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Relevance of a complete road surface description in vehicle–bridge interaction dynamics

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ABSTRACT

A fully coupled method for reproducing road vehicle–bridge dynamic interaction is presented in which finite element models are used for the structure, multibody dynamics models for the vehicles and interaction is represented by means of a contact with the linear penalty method. This model can reproduce structure, vehicle and interaction (lift-off) nonlinearities and has been implemented within an existing finite element commercial software. With regard to road irregularities a methodology for generating pairs of parallel profiles on the same road is developed and an expression for the coherence function of road surfaces, which simplifies the generation of such profiles, is proposed. These methods are applied to two different bridges. Results show the relevance of considering a complete surface definition when dynamic response of road bridges and vehicles is analysed. Bridge traffic-induced dynamic behaviour is the main issue in this study; attention is also paid to the vehicle vibration as it is also influenced by the road surface description. Lift-off model capabilities are shown by considering a bump on the bridge surface.

1. Introduction

Calculation of the dynamic effects produced by road vehicles when crossing over bridges and viaducts is used to assess the increase of dynamic forces and displacements with respect to the static results [1], this is commonly expressed as a Dynamic Amplification Factor or Dynamic Increment. On the other hand, dynamic models are also used for other issues; to assess the fatigue life of the different parts of the structure [2], for environmental vibration issues [3], to determine the safety and comfort of the traffic over bridges [4] or in structural health monitoring (SHM) [5]. In the last years, rise of vehicles masses and running speeds added to the fact that light and flexible bridges are more common have led to a consequent increase in dynamics influence.

Interaction models in which energy interchange between vehicles and structures is considered include the following main features: (1) dynamic model for structure subsystem; (2) dynamic model for vehicle subsystem; (3) interaction model; (4) road roughness description; and (5) numerical solution algorithms for the equations.

Vehicle models found in the literature can be arranged in three main groups with different level of complexity: 1D models where only vertical displacements of axles and body are included [6,7], 2D models in which the projection of the vehicle on a longitudinal vertical plane is considered and the movement is constrained to that plane [5,8] and 3D models where the whole automobile is modelled [1,3].

A common technique for simulating vehicle–bridge dynamic interaction is to solve vehicle and bridge subsystems independently; interaction is considered through an iterative process where force transmission and deflection compatibility are verified at each wheel. The most usual option amongst those methodologies is to use direct integration in time for vehicle and modal superposition for structures [1,8]. Another way to analyse dynamic interaction between vehicle and bridge consists of solving the fully coupled system [9,10]. In this approach vehicle and bridge masses, dampings and stiffnesses are stored in the same matrices. In Ref. [9] modal projection is employed for the bridge subsystem, hence bridge nonlinearities cannot be reproduced, and wheel-bridge separation is not allowed. In [10] another fully coupled method is presented but loss of contact is again not permitted.

In this paper a fully coupled model is proposed; vehicles are considered as three-dimensional Multi-Body Systems (MBS), structures are modeled by means of Finite Element Models (FEM) and dynamic interaction through a contact implemented with the penalty method. This model is capable of taking into consideration geometric and material nonlinearities from both the vehicle and

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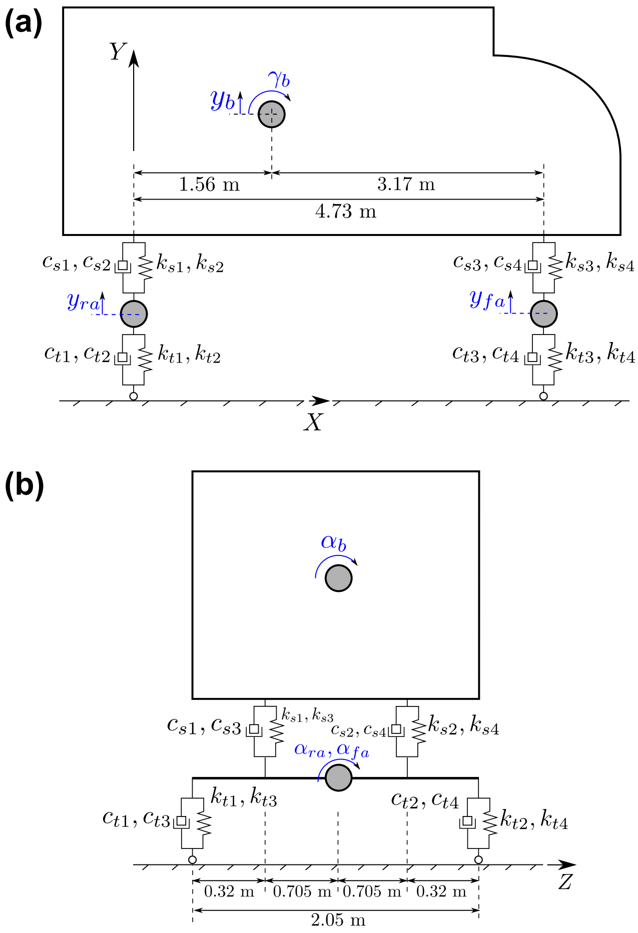

Fig. 1. H20-44 model: (a) Side view. (b) Rear view.

the structure. Moreover, unlike other methods wheel-road separation can also be reproduced. This model can be implemented within an existing finite element software with multibody capabilities. For the work presented in this paper Abaqus software was employed [11]. Structures can be modelled with any kind of finite element or even a combination of them; shell elements are used in this paper. This procedure has still some limitations: contacts between the bridge deck and the moving tires of the truck are assumed to be point contacts and there exists no lateral relative movement between the wheels and the bridge surface. Vehicles are assumed to run at constant speed, hence no longitudinal forces due to acceleration or braking are considered.

In general, road roughness is the main source of dynamic excitation in road dynamics. In site-specific problems the actual road profile can be measured and employed in the calculations. When the actual profile of a particular road stretch is not appropriate but a set of profiles that are representative of a certain sort of roads, stochastic definitions for the generation of synthetic profiles are used (e.g. [1,8,12]). It is a commonly assumed hypothesis that the randomness of the road surface roughness can be represented with a normal stationary ergodic random process described by means of its Power Spectral Density (PSD).

In road vehicle–bridge interaction is frequently assumed that the road profile is constant along deck width. This simplification can be found both when road profile is measured in situ and also when synthetic profiles are employed. This entails that the road profile is the same under all wheels. Nevertheless, when a four wheeled vehicle runs over a road, left and right wheels do not follow the same path, thus the profiles under each side tyres are different, but those profiles are not independent. This can only be considered when 3D vehicle models are employed.

Some attempts for considering this can be found in the literature, e.g. [13]. These procedures are complicated to implement and expensive to compute. As a result in almost all the work in this field difference between profiles is still being neglected, either when bridge response is studied [1,2,8,12] or when safety and comfort in vehicles is to be assessed, for example under cross winds [4,14]. A closed-form expression for the coherence function of road surfaces would simplify manifestly the problem.

Assumptions of surface homogeneity and isotropy are adopted in this work [15,16]. In order to compute the cross-PSD between both profiles a semi-analytical methodology is developed, that approach is explained in [17] where the dynamic behaviour of a vehicle running over a rigid pavement is studied. The semi-analytical approach is faster than the numerical one but calculation times are still long and implementation is not easy. Least-squares fitting is then employed and as a result an expression for the coherency function of road surfaces is proposed.

The main aim of this work is to study the influence of road surface description on the vehicle-induced dynamic response of bridges and to present a methodology to take this fact into account. An accurate definition of road roughness has a significant impact on vehicles dynamic behaviour, in consequence some results related to vehicle body vibration are presented.

In Section 2 of the paper models for vehicles, structures and their dynamic interaction are described and verified. Road roughness definition is detailed in Section 3. Two numerical applications are developed and analysed in Section 4. Finally, some conclusions from the work presented in the paper are summarised in Section 5.

2. Vehicle bridge interaction models

2.1. Vehicle

In this work a two-axle truck is employed; the model consists of three rigid bodies that represent the box and both axles. Each axle is connected with the box by springs and dashpots with the mechanical characteristics of the suspensions and is joined to the ground by the same kind of elements which represent the dynamic behaviour of the tyres. *X*,*Y* and *Z* axis are set longitudinal, upwards vertical and lateral respectively (Fig. 1). Vehicle body is assigned

Table 1
H20-44 mechanical properties; k_{ti} springs and c_{ti} dashpots represent vertical dynamic properties of tyres, k_{si} and c_{si} represent those corresponding to the suspensions.

Element	Notation	Value
Stiffnesses (N/m)		
Rear wheels	k_{t1},k_{t2}	1.57×10^6
Front wheels	k_{t3},k_{t4}	7.85×10^5
Rear suspensions	k_{s1},k_{s2}	3.73×10^5
Front suspensions	k_{s3},k_{s4}	1.16×10^5
Dampings (N s/m)		
Rear wheels	c_{t1},c_{t2}	200
Front wheels	c_{t3},c_{t4}	100
Rear suspensions	c_{s1},c_{s2}	3.5×10^4
Front suspensions	c_{s3},c_{s4}	2.5×10^4
Masses (kg)		
Rear axle	m_{ra}	1000
Front axle	m_{fa}	600
Body	m_b	17,000
Rotary inertias (kg m^2)		
Rear axle (roll)	$I_{\alpha,ra}$	600
Front axle (roll)	$I_{\alpha,fa}$	550
Body (roll)	$I_{\alpha,b}$	1.3×10^4
Body (pitch)	$I_{\gamma,b}$	9.0×10^4