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Analysis of the Oscillating Behavior of a Highway Bridge for Structural Health Monitoring

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Summary:

Bridges, being concrete structures, oscillate from excitation with impulsive forces. The details of these oscillations such as amplitudes, frequencies, and their decay coefficients bear information about the structural health of the bridge. Each tire of a passing vehicle excites the bridge with a short impulse of force, which contains a broad frequency spectrum. We developed a mathematical model to describe the resulting oscillations and compared the time response of the model with measurements taken at the deck of a bridge.

Keywords: Structural health monitoring, bridge monitoring, resonance analysis, vibration behavior, acceleration measurement.

Introduction

In this work, we investigated the impulse response of a highway bridge to excitation by vehicles passing the expansion joint. If the responses to the impulses from different vehicles prove to be similar, a change in the response characteristics has to be related to changing properties of the bridge like cracks or rust. Although there has been an extensive amount of research on the problem of bridge monitoring, one still faces challenges. Some methods require a large amount of sensors throughout the bridge [1], others need an artificial ultrasound excitation [2], and RF imaging methods often lack the necessary resolution [3]. In this work, we use the natural excitation by passing vehicles to monitor accelerations in the deck of the bridge with a single sensor. This will hardly bear information about the whole bridge, but it should provide information about the abutment, expansion joint, and a part of the deck.

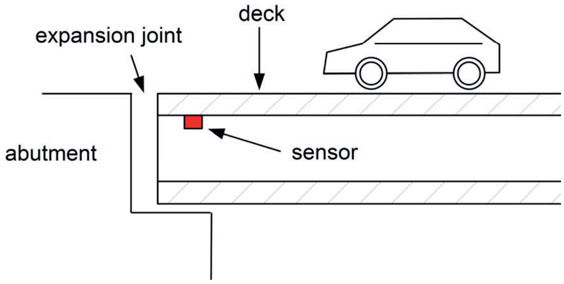

Fig. 1. Schematic drawing of the abutment and the deck of the investigated bridge.

Theoretical considerations

The bridge is regarded as a linear time-invariant (LTI) system. Every tire of a vehicle entering or leaving the bridge across the expansion joint excites the bridge with a Dirac impulse. As a consequence, impact sound waves are stimulated leading to a displacement of the surface of the deck. The impulse response as it becomes manifest in the acceleration of the deck's surface at a given point is modeled as a sum of decaying sinusoidal signals:

$$h_i(t) = \sum_j A_{ij} \cdot \mathrm{e}^{-\alpha_{ij} \cdot t} \sin(\omega_{ij} t) \cdot \varepsilon(t - t_i) \qquad (1)$$

with A_{ij} the amplitude of the *j*-th oscillation resulting from the *i*-th Dirac impulse. α_{ij} and ω_{ij} are the corresponding damping coefficients and oscillation frequencies, and $\varepsilon(t)$ denotes the Heaviside step function. In this work, we limited the number of relevant waves to three.

Measurement system and setup

The measurement system consisted of a custom-built data logger and a commercial acceleration sensor. The latter (ADXL355) had a resolution of about 4 µg/LSB, a 3 dB-bandwidth of 1 kHz, and a sample rate of 4 kHz. All three axes of acceleration were continuously logged with an Arduino-based logging system. The memory and the battery both lasted for about 36 hours. The sensor was placed on the deck of the bridge near the expansion joint (see Fig. 1).

Measurement results

To fit the model function (1) to the measured response of the bridge, we first extracted periods from the measured time-dependent vertical acceleration that are obviously associated with a passing vehicle. An example presenting fit and measurement is given in Fig. 2. The damped oscillation occurring first in chronological order is due to the first tire touching the expansion joint (which was right front in this experiment), the second oscillation is due to the second tire (left front in the example), etc. In the example, the oscillations corresponding to tires number one and three exhibit higher frequencies and lower amplitudes than those caused by tires number two and four.

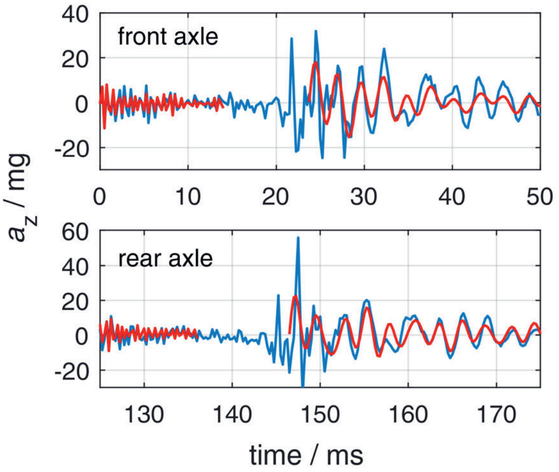

Fig. 2. Measured (blue) and fitted (red) vertical acceleration. See text for further details.

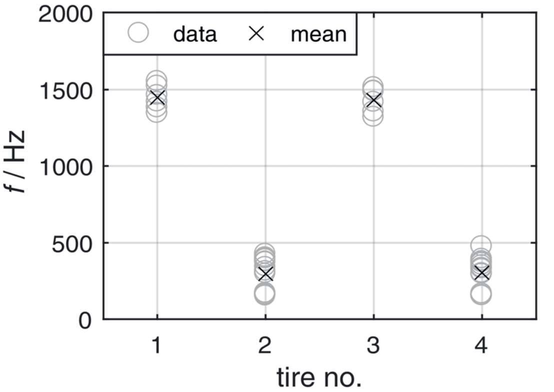

Fig. 3. Dominant frequencies excited by five different vehicles, displayed separately for each tire. Outliers were excluded.

The impulse responses to five different vehicles were fitted as described above. In order to investigate the benefits as well as the limits of the model, the three dominant frequencies from each of the four impulse responses for every vehicle were extracted from the corresponding frequency spectra and used as starting points for the fit. The fitted frequencies ω_{ij} are displayed in Fig. 3. Two clusters can be formed, one for the first and third impulses and another one for the second and fourth impulses.

Discussion

From the measurement results, it is evident that some tires cause bridge responses that are very similar between them but different from the responses to other tires. In our measurements, the tires causing similar responses belonged to the same vehicle side. The origin of this classification could be twofold: (a) The vehicle suspension characteristics belonging to the same axle could change after contact of the first tire with the expansion joint. (b) The expansion joint itself acts as a separate resonator, the characteristics of which are influenced by the tire contact. This would require the bridge to be modeled as a system of coupled resonators.

Conclusion

We analyzed the oscillating behavior of a bridge at one point originating from impulsive forces generated by vehicles crossing the expansion joint. The vehicle tires triggered different responses of the bridge, depending on the position of the tire in the vehicle (left, right, front, rear). The extracted resonance frequencies of the damped bridge oscillations formed distinct clusters, corresponding to distinct tire classes. In order to model the oscillating behavior of the bridge in a way that predicts these clusters, the present model has to be extended to describe coupled resonators. We believe that changes of the clusters over time could be an early warning signal in that they predict an emerging damage of the bridge.

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References

[1] M. Chang, S. Pakzad, “Optimal Sensor Placement for Modal Identification of Bridge Systems Considering Number of Sensing Nodes,” *J. Bridge Eng.,* vol. 19, no. 6, (10pp), June 2014; doi: 10.1061/(ASCE)BE.1943-5592.0000594.

[2] N. K. Mutlib, S. B. Baharom, A. El-Shafie, and M. Z. Nuawi, “Ultrasonic health monitoring in structural engineering: buildings and bridges,” *Struct. Control Health Monit.*, vol. 23, pp. 409–422, March 2016; doi: 10.1002/stc.1800.

[3] S. Kharkovsky, J.T. Case, M.T. Ghasr, R. Zoughi, S.W. Bae, and A. Belarbi, “Application of Microwave 3D SAR Imaging Technique for Evaluation of Corrosion in Steel Rebars Embedded in Cement-Based Structures,” in: *AIP Conf. Proc.*, vol. 1430, pp. 1516–1523, 2012; doi: 10.1063/1.471639