VIBRATION MONITORING OF BRIDGES

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1. ABSTRACT

Traditional visual inspection tools, which are typically carried out annually, can only detect obvious damages like disruption, cracks or rust on the surface of bridges. Advanced non-destructive and destructive inspection tools are usually applied when visual inspection can't provide sufficient information. Besides these techniques engineering surveyors can conduct geometric deformation analysis that provides additional information for damage detection of structures. The implementation of appropriate methods for data acquisition and analysis to detect changes to the material, geometric and dynamic characteristics of structures is summarised under the term Structural Health Monitoring (SHM). The essential idea of SHM is to determine a normal behaviour of undamaged structures and to obtain qualitative conclusions from changes of this behaviour related to the current health status. Information about changes within the dynamic characteristics of structures can be detected by applying accelerometers, which are a component of Ambient Vibration Methods (AVM) as an integral part of SHM. Analysis of acceleration measurements can derive natural frequencies that depend on weight, material, stress and strain as well as the geometry of the object. Hence this data can be used to derive additional information about the capacity and condition of a structure.

In this paper we present a measurement system based on low-cost accelerometers that nevertheless performs measurements with high accuracy. This autonomously operatable device features a memory card slot, an internal battery, a waterproof housing and temperature resistant components. Additionally real time data transfer can be obtained via wireless LAN or USB connection to a computer. All necessary steps of data acquisition, processing and interpretation of vibration monitoring will be presented on a practical example.

2. INTRODUCTION

Structural Health Monitoring (SHM) of bridges has gained of importance during the last years and has been applied in various problem domains (FUJINO *et al.* 2010, LYNCH *et. al* 2006, WANG *et al.* 2006, WENZEL 2009). Large structures of importance have been equipped lately with sensors to perform permanent monitoring in order to provide its proprietor with online web access in real time regarding the current structural health status (JANG *et al.* 2008, MASRI *et al.* 2004, KIM *et al.* 2007b). The field of vibration monitoring is based on the analysis of vibration characteristics of bridges whereas its focus is set on natural frequencies, damping characteristics and mode shapes. In contrast to geodetic monitoring systems (DUFFY *et al.* 2001, FOPPE 2006, SKOURTIS *et al.* 2004), that are in essence restricted onto the acquisition and analysis of geometric deformation and dislocation of the structure, vibration monitoring can immediately detect changes of structural integrity and even determine type and location of an occurred malfunction (CURADELLI *et al.* 2008, KIM *et al.* 2007a, ZHOU *et al.* 2010). The fundamentals of this approach are based on the unique dynamic characteristics of bridges that are a derivative of the equation of motion and can be interpreted as a vibrational signature. Knowledge and analysis of the current natural frequencies can lead to fast and reliable conclusions about the condition of the structure. However CARDEN AND FANNING (2004) claim that there is no universal approach to detect any kind of damage in any kind of structure.

The possibility of deriving geometric changes from accelerometers arises by filtering and integrating the recorded signals, as NEITZEL *et al.* (2007) as well as ROBERTS *et al.* (2001) have already shown. Hence Vibration Monitoring adds another important component to the toolbox of monitoring which can help to minimise potential risks and hazards.

3. MEASURING SYSTEM

An autonomous low-cost sensor system for SHM as well as software for the analysis of vibrational characteristics has been developed by RESNIK AND GERSTENBERG (2011). The implemented 3-axis accelerometer chip is based on the micro-electro-mechanical system (MEMS) architecture (WILD-PFEIFFER AND SCHÄFER 2011). The designed device features a memory card slot and an internal battery that lasts for about 8 hours under maximum energy consumption and up to 80 hours under normal conditions, which makes it applicable at measurement campaigns. A waterproof housing and temperature resistant components ensures usability under adverse weather conditions. Furthermore real time data transfer can be achieved via wireless LAN or USB connection to a computer. An implemented high-pass filter offers the possibility to reduce offset and drift characteristics of the measured values. All mentioned features enable a real time control in the field in order to alter the measurement setup if necessary. Also raw data can be recorded for extensive post processing. Fig. 1 shows the introduced measuring system.

Fig. 1. USB Acceleration sensor with laptop (left) and wireless LAN acceleration sensor (right).

4. DATA ACQUISITION

The basic measurement process and the necessary data analysis are exemplified on the Komtur Bridge in Berlin, Germany, which has been chosen due to its very intense and clearly perceptible vibration behaviour. Fig. 2 shows the inspected structure and a schematic representation of the three bridge sections with a total length of 91 m and a width of 20 m.

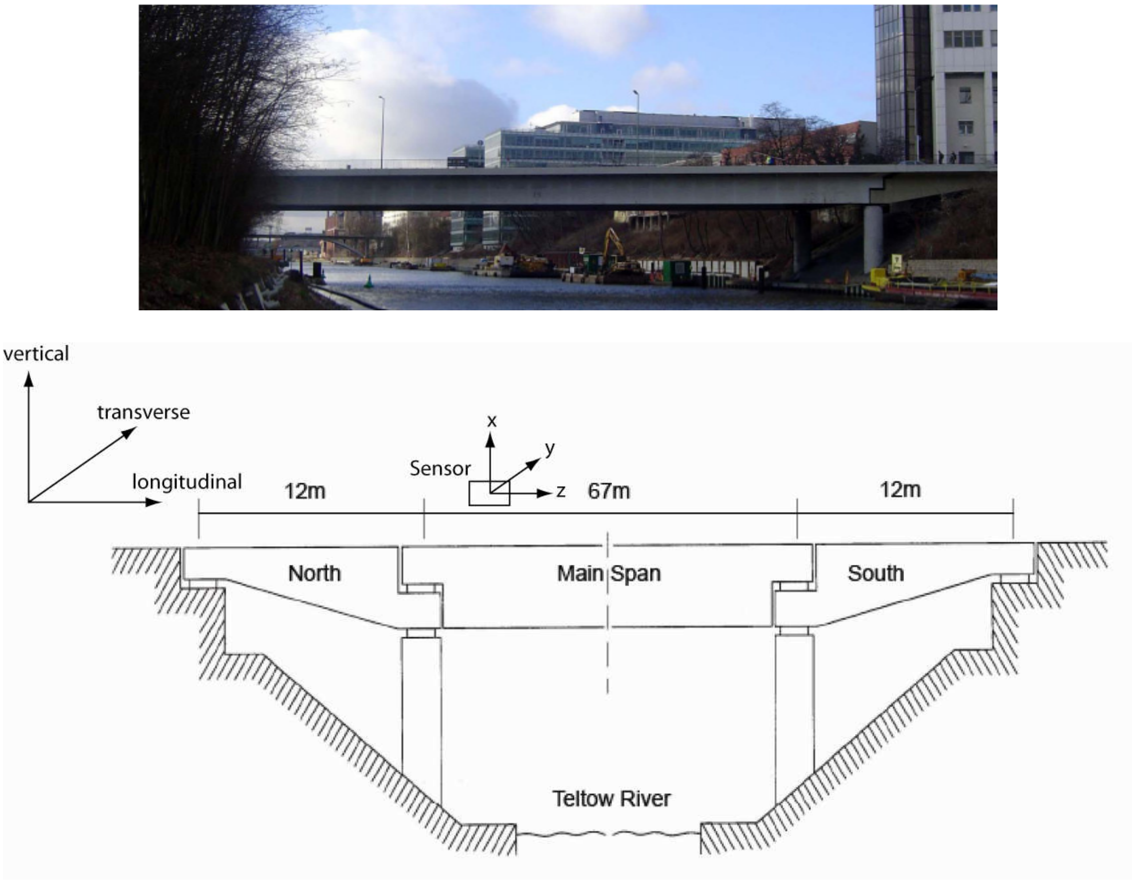

Fig. 2. Picture and a schematic representation of the Komtur Bridge in Berlin, Germany.

Due to the vibrational characteristics of bridges analysis of measurements in vertical direction provides the most relevant results and also measurements in the transverse direction can be considered for evaluation of natural frequencies. However, no significant natural frequencies could be obtained from measurements in longitudinal direction of bridges. According to the construction of the implemented MEMS accelerometer the noise of the measurement in direction of the z-axis is about ten times higher than the noise of the measurements in the xy plane, thus the z-axis has to be aligned parallel to the longitudinal direction of the bridge whereas the x and y axes can be used to carry out measurements in transversal and vertical direction.

4.1 Planning of the Measurement Configuration

Prior to the actual measurement of the bridge its construction has to be investigated in terms of mode shape and natural frequencies to obtain optimal sensor locations. For large and complex structures Finite Element Analysis should be conducted to achieve optimal sensor positions for the monitoring of dynamic behaviour (WENZEL AND PICHLER 2005 P. 78). As no significant natural frequencies are to be expected on pillars as well as on the beginning and end of a bridge no sensors need to be installed on these positions. In case of damaged bridge bearings the resulting frequencies can be detected without sensors that are placed on pillars through unexpected shifted frequencies and mode shape (WENZEL AND PICHLER 2005 P. 9). The final aim of these considerations is a suitable arrangement of the sensors that are able to capture all important properties of a bridge. Another problem arises when only few sensors are available to cover the whole bridge. An applicable solution is the separation into sub-sections and by combining several measurements epochs from different sections into one complete dataset in order to achieve full coverage. Therefore a reference sensor has to be defined, which is placed in one location that records the complete series of epochs.

4.2 Sensor Preparation and Measurement

In order to ensure the comparability of the signals of all used sensors a reference measurement on-site has to be carried out, where the accelerometers record vibrations within the same area. Based on this data a correction function for each sensor can be applied that represents a relative calibration. After sensor preparation the sensors will be placed onto previously determined positions along and on both sides of the bridge. The measurement is carried out during traffic and shall include sufficient evaluable measurements for subsequent analysis.

5. DATA PROCESSING AND INTERPRETATION

The recorded time series of each sensor can be rectified with the corresponding, predetermined correction function and subsequently reduced of an offset and drift by a suitable high-pass filtering. In particular the sections of ambient vibration after occurred excitation are relevant for the determination of natural frequencies. Those sections of the time series are called ambient windows. Fig. 3 shows a typical time series of an acceleration measurement including an example of an ambient window which is additionally depicted in Fig. 4.

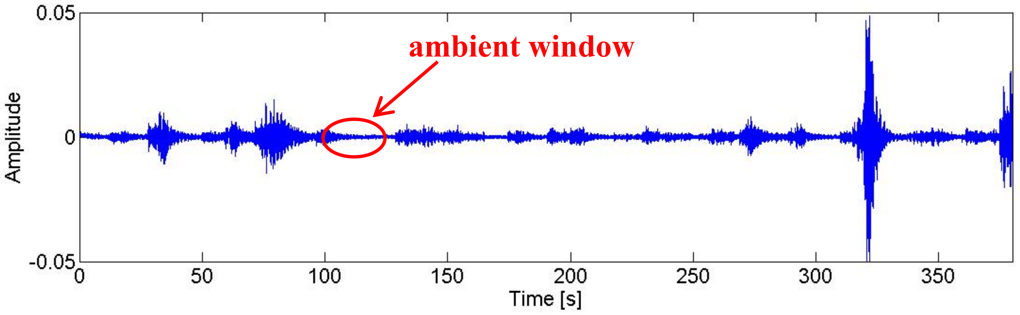

Fig. 3. Time series of an acceleration measurement.

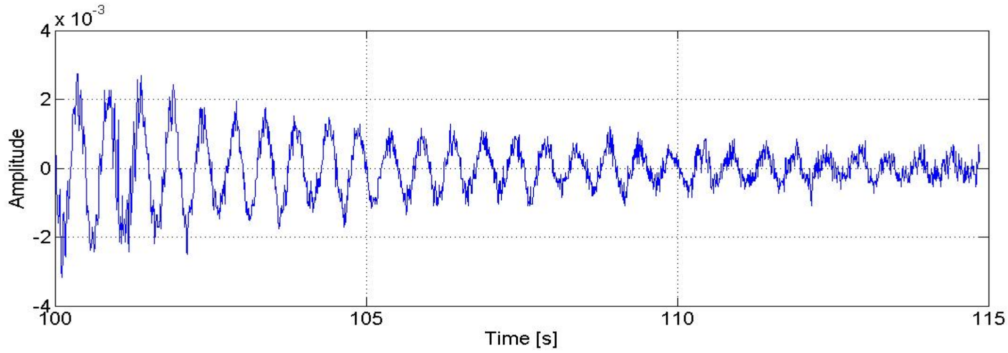

Fig. 4. Ambient window.

For the selected ambient windows of the time series the frequency spectrum is calculated according to the Fast Fourier Transform algorithm (FFT) and averaged over all sections (Resnik 2010). As an example the averaged frequency spectrum for the vertical acceleration in the middle of the bridge is shown in Fig. 5. The smoothed Power Spectral Density (PSD) of the time series is determined in accordance to the Welch method (Welch 1967) and is shown in Fig. 6. In both spectra the natural frequencies at approximately 2 Hz and 2.6 Hz can be identified considerably.

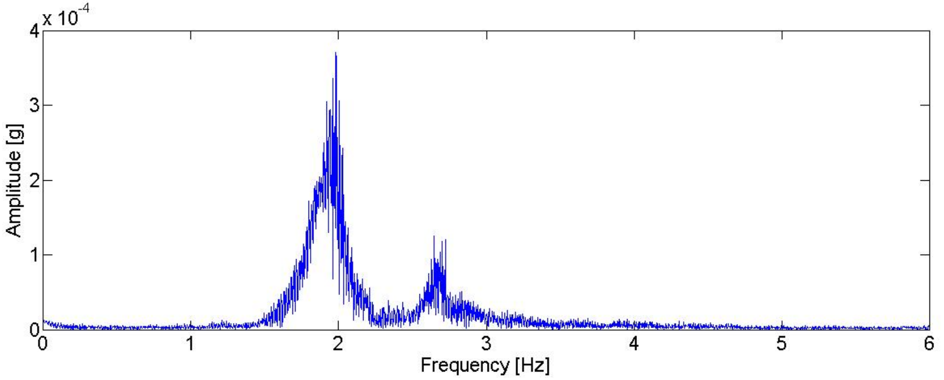

Fig. 5. Averaged frequency spectrum (FFT).

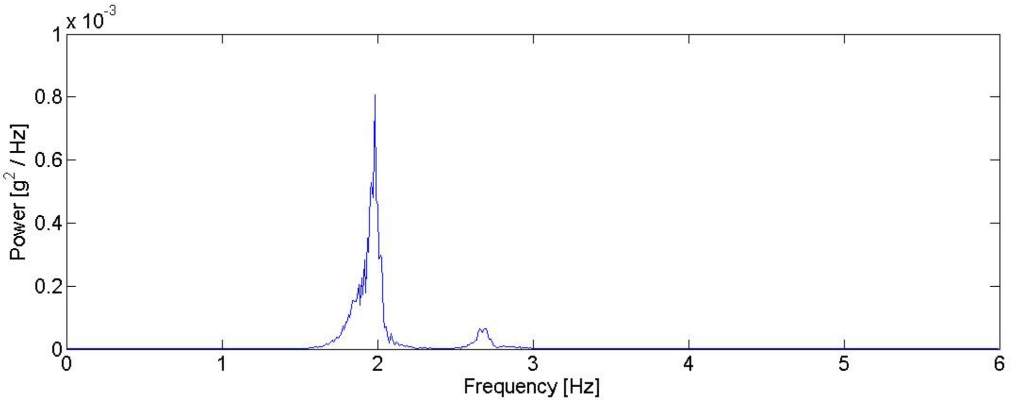

Fig. 6. Smoothed averaged power spectral density (PSD).

The Komtur Bridge has very distinctive vibration characteristics whereas natural frequencies can be easily identified within the frequency spectrum. For an automated analysis of the data the identification of the natural frequencies in the PSD is easier to implement and is less sensitive to noise. In particular higher order natural frequencies usually have a minor impact onto the signal as it is very difficult to distinguish it from the noise within the frequency spectrum. The averaged PSD often enables a definite identification of higher order natural frequencies compared to FFT. These calculations are carried out for all sensor positions on the vertical and transversal axes.

In order to compare natural frequencies the averaged PSD of an axis, where only measurements from the west or east side of the bridge have been taken into consideration, are combined to one single plot and is referred to as trend card. The frequencies are plotted on the x-axis against the sensor locations over the entire length of a bridge element with interpolated PSD between each sensor position. This allows identification of changes regarding the natural frequency along the bridge and the comparison of the west and east side of the bridge. The gradient of the frequency over the complete length of the bridge's main element is shown in Fig. 7 and represents the highly noticeable frequency that has been derived from PSD.

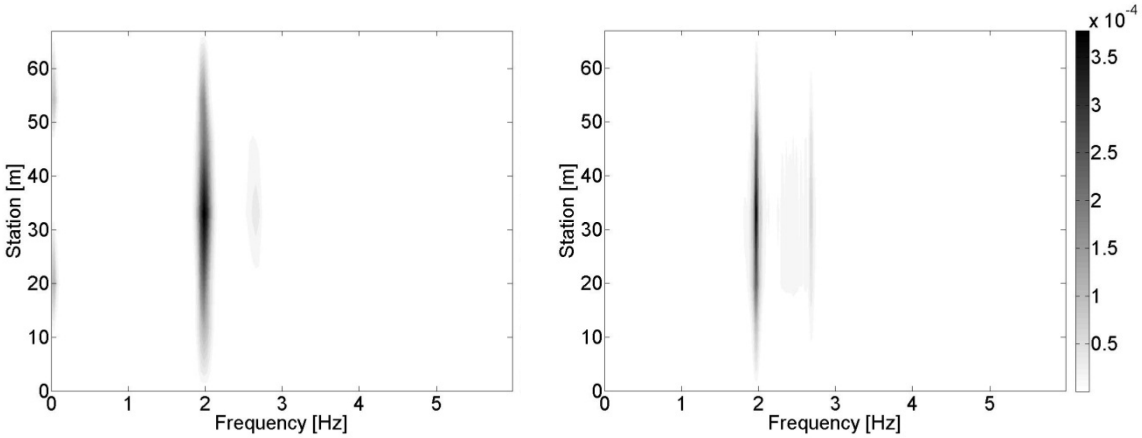

Fig. 7. Trend card of the vertical natural frequencies for the west (left) and east side (right) of the main element.

The trend cards from both sides of the bridge offer identical characteristics whereas the resulting natural frequency of approximately 2 Hz is located in the expected range for such bridges, as represented in Fig. 10. For the shorter elements in the north and south of the bridge the trend cards, depicted in Fig. 8 and Fig. 9, are partially noisy showing fuzzy areas for natural frequencies. These effects are partly caused by the length of the

bridge and based on the fact that the time series offer only marginally analysable ambient windows despite of long measurement durations. Additionally it should be mentioned that the north and south elements, that appear to be identical, show different natural frequencies of approximately 17 Hz and 11 Hz. This disparity was discussed during the presentation of the results at the Berlin Senate Department for Urban Development and it turned out that different bearings have been installed. One element has a fixed bearing and the other one a slide bearing. Furthermore conductions are integrated into the north element. Both structural conditions have a major impact onto the resulting natural frequencies and thus confirm our results. However, the measurements from both sides of the bridge provide identical results and the natural frequencies are within the expected range for bridges of this length.

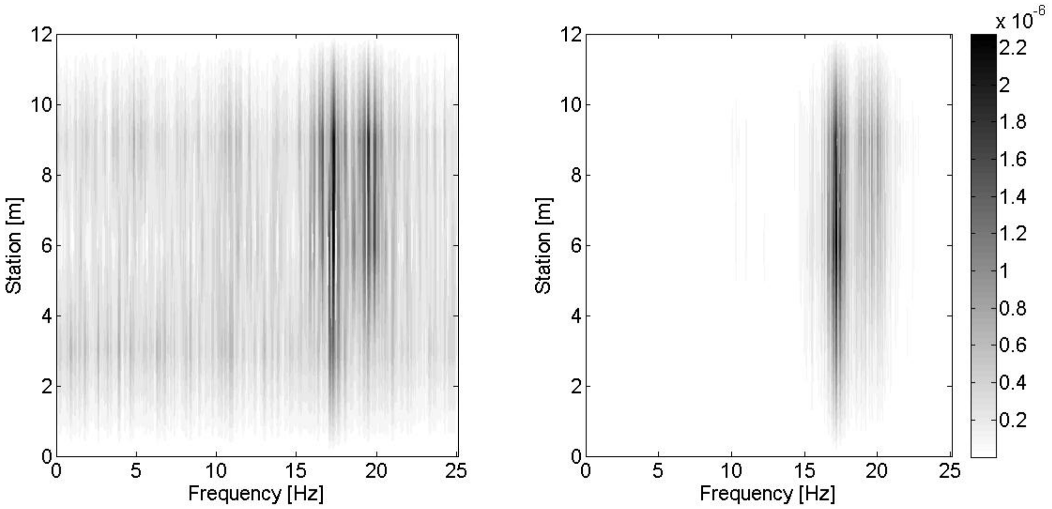

Fig. 8. Trend card of the vertical natural frequencies for the west (left) and east side (right) of the north element.

Based on these results further vibration monitoring of the bridge can be obtained. A change of these fundamental natural frequencies indicates global damage and occurs immediately after malfunction. Thereby a permanent monitoring of the dynamic behaviour of the bridge enables a real time determination of the global condition of the structure. An analysis of the signal in terms of mode shapes, modal flexions and damping characteristics allows sophisticated statements about local damage and material fatigue within the structure (WENZEL AND PICHLER 2005 P. 159).

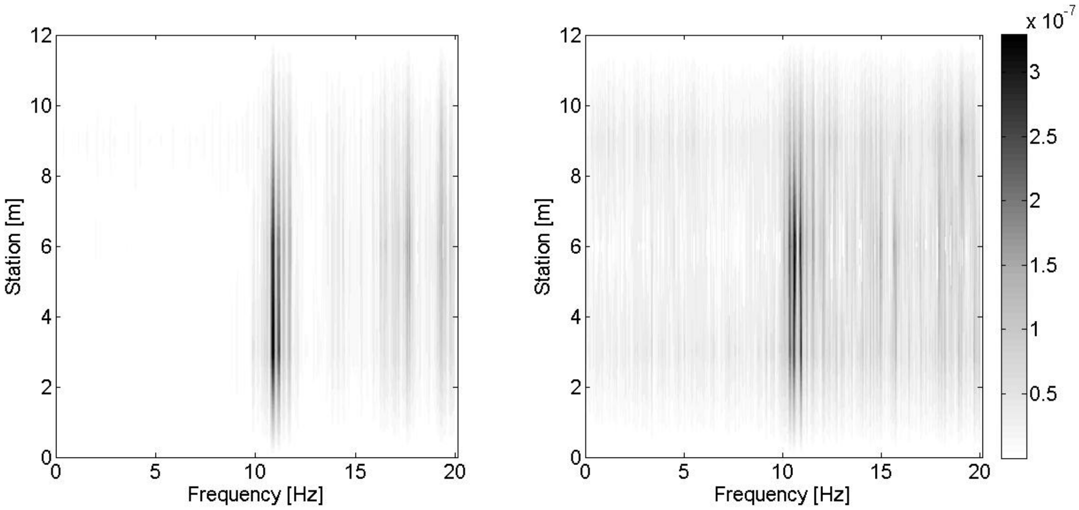

Fig. 9. Trend card of the vertical natural frequencies for the west (left) and east side (right) of the south element.

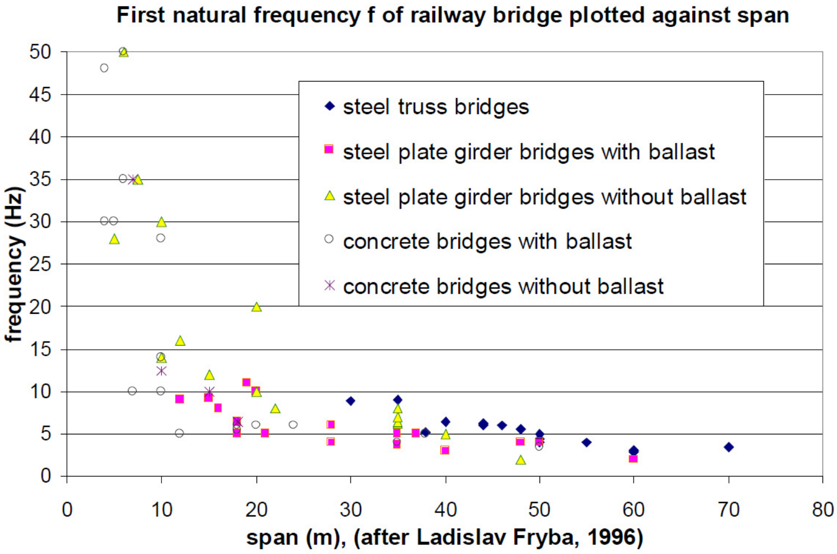

Fig. 10. Natural frequencies of railway bridges (MENG *et al.* 2004).

6. CONCLUSIONS AND OUTLOOK

A wireless low-cost monitoring system for vibration monitoring of structures as well as necessary steps for data acquisition, analysis and interpretation have been presented in this paper. Furthermore a proper data acquisition is fundamental for signal processing which influences the resulting quality of natural frequencies. A previous planning of measurement configuration is essential whereas on-site verification of the signal in terms of ambient windows is recommended. Further work will focus on the evaluation of mode shapes and damping characteristics as well as the evaluation of displacement values derived from acceleration measurements. Thus far only separate investigation has been conducted via GPS (KURAS 2009) and microwave interferometry (KURAS *et al.* 2009). Hence comparative measurements by using accelerometers, total stations, GPS, a laser tracker as well as the IBIS-S system which is based on the principle of microwave interferometry will soon be carried out in order to determine accuracy and reliability for the derived displacements and frequencies.

A prospective combination of geometric and dynamic monitoring of structures and the implementation of geodetic strategies for an upcoming dynamic deformation analysis will provide a much more reliable and comprehensive tool for engineering geodesy.

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