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APPLYING A TWO DEGREE OF FREEDOM MODEL FOR DRIVE-BY IDENTIFICATION

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Abstract: *A new concept of drive-by identification is examined applying the analogy with a Two Degree Of Freedom (DOF) system where the bridge is considered the ground-supported spring-mass and the moving spring-mass the second DOF. The response of the moving spring-mass is simulated on a bridge model using different road profiles and compared to parameters of the corresponding two DOF system. The focus is the spectral shift that can be observed on the moving spring-mass during its passage along the bridge and could possibly be applied for drive-by identification. The accuracy mainly depends on the relation of the moving spring-mass to the bridge mass and the relation between the natural frequency of the spring-mass and those of the bridge. The simulations showed that road profile can significantly reduce the accuracy of identified results, which imposes limits on practical applications.*

Keywords: Drive-by identification, structural health monitoring, finite element analysis, road roughness, two DOF system.

1. Introduction

Drive-by Identification has been studied since the closed-form solution for a sprung mass on a beam was published (Yang, 2004). A recent review of the achievements in the field of Vehicle Scanning Method (VSM), formerly called "drive-by identification", can be read in (Wang et al., 2022). However, the theory formulated by (Yang, 2004 and 2021) only applies when the vehicle mass is negligible compared to the bridge mass. In this case the effect on the spring-mass will also hardly have any measurable effects on the bridge vibrations. When the moving spring-mass is insignificant it is reduced to a kind of moving transducer that measures vibrations induced by other phenomena, which may not always provide credible results because the loading can change over time.

This article considers the case where the moving vehicle mass with a spring-mass is significant. It should be noted here that an ideal moving spring-mass is nearly impossible to achieve under practical circumstances; a sprung mass cannot roll directly on a roadway or rail because it has to be pulled by another vehicle or have its own drive. Therefore, the effect of the moving mass has to be considered along with the effect of the moving spring-mass. The moving mass continuously changes the natural frequencies of the mechanical system (bridge + moving body) as a function of its position. Moreover, the moving spring-mass also causes a spectral shift of the natural frequencies—similar to the one that occurs when two single DOF systems are coupled together, as in the case of a tuned spring damper (Ormondroyd, 1928). The main advantage of this approach is that the moving spring-mass parameters are known, thus "only" the 2nd DOF—a bridge DOF parameters—need be identified from the response.

To estimate the chances that the above-mentioned spectral shift could be used for bridge frequency estimation on a vehicle driving along the bridge, a simulation case study was performed. The response of a moving vehicle consisting of a mass and spring-mass when driving across a bridge model was analyzed using different road profiles (RP). The shifted spectral peaks of the spring-mass were extracted from the response and compared to theoretical values of the corresponding two DOF system. Because the vehicle

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mass causes a continuous change in bridge parameters, only the response from driving over a middle section of the bridge model was used in order to keep the parameter changes as small as possible.

2. Assumptions & objectives

Free vibrations of a bridge can be described using modal decomposition. The modes of the bridge (or beam in this article, see Fig. 1) are continuously altered by a passing spring mass with dashpot due to dynamic coupling effect. Within short sequences, the frequencies of the system "bridge & spring mass" can be averaged and considered constant. The inaccuracy caused by averaging is known and can be considered as a system uncertainty. Statement: mostly influenced is the bridge mode closest to the natural frequency of the passing spring mass. The article examines if the frequency of this mode and the spring mass frequency could be measured on the passing spring mass and applied for the identification of bridge natural frequencies using the analogy with a two-DOF system.

3. Simulations

Simulations were computed for a laboratory bridge model consisting of a 4 m long simply supported beam made from Jäckel steel U-210x50x4 with a first natural frequency of 7 Hz and the mass of 33.3 kg (see Fig. 1). The simulations of the passage of a spring mass across the beam were carried out using the method described in (Bayer, 2023). The four parameter sets given in Tab. 1 were considered here with the vehicle speed limited to 0.1 m/s for clarity of presented results.

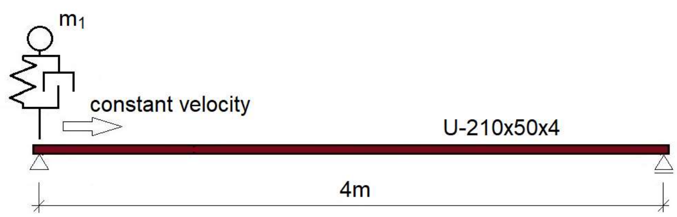

Fig. 1: Considered mechanical system.

m_1 [kg]	$f_n(SM)$ [Hz]	$f_n(B)$ [Hz]	m_1/m_2 [%]	$f_n'(SM)$ [Hz]	$f_n'(B)$ [Hz]	$\Delta(SM)$ [%]	$\Delta(B)$ [%]
0.245	6.72	6.77	1.48	6.36	7.15	-5.38	5.68
0.620	6.72	6.77	3.76	6.14	7.40	-8.59	9.40
0.245	9.50	6.77	1.48	9.63	6.68	1.37	-1.35
0.620	9.50	6.77	3.76	9.81	6.55	3.30	-3.20

Tab. 1: Decisive parameters of a two DOF system applied in the simulations (m_1 moving spring mass (SM), m_2 bridge(B) modal mass, f_n natural frequency, f_n' natural frequency of the coupled system, Δ frequency shift due to the coupling of the two DOFs).

The following major limiting conditions were expected:

- The parameters of the bridge-vehicle mechanical system change according to the position of the vehicle. E.g., if a 10 s-long middle-section vibration sequence is needed for evaluation in the considered case, the fact has to be taken into account that due to the moving mass the bridge natural frequency changes during this short sequence by about 0.5 % at the considered speed of 0.1 m/s. Increased speed means a longer driving sequence and thus a greater frequency change.
- The spectral shift depends on the mass relation and the frequency distance of the two idealized DOFs. The effect is illustrated in Fig. 2. It follows that a measurable shift presumes a mass relation of at least 0.1 %.
- Road roughness has an influence on the measured data and will be examined further below.
- The reduction of the multi DOF system to two DOFs: The natural frequency of the moving spring-

mass has to be much closer to the traced (measured) bridge natural frequency than other bridge frequencies. Therefore, the most reliable case is when the frequency of the moving spring is lower than the first bridge frequency.

The RP was simulated according to the ISO standard 8608 applying appropriate model scales.

It was realized that the effect of the road roughness exceeds decisively the dynamic effect of the moving mass & spring-mass. However, the question is whether ISO 8608 is applicable to the low speeds that are preferable for the considered drive-by method. This can be confirmed only by experiments.

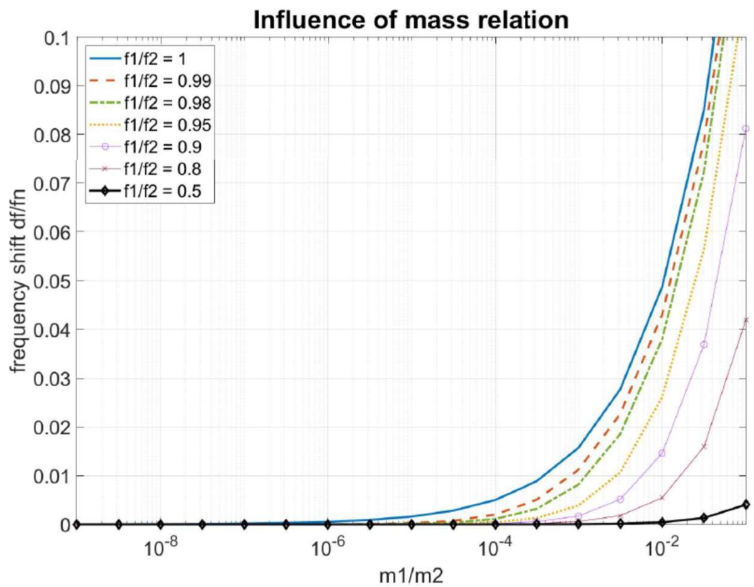

Fig. 2: Effect of the mass and frequency relation of a two DOF system on frequency shift.

The simulations of a moving spring-mass on a bridge showed that one of the peaks corresponding to a two DOF system may be missing in the response. In simulations with a RP, both of the peaks are usually recognizable. Another effect of a coarse RP is that the spectra of measured vibrations are split into many small irregular peaks that make the identification of the particular frequency peak quite difficult.

In order to assess how precise the identification of the peaks corresponding to spring-mass frequency and bridge frequency can be, 25 passage simulations for each parameter set were calculated considering RPs of classes "A" and "C".

m_1 [kg]	f_n(SM) [Hz]	f_n(B) [Hz]	$f_{n,est}'$(SM) [Hz]	$f_{n,est}'$(B) [Hz]	$f_{n,est}'$(SM) Err [%]	$f_{n,est}'$(B) Err [%]	Max. Err [%]
0.245	6.72	6.77	6.39	7.19	0.456	0.55	2.22
0.620	6.72	6.77	6.22	7.46	1.32	0.81	2.65
0.245	9.50	6.77	9.61	6.75	-0.228	1.06	3.34
0.620	9.50	6.77	9.80	6.69	-0.143	2.08	2.84

Tab. 2: Identified peaks $f_{n,est}$ from 25 simulations with RP class "C"(Err error, other symbols see Tab. 1).

4. Identification

A single-degree-of-freedom PSD response was fitted to the simulated (instead of measured) responses at manually pointed peaks using the "fmincon" optimization procedure in MATLAB. The fit result depends on the number of frequency lines considered, and suitable starting values are also essential for a good curve fit. In the case where the frequency peak is split into more peaks due to the road profile, the optimization result may envelop a number of peaks together or choose one of the peaks as dominant. The results presented in Tab. 2 for the RP of class "C" were achieved by choosing three frequency lines to the left and right from a subjectively assumed center of a peak using a frequency resolution of 0.1 Hz. The results for the class "A" are only better by 0.3 % on average than for those presented in Tab. 2 for RP "C".

Knowing the two peaks in the vehicle response, the bridge frequency can be estimated using the theoretical model of the two DOF undamped system, which leads to Eqs. (1) and (2)

$$m_2 = \frac{\lambda m_1(k_1+k_2)-k_1k_2}{m_1\lambda^2-k_1\lambda}, \tag{1}$$

$$\omega_0^2 = \frac{m_1m_2\lambda_1^2-\lambda_1k_1m_1-\lambda_1k_1m_2}{(\lambda_1m_2m_1-k_1m_2)}, \tag{2}$$

where m_1 and k_1 are the known mass and stiffness of the moving spring mass, respectively, λ is the power of the peak circular frequency, m_2 and k_2 are the modal mass and stiffness of the bridge, respectively, and ω_0 is the natural bridge frequency.

A part of this estimation is identification of the bridge modal mass (m_2) which is quite sensitive to measurement error of the frequency peaks. An accurate estimate of the bridge modal mass from a theoretical model can increase the reliability of the bridge frequency estimation, or it can make it possible to estimate the bridge frequency from only the frequency shift of the vehicle, which is quite an appealing idea.

5. Conclusions

A new approach for drive-by identification was suggested and examined using simulations. The differences for rough road profile "C" in Tab. 2 together with the influence lines in Fig. 2 can help to define a relevant vehicle mass and vehicle frequency to be used in future applications of the method.

In spite of the fact that the method seems to require quite large vehicle masses or a small distance between the traced and vehicle frequencies, it might be suitable for e.g., approximate 1st bridge frequency estimation. In the case of frequent passages of the testing vehicle across a bridge, for example within the framework of public transport, there may be potential for more precise monitoring of bridge frequencies. Reducing the driving velocity to a minimum can also help to overcome the negative influence of road profile.

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