotive manufacturing unit in eastern part of India.