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DAMAGE DETECTION USING A COGWHEEL LOAD – NUMERICAL CASE STUDY

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Abstract: *A moving impulse load generated by a heavy cogwheel (CW) can be used as a testing excitation for bridges. This proposed type of dynamic load acts along the entire driving path, its intensity is adjustable, and it can be very efficient in the case of resonance. However, higher harmonic components are an inevitable effect of this type of loading, complicating the vibration analysis. The present study investigates suitable procedures to detect and locate damage in structures using a cogwheel load and only one or a few transducers mounted on the bridge. This arrangement seems to be sensitive to early damage indication. Damage localization is also possible, but further research will be required to increase its credibility.*

Keywords: Bridge Testing, Damage Detection, Impulse Loading, Vibration Analysis, Bridge Health Monitoring.

1. Introduction

Bridge load testing is as old as the first bridges, and ways of testing them have been systematically evolving for more than a hundred years (Farrar, 1999, Pirner, 2010, Cunha, 2013, Venglár, 2018, Benčat, 2018, Lantsoght, 2019). The dynamic properties of bridges are tested using either usual traffic, ambient vibrations, dynamic shakers, rockets, dropping weights, the passing of heavy vehicles or vehicles passing across an obstacle (Cantieni, 1984), and recently, drive-by testing (Yang, 2004 & 2005). Each type of loading has its advantages and disadvantages and therefore also typical fields of application (Commander, 2019). As a new alternative, a testing load in the form of a cogwheel has recently been proposed by the author (Bayer, 2018).

It was realized that the cogwheel load generates higher harmonic components, it can be very efficient in the case of resonance, it acts along the whole bridge, and it is insensitive to surface changes (Bayer, 2019). But the effect of moving mass (Sevilla, 1964) may not be negligible here.

The basic idea is that a few transducers mounted on the structure for the purposes of structural health monitoring (SHM), or mounted quickly onto the structure just before a test, could be used to detect and locate significant damage after the passage of a well-defined load (here the cogwheel). Repeated tests could promise reliable information about the condition of the bearing structure.

Static influence lines can be used for both damage detection and damage indication (Bayer, 2017). However, the CW is not heavy enough to provide a significant static load, and the dynamic response to the pulses contains higher harmonic components, the intensity of which is considerably higher than the free decays or the static deformations of the structure. The primary question is, which sensitive quantities can be derived from measurements that provide us with desired information under the given conditions? Classical experimental modal analysis is not applicable here because the initial conditions are continuously changing during the passage of the impulse load. Suitable procedures reported in connection with damage detection are numerous (Sinou, 2009 and Salgado, 2008), but only the flexibility approach is adopted in the presented numerical study (Padney, 2004) giving the first answers, and not necessarily the best possible ones, as the investigation is just at the beginning.

The study serves as a preliminary analysis for tests yet to be carried out, and does not comment on any kind of uncertainties, as they will be estimated much more reliably in future experiments.

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2. Structure & Damage Simulation

As the experimental facility used for drive-by testing in the past is still available, the analytical model corresponds to this facility. It is a 4 m long simply supported beam made from Jäckel steel U-210 x 50 x 4 mm and has a mass of 33.3 kg. The measured and analytical natural frequencies of the model are presented in Tab. 1.

Tab. 1: Changes of natural frequencies due to the simulated damage.

Nat. Freq. [Hz]	Damage 1, cut 4 mm change in [%]	Damage 2, cut 8 mm change in [%]	Damage 3, cut 12 mm change in [%]
7.11	-0.08	-0.24	-0.66
13.52	-0.04	-0.10	-0.30
28.24	-0.11	-0.30	-0.89
36.71	-0.04	-0.04	-0.28
55.37	-0.06	-0.19	-0.50
61.90	-0.01	0.02	-0.10

The damage was simulated by a theoretical symmetrical saw cut in the left and right flanges at the location 0.7 L of the span L. The saw cut depth increased stepwise in three consecutive stages: 4, 8 and 12 mm, which corresponds to locally reducing (width of 0.0005 L) the bending stiffness by 11.5 %, 21.5 % and 30.4 % respectively. The corresponding effect on the natural frequencies is shown in Tab. 1. The changes in the spectrum are very small, but if damage detection is to be efficient, such changes should be observable.

The response of the beam was simulated as a traveling mass of 0.5 kg accompanied by -5 N square impulses of a duration of 0.02 seconds at a distance of 25 mm using a driving speed between 0.15 and 0.2 m/s by ANSYS (Transient Analysis).

The accelerations and strains in the middle of the beam at the sampling frequency fs = 1000 Hz were chosen as the traced quantity (to be measured in the future).

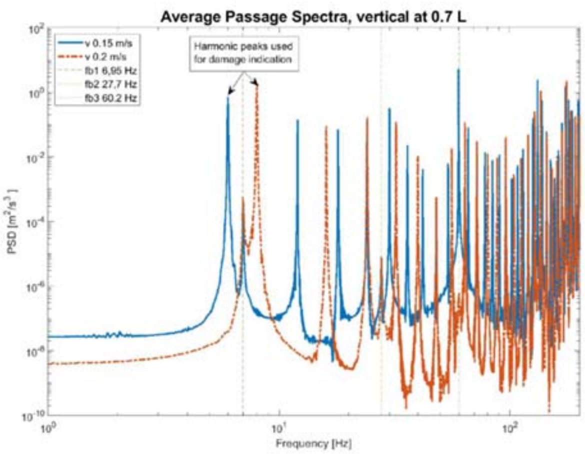

Fig. 1: Average PSD during passage at the midpoint of the beam.

3. Damage Detection

The impulses of the moving cogwheel cause higher harmonic components, especially in the accelerations of the beam. At normal speeds, the crossing of the CW over a bridge would take several seconds, which promises a relatively high resolution of the power spectral density (PSD) spectra measured at a point on the bridge so that it may be a good damage indicator. The greatest changes occur at the small peaks that correspond to the natural frequencies (see Fig. 1). They are, however, in a general case, far below the level of the effects of the periodic excitation and its harmonic peaks. Therefore, the harmonic peaks in the vicinity of structural natural frequencies were suggested for damage indication. Harmonic peaks below the natural frequency will increase, and harmonic peaks above the natural frequency will decrease. As there is a direct relation between the CW speed and the impulse frequency it generates, only two passages of the CW with a speed increment adjusted to frequencies around the first natural frequency of the bridge are needed to reveal a change in the spectrum, provided we know the spectra of the intact bridge. A shift towards lower frequencies in a chosen wider frequency band should also reveal a drop in natural frequencies.

The forced passage modes (FPM) measured at a point are not identical to power mode shapes (Fang, 2009) because they also include information about the accumulation of vibration energy during the passage and the changes in natural frequencies due to changing mass position. Moreover, they are prone to beats in the vicinity of the natural frequencies (see Fig. 2). It is assumed that the driving speed will have to be low, but even at low speeds there are only short periods between the impacts of the cogwheel. Short evaluation times are also necessary in order to obtain a good space resolution for the damage localization. Another possibility is the extraction of FPMs using a narrow band-pass filter.

In this way it is possible to obtain a PSD-coordinate at each impulse position, and evaluate the FPMs from them at particular frequencies on (Fig. 3).

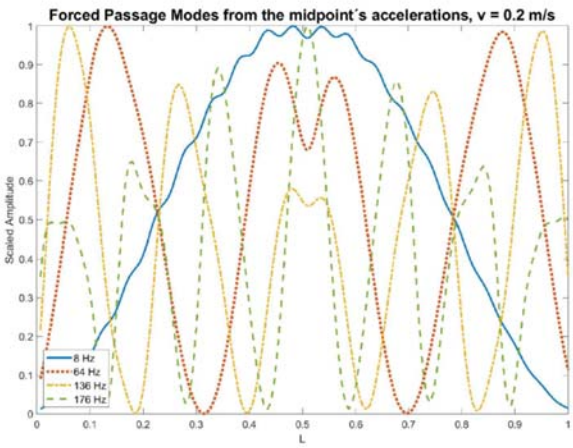

Fig. 2: FPMs extracted from the accelerations of the midpoint, passing velocity v = 0.2 m/s.

The FPMs are dominated by the natural mode shapes offering the possibility to treat them as natural modes and use them to evaluate approximate flexibilities that are sensitive to local damage. The flexibilities can be computed using the theory by (Pandey, 1994). The Flexibility difference is only a good location estimator if the beat phenomena are negligibly small compared to the damaging effect. This is the case when the FPMs are dominated by a single mode and not very close to the resonance where the beat phenomena may be rather intensive. Practically this means tuning the impulse frequency (velocity) not to resonance, but also not very far from it. The result for a successful damage localization is given in Fig. 3, evaluated for the three damage cases (DC) from Tab. 1, taking into account three modes. Note that the second mode of the DC3 fails to identify the damage location well, which may happen as a result of the mentioned simplifications. However, eliminating the effects of the beat phenomena under the nonlinear conditions of passing mass is a rather complicated task that is still under investigation.

From a practical point of view, this means that using more passes at different speeds as well as more transducers will increase the reliability of the damage localization. Another possibility is the use of very slow step-by-step motion at the expense of lower loading intensity and considerably longer testing times.

4. Conclusions

Assessing the condition of a bridge by means of a cogwheel generating regular force impulses along the driving path and only a few vibration transducers may be a sensitive indicator of structural damage according to the presented preliminary numerical study. The advantage is that the test only takes several seconds for the passage of the cogwheel, and the damage indication is available shortly after the test.

Damage localization from the same experimental setup is also possible. The proposed relative flexibility difference of FPMs is sensitive to the damage location, though the presented localization procedure is not yet completely free from bias because of beat phenomena and nonlinear effects of the passing mass.

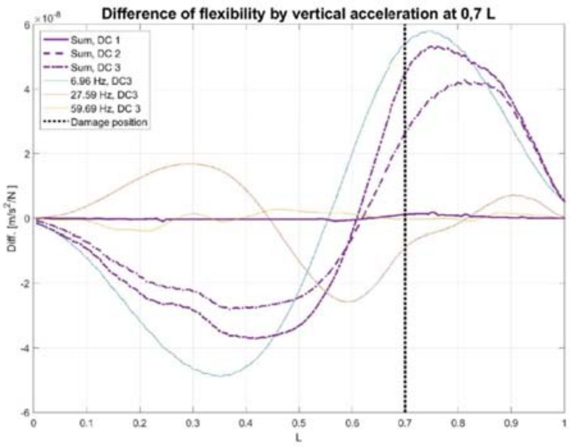

Fig. 3: Differences of flexibility at the midpoint 0,7L, passing velocity v = 0.2 m/s.

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