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Letter to the Editor

Comments on "Vehicle–passenger–structure interaction of uniform bridges traversed by moving vehicles"

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1. Introduction

This recently published paper [1] is devoted to the important problem of the vibration of a bridge traversed by a vehicle. As noted in the Introduction, "This paper further investigates the dynamics of vehicle–structure interaction of a bridge traversed by moving vehicles taking into account the passenger dynamics" [1, p. 613]. The bridge is modelled as a simply supported Euler–Bernoulli beam with a smooth surface, and the vehicle, as a six-degree-of-freedom (6-d.o.f.) linear subsystem. For a particular system configuration with "arbitrarily chosen" parameters [1, p. 621], the authors numerically solve the problem of finding the "critical" speed, which is defined as a speed for which either the beam response or the bending moment takes its maximum value. The problem statement dealt with in the paper is quite standard, and the resulting system of differential equations is solved numerically by means of MATLAB and MAPLE solvers [1, p. 621].

Clearly, numerical examination of a model that is not a prototype of some real system is of little interest unless some general conclusions, which can be applied to other, more pertinent, configurations, arise. This paper does contain one important conclusion, namely, that the quarter-car (QC) model "does not provide adequate information for both vehicle dynamics and bridge characteristics" [1, pp. 623, 634]. If this conclusion were true, it might have a great impact on all studies in this field in view of the fact that the QC model is widely used by many researchers. Unfortunately, no attempt has been made in the paper to try to understand what the cause of the insufficiency of the QC model could be, and the conclusion relies solely on the comparison of numerical results obtained for the 6d.o.f. and QC models.

The basic purpose of this note is to show that this conclusion is not correct both for the particular system considered in Ref. [1] and as applied to a general bridge–vehicle system. To be more specific, the following two statements are valid: (1) The vibrations of the particular beam considered in Ref. [1] due to the 6-d.o.f. and 2-d.o.f. (QC) models do not differ; i.e., the conclusion

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about insufficiency of the QC model has been derived based on erroneous numerical results. (2) The vibrations of a bridge, with a smooth surface and zero initial conditions, due to different vehicle models with the same weight are about the same; i.e., it makes little difference as to which vehicle model is used as long as the bridge surface is smooth and neither vehicle nor bridge are vibrating at the moment when the vehicle enters the bridge.

2. Adequacy of the simplest vehicle models for modelling vibration of bridges with smooth surface

2.1. System considered in Ref. [1]

The conclusion reported in Ref. [1] is based on the comparison of the results for the 6d.o.f. and QC models, which are depicted in Figs. 9 and 10 [1] and demonstrate that the two solutions are different. However, upon due consideration of these figures, one can see that the results shown are obviously not correct, because … they simply cannot be correct. Indeed, consider, for example, Fig. 9 [1]. It shows that the beam deflections due to the two models are nearly the same when the vehicle is on the beam. However, when the vehicle leaves the beam, and the beam starts to vibrate freely, the picture suddenly changes, as if one bridge has been replaced by another. Most likely, the difference in the two solutions is simply due to a trivial error in the codes or input data.

To make certain that the curves in Figs. 9 and 10 are not correct, the author of this note carried out the computations with the QC model using the data given in Ref. [1] and compared the results obtained with those in Ref. [1]. The solutions for the QC model turned out the same as those for the 6-d.o.f. model in Ref. [1] for all speeds considered. The results corresponding to the speed 72 km/h are depicted in Fig. 1. The solid and dashed lines show the time histories of the beam

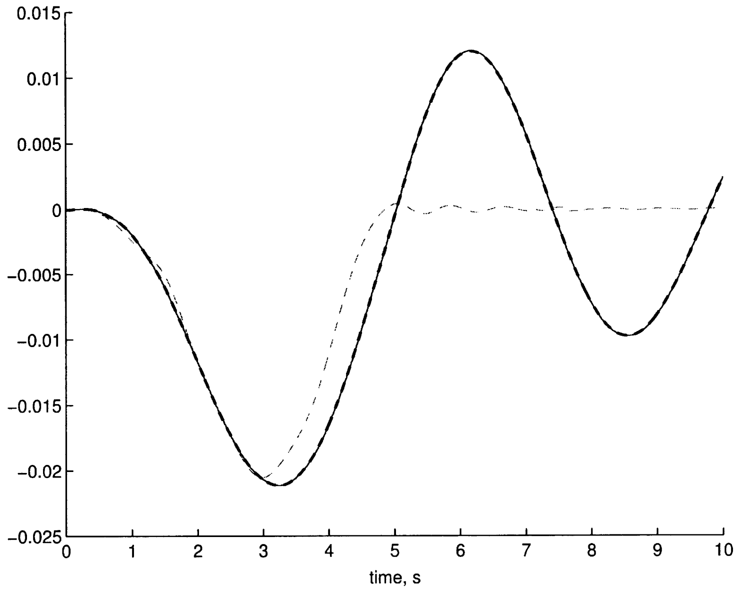

Fig. 1. Time history of the QC vehicle body bounce (dashed line) and mid-span deflections of the beam corresponding to the QC model (solid line) and the "moving force" equal to the vehicle weight (bold dashed line) for $v = 72\,\mathrm{km/h}$.

mid-span deflection due to the QC model and the displacement of the car body, respectively. As can be seen, these curves are evidently different from the solid lines in Figs. 9 and 10 [1], which correspond to the QC model, and, visually, look like the dashed curves corresponding to the 6-d.o.f. model, shown in the same figures.

Moreover, replacement of the QC model by a moving force equal to the vehicle weight resulted in the identical curve, which is depicted in Fig. 1 by the bold dashed line and coincides with the solid line corresponding to the QC model. The latter is explained by the fact that the bridge mass in this example is about 1000 times greater than the mass of the vehicle. As a result, the deflection of the 100-hundred-meter-long bridge is negligibly small (less than 2 cm at mid-span) and cannot excite sizeable vehicle vibration. The numerical experiments with this beam traversed by the QC model showed that the dynamic component of the tyre force was less than 1% of the vehicle weight for all speeds considered, which completely explains why the moving force and moving vehicle solutions coincide.

Finally, further evidence of error is available by noting that, in the example considered in Ref. [1], the total mass of the driver and passenger is less than a ten thousandth of the mass of the bridge. Obviously, the incorporation of these additional two degrees of freedom into the vehicle model cannot affect the vibration of this bridge.

2.2. *General case of a bridge–vehicle system*

The author's confidence in the fact that the difference in solutions obtained with the use of different vehicle models with the same weight is small in the case of a smooth roadway and zero vehicle and bridge initial conditions relies on the analysis of results reported in the literature, his own numerical experiments, and common sense. Here, referring to a "small difference" in two solutions, we mean some integral vibration characteristics, such as, e.g., maximum bridge deflection or the dynamic increment (DI), rather than the notion that these solutions are locally equivalent.

Examples substantiating this point can be found in numerous publications. Some results on the comparison of vibrations of various beams with a smooth surface due to different vehicle models (moving force, s.d.o.f., 2-d.o.f., and 4-d.o.f. oscillators) are presented in Refs. [2–4], which show that the difference in the DIs for the corresponding solutions is negligible. This statement again relies on common sense. Indeed, when a vehicle traverses a bridge with a smooth surface and enters with zero initial conditions (exactly the case considered in Ref. [1]), no sizeable vehicle vibrations are excited in view of the finiteness of the passage time and the relatively small amplitude of the bridge vibration (compared to the vehicle vibration excited by typical road surface irregularities). Then, the dynamic components of the contact forces are small compared to the vehicle weight, and the bridge vibration is determined mainly by the vehicle weight. The latter, in particular, implies that, in the case of a smooth bridge surface, even the model wherein the vehicle is represented as a moving force equal to the vehicle weight, the so-called moving force (MF) model, is often quite sufficient. This conclusion is justified by results reported in the multinational DIVINE project [5], which notes that "for a smooth profile, the influence of the truck suspension is insignificant," as well as by numerical results discussed in the previous section (Fig. 1).

3. Dependence of the maximum beam response on speed

It follows from the above discussion that no actual vehicle–structure interaction exists in the example considered: the bridge vibrates under the action of the weight of the moving vehicle. By taking into account that the damping in the beam considered is light, this implies, in particular, that the problem of finding the "critical" vehicle speed can be solved without intensive numerical calculations carried out in Ref. [1].

The relationship between the maximum beam deflection and the speed of the moving force can be obtained in analytical form [6]. The maximum deflection of a dimensionless, simply supported, undamped beam subjected to a unit moving force can be found as [6]

$$\max_x \max_t |w(x,t)| \approx \max_t |w(L/2,t)| = \frac{2}{\omega_1^2} \Phi_1(\beta_1), \tag{1}$$

where the function $\Phi(\beta_1)$ is shown in Fig. 2 (solid line), borrowed from Ref. [6], ω_1 is the beam fundamental frequency, $\beta_1 = v/v_1$ is the dimensionless speed, and $v_1 = \omega_1 L/\pi$. Eq. (1) is based on a one-mode approximation of the beam response, the error of which is shown to be less than 1% [6, Fig. 4] in the range of speeds of interest (including the range considered in Ref. [1]). Other details, such as, e.g., how to recalculate the response of a dimensionless beam into that of a dimensional beam, can be found in Ref. [6].

Substituting the beam data from Ref. [1], one can easily find that $v_1 \approx 152$ km/h. Thus, the speed range [40, 120] km/h considered in Ref. [1] corresponds to the interval [0.3,0.8] of β_1. In this

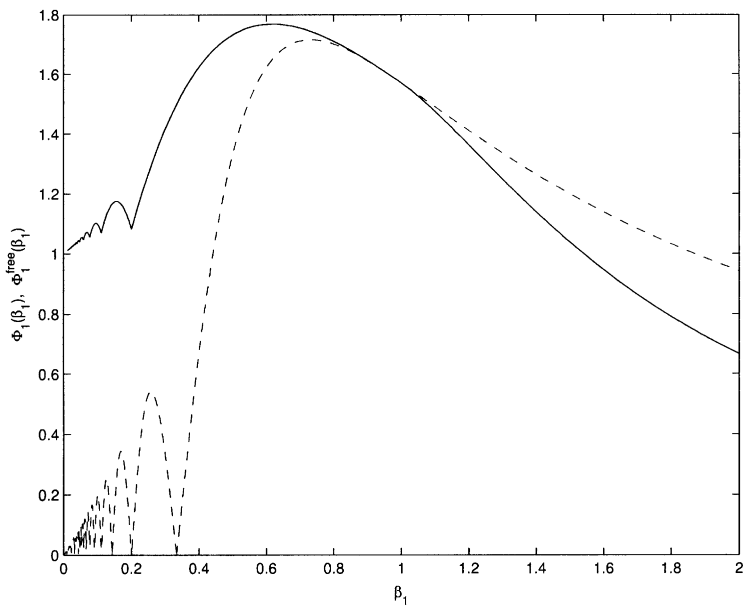

Fig. 2. Functions $\Phi_1(\beta_1)$ (solid line) and $\Phi_1^{\text{free}}(\beta_1)$ (dashed line) showing dependence of the maximum forced and free responses of the dimensionless beam on the dimensionless speed of the unit force.

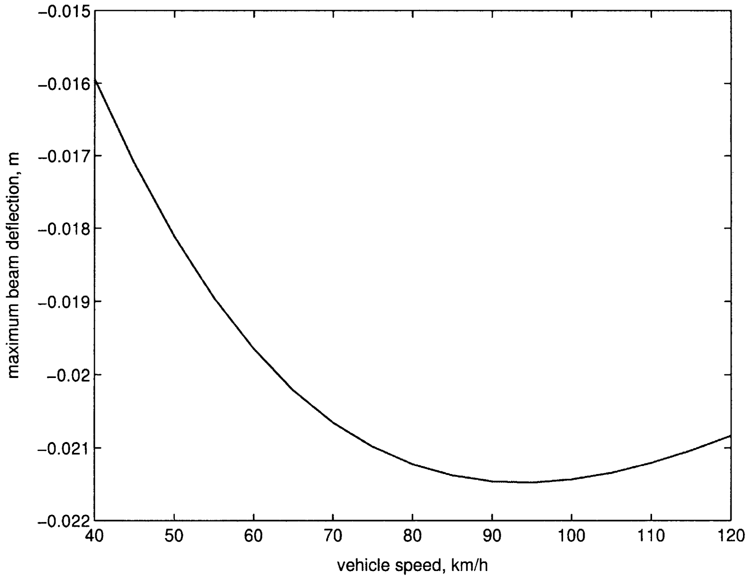

Fig. 3. The maximum dynamic deflection of the beam versus vehicle speed.

range of β_1, the function $\Phi_1(v/v_1)$ is given by [6]

$$\Phi_1(v/v_1) = \frac{1}{(1-(v/v_1))} \sin \frac{2\pi}{(1+(v/v_1))} \tag{2}$$

and takes its maximum value at $v_{peak} \approx 0.62 v_1 \approx 94\,\text{km/h}$ (cf. with 91.2 km/h obtained numerically in Ref. [1]; it should be noted that, when the speed varies from 70 to 115 km/h, the relative variation of the maximum deflection is within 5% [6]). Note that the curve in Fig. 14a [1] showing the numerically obtained dependence of the maximum beam response on the vehicle speed is approximately, up to the sign and the scaling factor, just a fragment of the curve shown in Fig. 2 by the solid line in the interval [0.3,0.8]. Indeed, substituting $v_1 = 152\,\text{km/h}$ into (2) and multiplying the resulting function by the factor $2PL^3/(\pi^4 EI)$ [6], where P is the vehicle weight, one gets the curve shown in Fig. 3, which is almost identical to the curve shown in Fig. 14a [1]. The small difference (about 1 mm) in the height of these two curves is due to the light damping in the beam model considered in Ref. [1].

The analysis of data on highway bridges reported in the literature shows that the values of the vehicle speed usually do not exceed 20% of v_1; i.e., the values of the dimensionless speed β_1 fall in the interval [0,0.2], where the character of the dependence of the maximum beam response on the vehicle speed is very different from that in the interval [0.3,0.8] considered in Ref. [1]. Thus, the "randomly chosen" bridge considered in this work has nothing to do with those that are likely to be met in real life (the fundamental frequency of this beam is as little as 0.21 Hz!), and such a selection is not appropriate for the case study.

4. Conclusion

The author does not mean to imply that the simplest vehicle models (such as a MF model, or SDOF oscillator, or QC model) are sufficient in bridge-related studies or that more elaborate vehicle models with many DOFs are not needed. If the bridge surface is not smooth, the roadway irregularities can excite sizeable dynamic forces that do, indeed, affect the bridge dynamics, especially if the ratio of the vehicle and bridge masses is not small. Generally, road surface irregularities excite several vehicle eigenvibrations (e.g., body bounce, axle hop, pitch, roll, etc.), and the contribution of each to the total vehicle vibration depends on the typical irregularity wavelength, vehicle eigenfrequencies, and speed. Hence, the number of degrees of freedom in an adequate vehicle model should be sufficient to represent all eigenvibrations that can result in sizeable components of the tyre forces in a frequency range of interest. However, even in this case, it is often possible to reduce the model to a system with one or two degrees of freedom [4] with no loss of accuracy. The choice of an adequate vehicle model should be determined by the particular problem under consideration and must take into account the eigenfrequencies of the bridge and vehicle, as well as the character of the bridge surface. These issues are discussed in more detail in Ref. [4].

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