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A Kriging modeling approach applied to the railways case

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Abstract

This paper deals with Kriging modeling applied for optimizing the braking performances for freight trains. In particular, it focuses on mass distribution optimization to reduce the effects of in-train forces among vehicles, e.g. compression and tensile forces, in-train emergency braking. Kriging models are applied with covariance structure based on the Matérn function, and by introducing specific input parameters to better outline the payload distribution on the train, by also evaluating the shape of the payload distribution. Satisfactory results have been obtained considering compression forces, tensile forces and their sum, and by also evaluating residuals and diagnostic measures.

Keywords: experimental design; computer experiments; Kriging; braking system

1. Introduction

Among the different statistical models applied to engineering and technological issues, Kriging modeling is one of the most important since it allows for using simulations through computer experiments and, further, to deal with a specific and suitable covariance structure for data. Moreover, through the Kriging modeling, the experimental region is investigated by considering the reliability of prediction, e.g. the Kriging variance, which is smaller when the predicted point is located nearby the training set of starter data (X) and larger as moving away from X. In literature, starting from the seminal contribution of Sacks et al. (1989), the studies on Kriging have been particularly developed since 2000. Regarding to the definition of the covariance structure for the stochastic part of the model, novel issues are suggested by Del Castillo et al. (2015), while Pistone and Vicario (2013) focus a peculiar attention on the strong correlation for spatial data. Zhou et al. (2011) deal with Kriging modeling by also considering qualitative variables. Arcidiacono et al. (2012) have also developed research activities with the support of Lean Six Sigma. However, Kriging modeling approach was more appropriate for this particular application: when considering computer experiments and Kriging

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modeling, a crucial feature is the design of such an experiment. In this regard, Space-Filling design are widely accepted as one of the most appropriate one. This is mainly due to the fact that they allocates the design points as uniformly as possible in order to observe the response in the entire design space. The most widely used class of Space Filling design for computer experiment is that of Latin Hypercube Design (LHD) introduced by McKay et al. (1979). This work is based on the research of Arcidiacono et al. (2017) where the innovative contribution consists in applying Kriging models to the railway field, in order to optimize the payload distribution of freight trains. In particular, the procedure is applied to evaluate the braking performance (considered in terms of in-train forces exchanged by consecutive vehicles of train) of a freight train transporting scrap material. Kriging modeling is applied by investigating the whole experimental region of a simulated experimental design generated by LHD based on Sobol sequencies, which ensures a valid choice of simulated trains. In order to increase the accuracy of the obtained results, the computer experiments are performed through the software TrainDy by Cantone (2011), whose pneumatic model is described by Cantone et al. (2009) and is certificated internationally for this type of calculation. The manuscript is organized as follows. In Section 2 the basic theoretical and modeling issues on Kriging methodology are briefly described. In Section 3 the Kriging model results related to the optimization of the payload distribution of freight trains are reported. Future research that are currently carried out are briefly described in Section 4.

2. Kriging methodology: theoretical issues

The seminal contribution of Sacks et al. (1989) introduced a concept of simulated designs substantially different by the physical and classical experimental designs of Cox and Reid (2000): the observation is predicted according to a simulated model of the process under study in order to deeply analyze the causal relationships between input and output variables. The seminal paper of Sacks et al. (1989) was the fundamental source for many and interesting papers published during 1980's and 1990's, where the basic theory of Kriging method for statisticians was developed; these new inputs introduced and faced a new concept of design and simulations, where the concept of deterministic model and the concept of experimental design were really changed.

Lets start by considering a set S of n experimental points $x_i \in X$ (input) and the corresponding response values (output) y_i, $i = 1, \dots, n$, e.g. $S = \{(x_1, y_1), \dots, (x_i, y_i), \dots, (x_n, y_n)\}$. Therefore, the set of trials X is selected within the experimental region, and each y_i is the realization of a random variable $Y(X)$. The Kriging method is carried out in order to predict new simulated observations on the basis of the information gained through S. The final aim is an optimal prediction of Y through a statistical model involving a deterministic part, $\mu(x)$ also named trend function, and a stochastic part, $Z(x)$ the latter replacing the error component for a standard statistical model, as in the following formula:

$$Y(x) = \mu(x) + Z(x) \tag{1}$$

The main type of Kriging mainly applied could be summarized as follows:

1. Ordinary Kriging that assumes a non random constant deterministic part ($\mu(x) = \mu$) so as in this case the trend function does not vary in time and space, while Z(x) identifies a spacial stochastic process that here reduces to the covariance between any two points.
2. Universal Kriging that assumes a no more constant trend that is modeled through some regression function $f(x)$.

Prediction is based on the allocation of a simulated experimental point by taking into account the covariance structure of the data and the set S of starting real experimental data. To this end, in order to achieve a satisfactory prediction, it is relevant to define a fitting measure which assures: i) the best identification for the covariance structure; ii) the assumption of unbiasedness. In the literature, some measures are defined, also depending on the estimation method applied (Maximum Likelihood (ML), Ordinary Least Squares (OLS), moments method) and also depending on what we know of the real process, in particular when the covariance structure is unknown.

When considering the Kriging modeling applied at improving the assembling of freight trains, estimates are performed trough the ML method following the Empirical Best Linear Unbiased Predictor (EBLUP) property. In general, the covariance function mostly applied are related to the exponential, Gaussian and spherical models: in our case we