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A statistical analysis of the dynamic response of a railway viaduct

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ABSTRACT

A statistical analysis of the dynamic response of a railway viaduct, modelled after an actual structure, is presented. The finite element model of the viaduct is based on the data provided by the Portuguese Railway Company REFER EPE. The train load is simplified by a set of constant moving forces and the range of velocities implemented corresponds to typical velocities of circulation. The viaduct is composed of eight modules, but, for the sake of simplicity, only the first viaduct module is included in the analysis.

In order to perform the statistical analysis, the viaduct is subjected to a two-level factorial design. It is shown that key parameters cannot be analysed individually because in some cases interaction effects can be more important than single effects.

Response functions of significant results are presented. Their usage for dynamic response estimates is exemplified. Further it is shown how they can be used for the determination of a probability that a certain value of interest is exceeded, provided the range of key parameters corresponds to the interval of uncertainties, where the true value obeys the normal distribution.

This type of straightforward application of statistical analysis highlights the interaction of adequately selected key parameters, provides useful information for design guidelines and is believed to lead to better planning and more realistic representation of the actual response of railway bridges.

1. Introduction

1.1. General

Railway bridges are important connecting infrastructures that require specific design considerations supported by an adequate numerical modelling. The wide range of factors that influence the design, followed by the choice of the adequate numerical procedure, requires a fair amount of simplifications of this complex system.

Deterministic analyses of complex engineering structures can lead to wrong conclusions, because of uncertainties in the input data. Therefore a statistical treatment of input as well as output should be accomplished. In this context determination of key input data governing the dynamic response of the system is extremely important. Numerical models usually require calibration measurements to achieve the model/structure agreement. However, field measurements are also subject to experimental error.

Although simplified models of railway tracks are widely used, the growth in numeric and computational efficiency made complete models involving several structural details feasible and preferable. The computational speed is a very important factor and based on hardware and algorithmic efficiency has been constantly improving over the years. Therefore, some computationally intensive statistical methods have become usable. Statistical methods can enhance the analysis by providing results that are more realistic, and consequently give a better insight on the situation of interest and help in the calibration of the models.

1.2. Bridge and train models

Over the last centuries various types of bridge models have been developed to address the fundamental problems of bridge dynamics. Due to the rich history and considerable extent of the topic a general review would be unnecessarily lengthy. The progress in numerical methods, like the finite element (FE) method, presents very accurate and efficient modelling of complex mechanisms [1]. The components of the bridge and railway track can be modelled in a simpler or a more sophisticated manner depending on the objectives of the model [2].

There are essentially two cases of dynamic models: either with continuously distributed mass, or with lumped masses along the length of the bridge. Other models implement a combination of

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those two approaches. Some of the continuum models of simply-supported Euler–Bernoulli beams [2–4] were by far the most popular, due to their simplicity and ability to lead to closed-form solutions. These models are still frequently used, e.g. in the analysis of a bridge-track-train interaction [5]. Despite the fact that these continuum models are a good first approximation of the bridge system, their practical applicability is limited to bridges of simple configuration.

There are mainly three types of models with regard to loading: (i) the moving force model [6,7]; (ii) the moving mass model [8,9]; and (iii) the moving system model [10,11] that comprehends a system of masses, springs and dampers. In the present work the moving force model can be safely used since the ratio of the moving mass load over the mass of the bridge does not exceed 30% and the load velocity will not reach 20% of the critical one, as shown by parametric analysis [12]. This simplification was already used in the authors' previous work [13] and it is also mentioned in the monographs [1,2].

1.3. Design of experiments

To idealise railway bridges the associated components of the structure are subject to certain simplifications and the input data to a related numerical model are supplied with a certain level of uncertainty. The additional overall complexity of the problem can significantly mislead the calculated response when deterministic models are employed. Statistical method analyses implement data within a certain range and consequently the calculated response is determined with a certain probability of occurrence giving a better insight of this problem. This approach of combined dynamic response of bridges with statistical treatment by design of experiments is under growth in the scientific community. It can be found in [14] and related works of the first author. In Karalar et al. [15] statistical methods are applied to the analysis of isolation of bridges. Structural health monitoring (SHM) on bridges is another field of structural engineering that is currently employing statistical treatment [16,17].

Previous works addressing parametric analyses of railway bridges considered the influence of key parameters (factors) individually. It is clearly shown in many statistical publications [18–20] that this one-variable-at-a-time strategy fails frequently because it tacitly assumes that the maximising value of one variable is independent of the level of the other. Simultaneous consideration of the influence of several key parameters provides a better representation of reality.

Statistical analysis of numerical results allows to define a set of key input data and key results, in order to study complex mechanisms interactions and understand if the involved factors play a role in the response in an interactive or simply additive way. Key factors are selected by the user and the factorial experiment stands for the statistical analysis of the variance of the results due to the changes in the key input data. One of the possible usage of such outcomes is the calibration of numerical models. Then the determined key results identify the characteristics to be measured by in situ experiments [21] and the key input data serve for model calibration. The experimental design, if adequately adjusted to the situation can reduce significantly the experimental error. Another usage, implemented in this paper, is to consider the variations of key input data in accordance with the uncertainty of the actual values, i.e. to assume that the key input value occurrence within the specified interval verifies the normal distribution with the mean coincident with the middle value. Associated standard deviation has to ensure negligible probability outside this interval. Then from the approximate response function it is possible to determine the probability of exceedance of a certain result depicted by the user.

Dynamic analysis of a viaduct involves a large number of variables and is therefore unsuitable for a direct factorial analysis. It is preferable to run several parametric studies first and gradually select the most relevant factors. In a previous work [13] ballast stiffness, concrete stiffness, soil stiffness, train speed, ballast damping and rail-pad damping were selected as key factors. In this context the concrete stiffness is represented by Young's modulus. The main conclusions regarding peak displacements revealed dominance of single effects, led by the concrete stiffness for displacements at the deck level and by the train speed for displacements at the soil level. Peak accelerations showed strong interactions between factors led by the train speed and its interaction with the ballast stiffness. It was concluded that this interaction deserves more attention, which is conducted in this paper. Due to the fact that the influence of the concrete modulus is obvious and affects significant part of the model, this factor was omitted and attention was focused on the railway superstructure. It is shown that the superstructure parameters can influence significantly the global behaviour. In order to detail the ballast stiffness interaction with the train speed, also dynamically activated ballast mass, ballast constitutive model and damping are included in the analysis. The ballast behaviour model is considered in this paper as the only qualitative factor. Only one single force and one value for the reference train speed 180 km/h was used in [13]. Hence, special attention is placed here on the train speed and on a more realistic train model.

The question of whether the train speed is a valid factor in the two-level factorial analysis is addressed in detail. It is known (e.g. Yang et al. [1]) that structures subjected to repetitive moving loads increase their dynamic response at resonance speed. The analysis presented in Yang et al. [1] is valid for simply supported beam representing the bridge. This analysis can be extended to double beam with an elastic layer. Results are not easily obtainable analytically, but a simple model can be tested numerically. Details of this analysis are given in Section 4.1. It was concluded that within the range of typical train velocities it is safe to perform two-level factorial design, where one of the factors is the train speed.

Given the summary above the objectives and new contributions of this paper are:

(i) To check the existence of new dominating factors and interactions that influence the dynamic response results with importance on the superstructure.
(ii) To show numerically that interaction effects can be more important than single effects.
(iii) To establish the final response function and to calculate the probability of exceeding a certain value of interest.

2. The Santana do Cartaxo viaduct

Train specification and in situ measurements of the soil foundation properties were supplied by REFER EPE [22]. The case study refers to a location in the Portugal North Line, second sub-link Setil Sul Vale de Santarém, which develops from km 56 + 625 until km 65 + 287 and is part of the rehabilitation of the North Line. The Santana do Cartaxo segment, where a new railway was included over a viaduct built at km 59 + 000 to km 60 + 000 (Fig. 1) is an exception in the rehabilitation, which otherwise follows closely the original railway route design. A more detailed description of the structure can be found in previous work of the authors [13].

The viaduct is composed by a set of eight module sections in the longitudinal direction. Each module is connected to the other through transition pillars which are larger and have more piles than the intermediate pillars. Designating by ascending direction (AD) the one from south to north and by (DD) the descending and opposite one, then the first of the eight modules comprises three spans of 25, 30, and 25 m, finalising a length of 80 m, while