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ANALYSIS SUGGESTION FOR VEHICLE SCANNING METHOD

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Abstract: *An analytical approach is suggested that can be conveniently applied in the framework of the Vehicle scanning method (VSM). It assumes that the modal parameters of a bridge will be imported from a finite element (FE) program into MATLAB, where the structural response caused by a moving mass and a moving spring mass is solved using coupling equations and numerical integration. A mathematical formulation of the solution is presented together with a short numerical case study that compares the results to a traditional closed form solution. It is shown that when comparing both forms of analysis the suggested approach is more accurate in the case of slow velocities of the passing sprung mass. Other advantages are that the method allows for the mass of the vehicle or (tractor) towing vehicle and a damping to be included in the calculation. The user-friendly preprocessing in commercial FE programs can also be considered an advantage.*

Keywords: Moving vehicle, Vehicle Scanning Method, Natural Frequency, Finite Element Analysis.

1. Introduction

The idea that the natural frequency of a bridge can be determined by means of a passing vehicle has been pursued since the closed-form solution for a sprung mass on a beam was published (Young, 2004). A recent review of the achievements in the field of VSM, formerly called "drive-by identification", can be read in (Wang et. al., 2022). In spite of its 20-year-old tradition, it is still in development without regular practical use. The idealization considered in the closed-form solution is nearly impossible to achieve under practical circumstances; the sprung mass cannot roll directly on a roadway or rail, it has to be pulled by another vehicle or have its own drive, most bridges cannot be modeled as a simply-supported beam, and damping cannot always be neglected. These shortcomings of idealization led to FE solutions that applied the Vehicle-Bridge Interaction (VBI) element (Young, 1997).

A promising alternative is the suggested approach, which does not require the VBI element and thus allows for the use of standard FE packages when modeling a bridge of interest. The eigenvalue parameters have to be processed further, as described below.

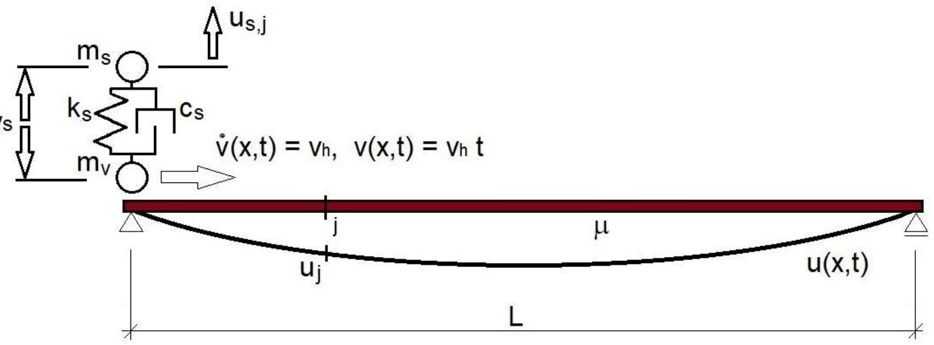

Fig. 1: Schema of the coupled system structure and moving vehicle

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2. Theory

Let us consider the system shown in Fig. 1, which can be described by eq. (1) to (3).

$$\mathbf{M}\cdot\ddot{\mathbf{U}}+\mathbf{C}\cdot\dot{\mathbf{U}}+\mathbf{K}\cdot\mathbf{U}=\delta_j\cdot\left(f_c-\mathrm{m}_v\cdot\left(g+\ddot{u}_j\right)\right)\ , \tag{1}$$

$$\mathrm{m}_s\cdot\ddot{u}_s+\mathrm{c}_s\cdot\left(\dot{u}_s-\dot{u}_j\right)+\mathrm{k}_s\cdot\left(u_s-u_j\right)=-\delta_j\cdot\mathrm{m}_s\cdot g\ , \tag{2}$$

$$\mathrm{f}_c=\mathrm{c}_s\cdot\dot{w}_s+\mathrm{k}_s\cdot w_s=-\delta_j\cdot\mathrm{m}_s\cdot\left(g+\ddot{u}_j+\ddot{w}_s\right)\ , \tag{3}$$

that together form the following system:

$$\mathbf{M}\cdot\ddot{\mathbf{U}}+\mathbf{C}\cdot\dot{\mathbf{U}}+\mathbf{K}\cdot\mathbf{U}=\delta_j\cdot\left(-\mathrm{m}_s\cdot\left(g+\ddot{w}_s+\ddot{u}_j\right)-\mathrm{m}_v\cdot\left(g+\ddot{u}_j\right)\right). \tag{4}$$

On the left-hand side, we have the system matrices of the structure, which in our case is the simply supported beam. The terms on the right-hand side represent the force of gravity and the inertia. The centripetal and the Coriolis forces are not considered because only velocities far below the critical velocity will be considered here.

After modal decomposition:

$$\mathbf{U}=\emptyset\cdot Q;\qquad \dot{\mathbf{U}}=\emptyset\cdot\dot{Q}\ ;\qquad \ddot{\mathbf{U}}=\emptyset\cdot\ddot{Q}\ ; \tag{5}$$

$$\emptyset^T\cdot\mathbf{M}\cdot\emptyset=\boldsymbol{I};\qquad \emptyset^T\cdot\mathbf{C}\cdot\emptyset=\boldsymbol{D};\qquad \emptyset^T\cdot\mathbf{K}\cdot\emptyset=\boldsymbol{\Omega} \tag{6}$$

and the selection of n significant modes, we obtain the system of n+1 equations:

$$\begin{bmatrix}\mathbf{I}+(\mathrm{m}_v+\mathrm{m}_s)\cdot\emptyset_j^T\cdot\emptyset_j & +\mathrm{m}_s\cdot\emptyset_j^T\\ +\mathrm{m}_s\cdot\emptyset_j & \mathrm{m}_s\end{bmatrix}\cdot\begin{bmatrix}\ddot{Q}\\ \ddot{w}_s\end{bmatrix}+\begin{bmatrix}\boldsymbol{D} & 0\\ 0 & \mathrm{c}_s\end{bmatrix}\cdot\begin{bmatrix}\dot{Q}\\ \dot{w}_s\end{bmatrix}+\begin{bmatrix}\boldsymbol{\Omega} & 0\\ 0 & \mathrm{k}_s\end{bmatrix}\cdot\begin{bmatrix}Q\\ w_s\end{bmatrix}=-\delta_j\cdot \begin{bmatrix}(\mathrm{m}_v+\mathrm{m}_s)\cdot g\cdot\emptyset_j^T\\ \mathrm{m}_s\cdot g\end{bmatrix}\ . \tag{7}$$

The first term (mass matrix) and the right side of the eq. (7) are time dependent because of the position dependent modes $\emptyset_j$. The modes $\emptyset_j$ have to be interpolated for each position j corresponding to the applied time resolution. The relation between time and position is given by the velocity v_h. The solution starts from initial conditions defined by eq. (8)

$$\begin{bmatrix}\boldsymbol{\Omega} & 0\\ 0 & \mathrm{k}_s\end{bmatrix}\cdot\begin{bmatrix}Q\\ w_s\end{bmatrix}=-\delta_j\cdot\begin{bmatrix}(\mathrm{m}_v+\mathrm{m}_s)\cdot g\cdot\emptyset_j^T\\ \mathrm{m}_s\cdot g\end{bmatrix}, \tag{8}$$

and can be obtained by numerical integration, e.g. by means of the algorithm HHT-α (Hughes,1983).

3. Numerical case study

A hypothetical case was chosen from the literature (Yang, 2021) for the purpose of verification. The applied model corresponds to Figure 1, with a span of 25 m, a 1x1.2 m cross section and a weight of μ=2000 kg/m. The Young modulus of 27.5 GPa and the moment of inertia 0.1 m^4 were used. The moving spring mass m_s was 900 kg and the vehicle mass m_v was neglected at first because of the intended comparison with the closed-form solution. The first natural frequency of the beam without the moving mass was 2.947 Hz. The passing velocity v_h was set to 5 m/s (18 km/h) and 1.389 m/s (5 km/h). No damping was used at first in order to be able to compare the solution to the analytical closed form, and then a proportional viscous modal damping of about 1.5% (α=0.1; β=0.0001) was used.

The FE model was assembled in ANSYS 17. A resolution of 126 nodes per driving path was chosen, forming a model of 756 nodes and 669 SHELL181 elements.

The first five natural modes with distinct amplitudes on the driving path (bending modes) in the frequency band 0-50 Hz were exported from ANSYS into MATLAB using the APDL commands. The solution then followed the schema described above. For the closed-form analysis, the equations from (Yang, 2018) were applied.

The obtained results in Fig. 1 and 2 confirm a good agreement with the results already presented in (Yang, 2021). A power spectral density (PSD) computed from the acceleration response of the spring mass for a passage with a velocity of 18 km/h is presented in Figure 3. This figure also shows FE-based results for a case of light damping and the moving mass equally divided between the two moving masses m_s and m_v (as defined in Figure 1). The two peaks at the natural frequencies that may help with the identification of those natural frequencies are nearly merged together here.

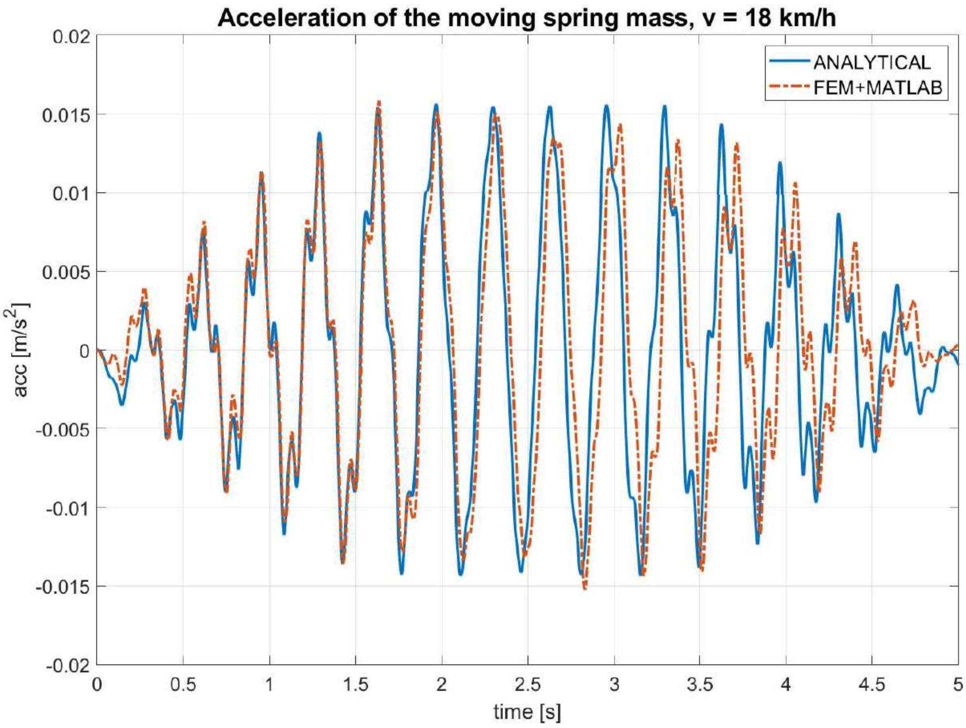

Fig. 2: Acceleration response of the moving spring mass, v = 18 km/h

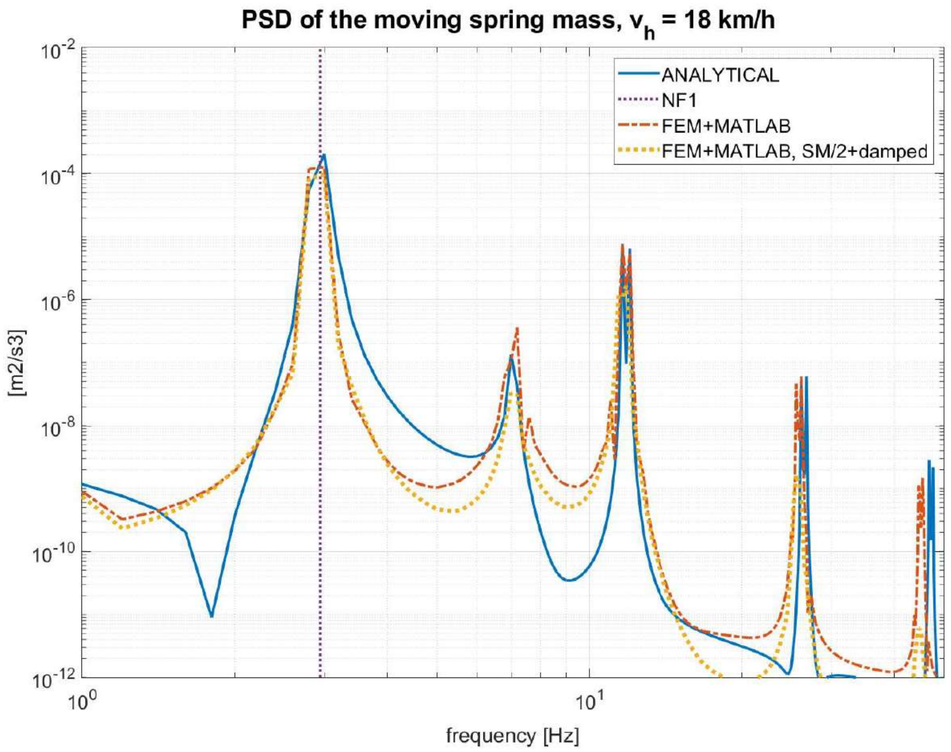

Fig. 3: PSD from the acceleration response of the moving spring mass, v = 18 km/h

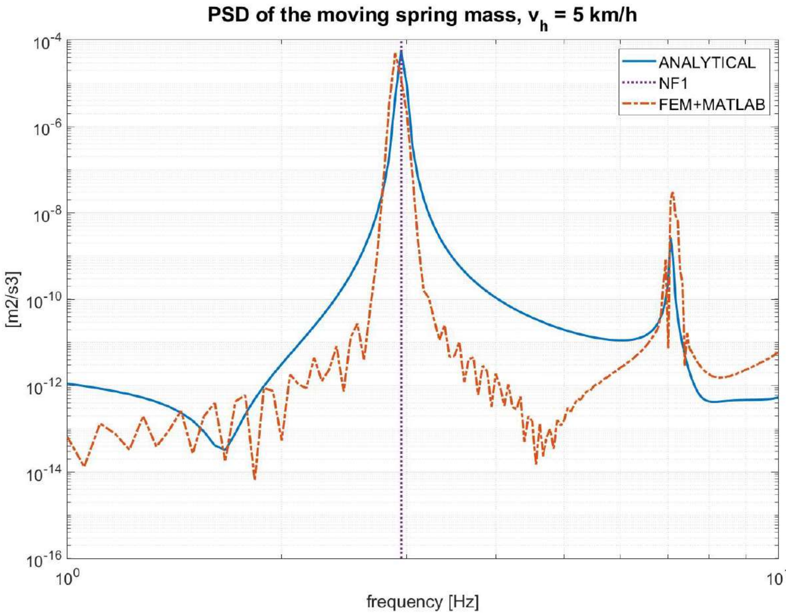

Fig. 4: PSD from the acceleration response of the moving spring mass, v = 5 km/h

Figure 4 shows the spring mass PSD for the case when the spring mass passes across the beam at a velocity of only 5 km/h. Note that the peak corresponding to the first natural frequency is lower in the FE-based solution than in the analytical one. If the mass relation between the spring mass and the bridge increases, this difference will also increase.

4. Conclusions

An approach was suggested and described that may be used for more precise frequency estimation in the framework of VSM. The subsequent numerical case study documented a satisfactory agreement with published results, and pointed out that for slow velocities the closed form solution overestimates the location of natural frequency peaks.

The suggested method allows the mass of the vehicle or the towing (tractor) vehicle and a damping to be included in the calculation. There is practically no limitation to the form of the modeled bridge structure, and the possibility of utilizing preprocessing in commercial FE software can also be considered an advantage.

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