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Statistical screening of modelling alternatives in train–bridge interaction systems

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ABSTRACT

The effect of parameter variations in railway bridges subjected to train loads has been evaluated within the framework of a two-level factorial experiment. Especially, the influence of train–bridge interaction in comparison to other parameter variations is highlighted. Variations in the system parameters were introduced, corresponding to modelling alternatives considering reasonable uncertainties in a bridge design model. The dynamic effect from a passenger train set has been evaluated at, and away from, resonance in beam bridges of span lengths 6, 12, 24 and 36 m. By means of the two-level factorial design, effects from changes in a single parameter, as well as joint effects from simultaneous changes in several parameters, may be evaluated. The effect of including train–bridge interaction through a simple vehicle model as opposed to moving forces was found most distinct at resonance. The effect of the choice of load model was furthermore shown largest for the bridges of span length 24 and 36 m, where it was found more influential or comparable to the effect of other system parameter uncertainties. The high influence of the load model may well be attributed to the fact that the natural frequencies of the 24 and 36 m bridges are close to the vertical frequency of the primary suspension system of the train. The reduction of response obtained with the train–bridge interaction model are discussed in relation to bridge frequency rather than span length, and compared to the Additional Damping Method given in the European design code.

1. Introduction

Following the increased demand on existing railway networks, as well as the vision of a well-developed network of high-speed railway lines, increased knowledge in the field of train, track and bridge engineering is needed. Especially the demand for higher speeds and longer train sets requires knowledge in the best practices of modelling the dynamics of the railway bridge-vehicle system. Dynamic train loads on bridges are usually simulated with a moving force (MF) model [1–6]. During the last few decades much attention has been focused on the issue of train–bridge interaction. In this context the dynamics of the train system is included in the model as a moving system (MS) composed of masses connected by springs and dampers [1,7–10]. To consider train–bridge interaction may in certain cases reduce the bridge response; furthermore, it enables the study of effects from track irregularities and the evaluation of passenger comfort criteria. Comparisons between the MF model and the MS model have been performed in for example [11–19]. More specifically, it has been confirmed [20–25] that several system parameters govern whether a MS model gives notably different results compared to the MF model. In [17] it is concluded that the reduction of bridge response from train–bridge interaction depends mainly on the primary suspension to bridge frequency ratio, the bogie to bridge mass ratio and the carriage length to bridge length ratio.

According to the European design code, Eurocode [26], a dynamic analysis is generally required in the design of railway bridges for speeds higher than 200 km/h. A limit is set for the bridge deck acceleration to avoid ballast destabilisation. The acceleration limit is an interesting subject of study as it is typically decisive in dynamic analyses [27]. It is furthermore sensitive to uncertainties in the system parameters. Thus, in this study, a two-level factorial experiment [28] was performed in order to evaluate the influence of variations in the system parameters in dynamic analyses of beam bridges. Especially, the influence of train–bridge interaction in comparison to uncertainties in other system parameters was highlighted. The results are compared to the Additional Damping Method (ADM) provided in the Eurocode [26]. The two-level factorial experiment is an efficient tool for the statistical screening of the effect of several factors on a process, or in this case, a model. Using factorial experimentation we are also able to detect whether any strong joint effects are present. These kinds of results are not available from screening procedures for

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one variable at a time; see for example [18]. Not many authors have used the two-level experiment concept in the context of bridge dynamics; available examples include [29,30]. Wiberg [29] implemented a factorial design studying individual and joint effects of several modelling factors in a detailed model of a prestressed concrete bridge, with the purpose of choosing the most influential parameters for model updating. In both [29,30] the train speed is included as one of the parameters in the experimental design. As the response does not vary linearly with speed, the speed was in the present study instead considered by performing analyses in a speed interval for each parameter combination. The effect of the studied parameters may thus be evaluated both at and away from resonance.

2. Experimental design

The flow chart in Fig. 1 depicts the methodology used in the statistical screening of modelling alternatives used in this study. It includes finite element (FE-) modelling with analyses according to a two-level (2^n) factorial design, in which 2 levels of $n = 6$ factors are evaluated, followed by a statistical evaluation of the results.

2.1. Two-level factorial experimentation

From the effect on a measurable response from variations (level 0 and level 1) in a chosen number of factors it is with the use of a factorial design possible to detect the most influential factors. It is also possible to detect joint effects, or parameter interactions, i.e. differences in the effect of one factor when another factor is varied from its high to its low level. If l replications of an experiment is performed and y_{ijkl} is the observation with factor A at level i, factor B at level j and factor C at level k, then the model equation for a 2^3 factorial design is given by [31]

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \rho_l + \varepsilon_{ijkl}, \quad (1)$$

where Y_{ijkl} is the estimated response, μ is the grand mean, α_i, β_j, γ_k are the effect of factor A, B and C, respectively, at level i, j and k. The estimated parameter interaction effect of the ith level of factor A and the jth level of factor B is given by $(\alpha\beta)_{ij}$, and so forth. The effect of the replicate l is given by ρ, and ε_{ijkl} are the error terms which are assumed to be random variables having a normal distribution with zero mean and variance σ^2. Furthermore, the effects are restricted to the conditions $\alpha_1 = -\alpha_0$, $\beta_1 = -\beta_0$, $\gamma_1 = -\gamma_0$. Equally, the sums of the two- and three-way interaction term effects are assumed zero, as well as the sums of the replication effects. As can be realised from Eq. (1), the change in the mean response μ from a change from level 0 to level 1 in one term corresponds to two times its effect α_i, β_j, γ_k,$(\alpha\beta)_{ij}$, ..., which is what will be referred to as the estimated effect, or simply the effect, of that term. Terms from main effects and parameter interactions are included in the model based on an F-test, testing mean squares (estimates of the variance σ^2) for a higher estimate of the variance from a between-treatment mean square, compared to the estimate of the variance from the error term. As an FE-model was used in this study, producing identical results for each run with unchanged input data, the experiment was performed without replication. With this in mind, the error in the statistical model may be estimated by pooling insignificant factors into the error term. Thereafter, the significance of each term may be evaluated using an ANOVA table, cf. [29,31]. Alternatively, a normal scores plot can be used to visualise the estimated effects and thereby distinguish the most important terms in the factorial model [28].

The choice of the low and the high level for each factor is critical and must be relevant for the problem at hand [32]. The factors may be quantitative or qualitative (on-off factors). As the two-level factorial model equation is linear, non-linear variations between the low and the high level of quantitative factors will not be detected. For a correct interpretation of the results, the chosen response variable should therefore be reasonably linear for changes in the quantitative factors within the range of the experiment.

2.2. Procedure of analysis

In the present study, 2^6 factorial experiments were performed on four different bridges. The six studied parameters are given in Table 1, with level 0 and level 1 values of which one is an on-off factor (the choice of load model type) and five are quantitative (axle load, beam stiffness, beam mass, beam damping ratio and rotational support stiffness). The variations from level 0 to level 1 were chosen to represent reasonable variations due to uncertainties in a bridge design model. The level 1 rotational stiffness of 0.8 GNm/rad represents a semi-encastré boundary condition, estimated using a procedure equivalent to the one used in [5]. The resulting ratio between the fundamental bridge frequency for the case of the constraint support condition and the hinged support condition is 1.03–1.23 for the herein studied bridges, which is comparable to findings in reference [33]. The response variables were chosen as maximum bridge deck acceleration and maximum bridge deck displacement, computed at 30 equally spaced sections along the beam. The FE-analyses were performed according to the 2^6 factorial design, and in the evaluation of the results the following procedures were used:

1. Inspection of response time histories and response versus speed plots to verify the results from the FE-models.
2. Normal probability plots and scatter plots of residuals to validate the factorial model.
3. Finally, normal scores plots of estimated effects for the evaluation of the most important terms.

Three out of the six factors in the factorial design (beam stiffness, beam mass and rotational support stiffness) affect the natural frequencies of the beam. Additionally, the simplified interaction

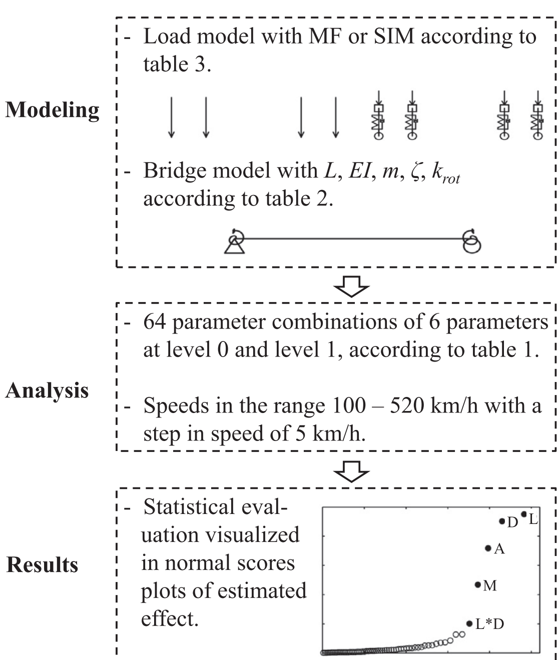

Fig. 1. The methodology used in the statistical screening of modelling alternatives.