# Structural Health Monitoring of Bridges using both local vibrations and structure-borne acoustic waves

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## Abstract

For the structural health monitoring of bridges, we investigated different acceleration signals excited by passing vehicles. By driving onto or off the bridge thereby crossing the expansion joint impulse like signals are excited by every passing axle. These signals travel as structure-borne acoustic waves through the whole bridge. The driving over the bridge between the joints also excites waves, but with limited ranges. Both signal types carry information about the physical properties of the bridge. Both signal types have been investigated for their reproducibility. In both cases, signals excited by trucks turned out to be more reproducible then signals excited by cars. Finally, the velocity of passing vehicles could easily be estimated from a Doppler shift in the limited-range signals.

## 1 Introduction

### 1.1 State of the art

The monitoring of structures such as buildings, dams, and bridges helps to reduce maintenance cost and improves the safety of the structures. Our work focusses on structural health monitoring (SHM) of bridges, especially large motorway bridges. There exists a variety of methods for this purpose. One of them exploits the mechanical vibrations in a bridge [1]. This usually involves the examination of modal parameters, e.g., resonance frequencies, damping factors, and mode shapes. The vibrations are observed by suitably placed acceleration sensors [2]. Structural damage of a bridge influences the vibration details, and the inversion of this relationship allows one to infer the health state of the bridge from measured vibrations [3].

### 1.2 Proposed method

Our approach uses 3-axis MEMS (microelectromechanical systems) accelerometers as sensors, does not rely on active signal excitation, and involves high-bandwidth signals. The signals to be measured are solely excited by the traffic across the bridge. In contrast to the usual focus on modal parameters, which only requires the observation of low-frequency vibrations, we consider a broader frequency band. We conducted experiments on an expressway (autobahn A9) bridge in northern Bavaria, Germany, with an overall length of 602 m. The bridge is constructed with prestressed concrete and was completed in 2001. The two roadways are not connected to each other and comprise three lanes and a hard shoulder each.

The experiments led to the identification of two different signal types. Figure 1 shows how the accelerometers were mounted under the road surface. A vehicle driving from the deck of the bridge onto the abutment across the expansion joint excites structure-borne sound waves with a broad frequency spectrum. The interaction between road surface and vehicle on the bridge continuously excites another type of waves with a shorter range, which is indicated by the accelerometer responses when a vehicle is within a close range to the sensor positions 1–4. The results of the two types of excitation are shown in Fig. 2 by way of an example.

In the experiments, the expansion-joint interaction of a vehicle could still be observed by accelerometers as far away as 600 m. The wave attenuation depends on the frequency of the wave and on the geometric and structural properties of the bridge. Vibrations due to type-2 (on-bridge) excitation were associated with a smaller interaction range, approximately 20–80 m, and exhibited a frequency spectrum different from that of signals due to type-1 (expansion-joint) excitation. It is clear, however,

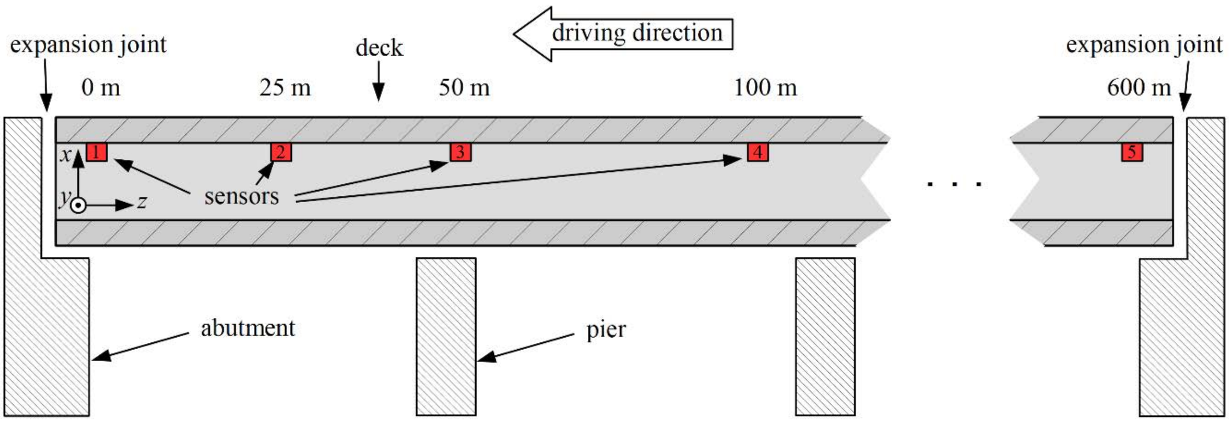


**Fig. 1** Schematic drawing of the monitored bridge. a) longitudinal cross section, b) transverse cross section.

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that changes of the effective material parameters caused by, e.g., internal cracks show up in both type-1 and type-2 signals.

Our main goal in this work is to further investigate the properties of the two signal types, their reproducibility, and their suitability for SHM purposes.

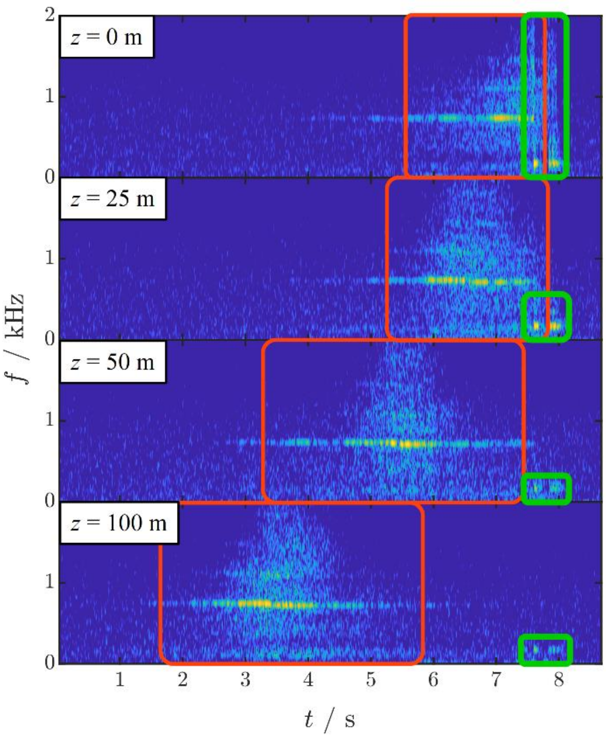


**Fig. 2** Normalized spectrograms, computed by short-time Fourier transform, of accelerometer 1–4 responses to the passing of a vehicle. Blue: no excitation; yellow: maximum acceleration (unity). Traveling-wave (type-1) signals excite all accelerometers almost simultaneously (highlighted in green), whereas local (type-2) signals are only observed when a vehicle is near an accelerometer (highlighted in red).

## 2 Experimental setup

We used 3-axis accelerometers from Analog Devices with a resolution of about 4 µ*g*, a 3-dB bandwidth of 1 kHz, and a sample rate of 4 kHz [4]. The sensors were mounted inside a metal housing for protection from environmental influences and placed as shown in Fig. 1. The sensors communicated with a host via SPI. An Arduino board with a 32-bit SAMD microcontroller was used for control and logging purposes. The measured data were saved to a microSD card (Fig. 3). In combination with a rechargeable battery, a typical measurement duration of 36 hours was achieved. A rechargeable battery allowed typical measurement durations of 36 hours.

To synchronize the measurements, external real-time clock (RTC) modules with I²C interface were used. Before the installation of the sensors, all RTCs were synchronized to the same PC. The remaining time error was on the order of 1 s. Every measurement file was adjusted manually to remove the better part (if not all) of this error.

The accelerometers, configured to run from their own integrated clock sources, showed a frequency drift. According to the time stamps, the clock sources disagreed with one another to an extent that it influenced the measurement results (the actual sampling rates deviated by about ±1 %). This will have to be counteracted by stable external clocks.

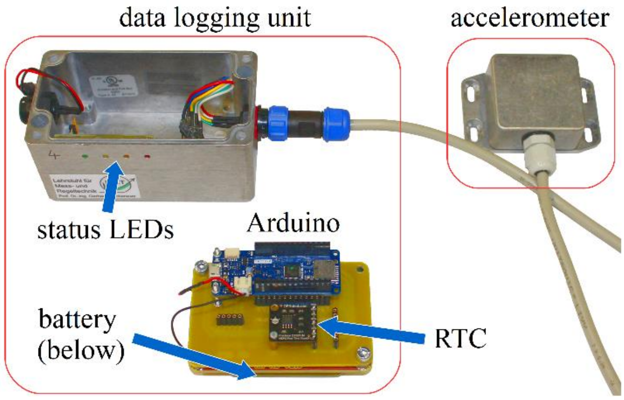


**Fig. 3** Measurement system.

## 3 Data analysis

### 3.1 Signal types

Figure 4a) shows a spectrogram of the z-directed acceleration measured by sensor 5 at $z = 600$ m when a truck with five axles drives from the road onto the bridge (phase I). While the truck is on the road no signal (except for noise) is measured. As the truck drives over the expansion joint, a broadband signal is excited by every axle; these signals are only a few milliseconds long (phase II). Additionally, the bridge starts to vibrate. The vibrations can be seen even better after the truck is fully on the bridge (phase III). In contrast to the broadband signals excited at the expansion joint, the local vibrations have only a few characteristic frequencies. These frequencies, the lowest of which is about 400 Hz, are not associated with resonance modes of the bridge as they are much too high – resonance frequencies of similar sized buildings are usually below 10 Hz [5].

Figure 4(b) shows the analogous response to processes at the opposite end of the bridge ($z = 0$ m). When the truck approaches the expansion joint, a local vibration is detected (phase I). As the truck drives over the expansion joint, the typical short-termed broadband signals occur (phase II). After the truck has left the bridge deck, no more signals are measured (region III). The two measurements at $z = 600$ m and $z = 0$ m show that the measured local accelerations are unambiguously the result of the interaction between the vehicle and the bridge.

In the measured y-directed accelerations, another type of signal is seen. The red box in Fig. 5(a) highlights the region of interest. As long as the truck is on the road, no signal is visible. When it drives onto the bridge, a low-

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frequency signal is excited. And when it leaves the bridge, all signals suddenly cease to exist except the highlighted one at below 50 Hz. Without doubt, this small-bandwidth signal is a resonance mode of the bridge.

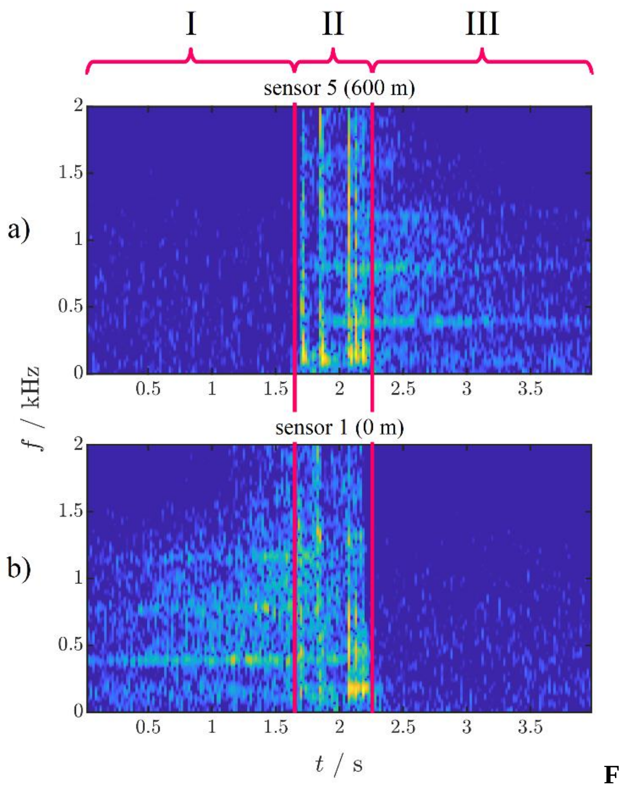


**Fig. 4** Normalized spectrograms of z-directed accelerations caused by a passing truck. Color scale according to Fig. 3. a) Truck driving onto the bridge at $z = 600$ m (sensor 5). b) Truck leaving the bridge at $z = 0$ m (sensor 1). See text for details.

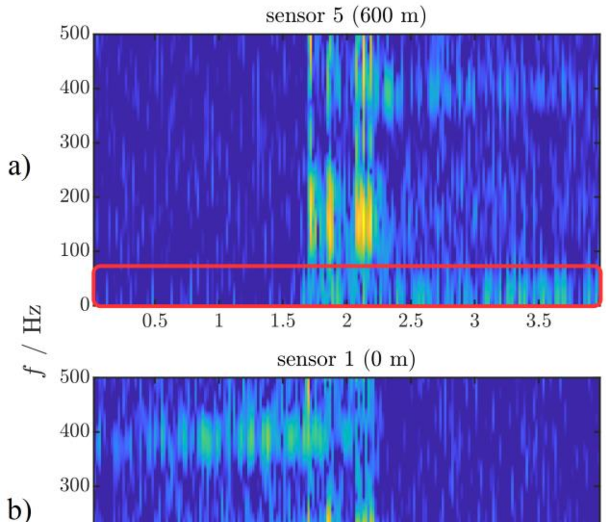


**Fig. 5** Same as Fig. 4 but y-directed accelerations.

## 3.2 Reproducibility

For SHM purposes, it is not necessary that every vehicle excite exactly the same signal pattern. However, when an average response is formed from the responses excited by many vehicles of the same type, it should be sufficiently similar to other averaged responses determined for other vehicles of the same type.

There are several features that could be extracted from type-1 signals, e.g., duration, amplitude, or dominant frequencies. For brevity's sake, we will only discuss the sound attenuation between the accelerometer positions as an exemplary feature. It is defined as

$$\alpha = 10 \cdot \lg \frac{\overline{|a_i|^2}}{\overline{|a_1|^2}} \quad \text{dB} ,$$

where $a_i$ is the acceleration measured by accelerometer $i$ caused by type-1 (expansion-joint) excitation and the overbar denotes time averaging. The attenuation turned out to be very similar for different trucks whereas the attenuation of the signals excited by cars varied more (Fig. 6). Trucks appear to be a better signal source than cars from a metrological point of view.

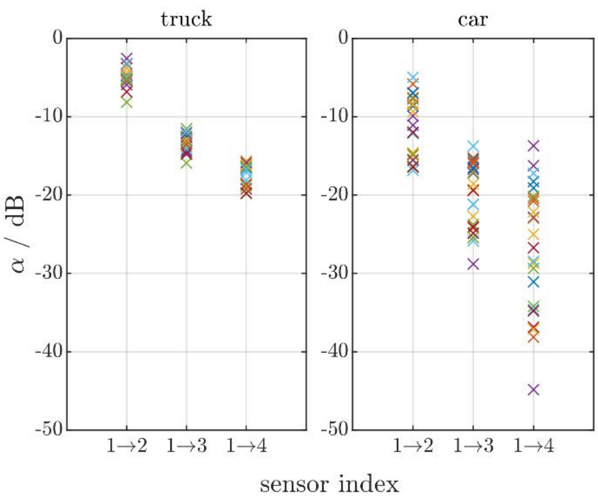


**Fig. 6** Signal attenuation between adjacent accelerometers. Every colored marker corresponds to an attenuation of a type-1 signal excited by a truck or car.

Useful features for type-2 signals could be, e.g., the amplitude and frequency of the dominant spectral component. The overall signal energy within a given time interval could also be used as a feature, but as the signals become quite long (3–4 s, cf. Fig. 2) they are rarely isolated from the signals excited by other vehicles. As an example, the dominant harmonics excited by several trucks and cars have been evaluated for Fig. 7. Dominant harmonics excited by cars are more or less randomly distributed over the whole measured spectrum, vary with accelerometer position and show a low signal-to-noise ratio. They can hardly be used for SHM purposes.

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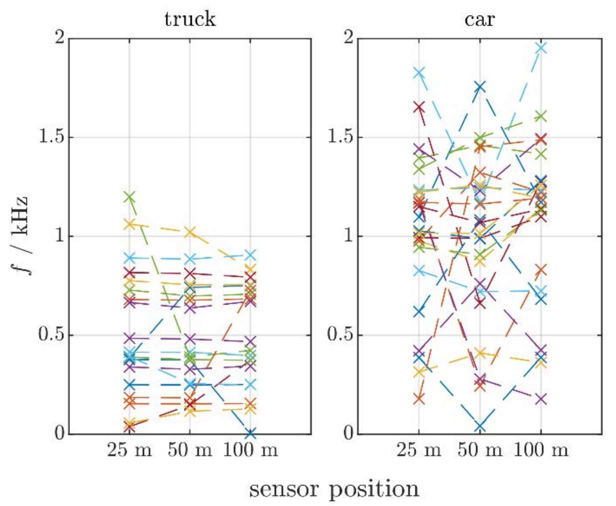


**Fig. 7** Frequency of the dominant harmonic of type-2 signals. Every color corresponds to the dominant harmonic of a type-2 signal excited by a truck or car.

In contrast, for a given truck, all accelerometers usually yield spectra with the same dominant harmonic. Which harmonic this is, however, varies between trucks. The usefulness as an SHM feature is an open issue as of now. What is certain is the suitability of the harmonic content for the identification of individual vehicles. This could be used for traffic monitoring.

### 3.3 Doppler shift

Type-2 signals, although essentially local, can be used to estimate the velocity of a vehicle by the Doppler effect. Fig. 8 shows a spectrogram of the z-directed accelerations excited by a truck at accelerometer 3 ($z = 50$ m). The frequency of the dominant harmonic is about 1.25 kHz while the truck approaches the sensor and jumps to a lower value as the vehicle passes the sensor and drives away. The Doppler frequency shift $\Delta f$ is

$$\Delta f = 2v\frac{f}{c}\,.$$

Here, $v$ is the vehicle velocity, $f$ denotes the averaged frequency excited by the approaching and leaving vehicle, and $c$ is the sound speed in the bridge deck. Assuming $v$ = 90 km/h, the upper limit of the mandatory speed limiter of a truck, leads to $c \approx 3100$ m/s. The strength and mixture of the concrete and the wave type (e.g. $A_i$- or $S_i$-Lamb wave [6]) are unknown, but typical sound wave velocities range between ≈ 2 km/s and ≈ 5km/s [6], [7].

## 4 Conclusion

It was shown that vehicles on a bridge generate two types of signals, structure-borne acoustic waves (type-1 signals) on the one hand and local vibrations (type-2 signals) on the other hand. The former can still be detected as far as 600 m away, whereas the latter are restricted to smaller areas with diameters on the order of some ten meters.

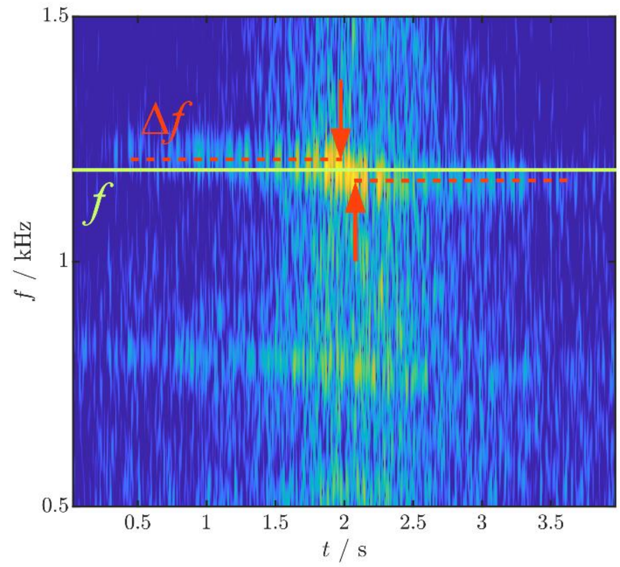


**Fig. 8** Normalized spectrogram of accelerometer-3 response to a passing truck with visible Doppler shift. Color scale according to Fig. 3.

Features extracted from type-1 signals proved quite reproducible, at least for trucks. The higher weight leads to higher levels of acceleration and therefore a better signal-to-noise ratio. Type-2 signals, in contrast, are very characteristic for specific vehicles; they can serve to identify vehicle classes and, by the Doppler shift, to estimate vehicle speeds. Their suitability as indicators of the structural health of a bridge, however, seems to be limited.

## 5 Acknowledgement

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