Investigation of Low-Cost Accelerometer, Terrestrial Laser Scanner and Ground-Based Radar Interferometer for Vibration Monitoring of Bridges

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ABSTRACT

Structural failures like the I-35W Mississippi River Bridge collapse on the first of August in 2007 is besides a huge economic loss often associated with personal suffering and underlines yet again how quickly existing inspection and monitoring methods may fail. Engineering geodesy has always been providing an important contribution to monitoring and deformation analysis of man-made structures. However, these geodetic approaches are restricted to a static point of view concerning the object's geometric properties. The dynamic characteristics of structures were not often taken into consideration. Admittedly vibration analysis of structures has increasingly become part of engineering geodesy and thus contributes more detailed information about the capacity and condition of e.g. bridges.

In this contribution the potential and limitations of a low-cost accelerometer sensor system and a terrestrial laser scanner (TLS) for vibration analysis will be presented in practice. Therefore a suitable sensor setup has been determined and measurements have been carried out. In addition oscillations of a bridge for reference purposes were observed with the IBIS-S system, which is based on the principle of microwave interferometry with accuracy down to the sub-millimetre and a sampling frequency of 200 Hz. This enables the possibility to determine real-time deformations of bridges.

The data of all three sensors have been analysed in terms of natural frequencies and damping coefficients using least squares adjustment. Furthermore acceleration measurements have been integrated and appropriate filters were applied to derive displacements which have been compared with those from TLS and IBIS-S. Hence this contribution provides information on which accuracies can be achieved for the derived parameters under real conditions which is fundamental for upcoming dynamic deformation analyses of structures.

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INTRODUCTION

A multitude of sensors and sensor arrays as well as combinations of various measurement systems is currently in use for dynamic testing in the field of structural health monitoring (SHM) of bridges. The basic concepts of SHM and an overview of its applications can be found in WENZEL (2009).

The most common measurement systems are arrays of accelerometer. Such a system in form of a spatially dense wireless sensor network (WSN) has been developed for long-term monitoring and recording of ambient accelerations by PAKZAD et al. (2008). A large part of the recent literature is focussing on wireless as well as mobile technologies, combining several measurement systems and methods. CAO et al. (2008) developed a WSN flexible system platform for data acquisition, validation, processing and visualization. HACKMANN et al. (2012) are approaching the combination of wireless sensor networks with pre-existing optional sensor-infrastructures both from the point of view of computational and structural engineering while concentrating on the data throughput rather than specific measurement systems. PRANA et al. (2000) are including GPS measurements into their setup, analysing a high-speed air-cushion catamaran with the use of fibre optic Bragg grating strain gauges, conventional resistive strain gauges, accelerometers and a Motion Reference Unit (MRU). BENEDETTINI and GENTILE (2011) constitute a modern approach to structural monitoring by comparing natural frequencies obtained from a traditional data acquisition system based on servo-accelerometers with those derived by non-contact radar measurements using an IBIS-S micro-wave interferometer.

MEASURING SETUP AND SYSTEMS

The potential and limitations of different sensor systems for modal analysis of bridges will be investigated under real conditions. Therefore measurements have been carried out on a bridge near Braunschweig, Germany, which has been chosen due to its intense vibration characteristic. The observed bridge, which is shown in *Figure **1***, has a length of approx. 76 m and width of 13 m. Due to the requirements of the positioning of the sensors and to ensure comparative measurements the sensors were placed close to the abutment indicated by a circle in *Figure **1***.

Figure 1. Observed bridge near Braunschweig, Germany.

Accelerometer Sensor System

For modal analysis of bridges a suitable low-cost accelerometer sensor system based on the micro-electro-mechanical system (MEMS) architecture was developed by RESNIK and GERSTENBERG (2011) and is depicted in *Figure **2*** on the outer left. The time synchronized acceleration measurements of at most 16 sensors can be transferred via USB connection to a computer over a distance up to 100 m. Accelerations can be measured with an accuracy of $\sigma = 20\ \mu g/\sqrt{Hz}$ and a sampling rate up to 600 Hz.

Figure 2. Low-cost accelerometer sensor system (left), TLS (middle) and IBIS-S (right).

Terrestrial Laser Scanner

Terrestrial laser scanners (TLS) are active 3D measuring systems that are capturing distances to objects in equal increments of arc around the rotation and tilting axis. TLS are able to measure up to a million points per second with single point accuracies of a few millimeters but are usually not commonly used for modal analysis of structures. However, some systems like the Zoller+Froehlich Imager 5003 are able to scan in a point mode which enables the possibility to perform distance measurements to a single point of an object with an extremely high sampling rate of 125 kHz. Hence measurements by using TLS can be relevant for modal analysis of structures. The suitability of TLS for determination of natural frequencies has been shown by VENNEGEERTS and KUTTERER (2007) on the investigation of the dynamic behaviour of wind turbines.

Terrestrial Interferometric Radar

The main principles concerning measurement and processing of satellite-based radar interferometry are known in the field of radar remote sensing since many years. In the last years a transfer of these principles to ground-based measurement approaches happened. These terrestrial, interferometric radar systems are referred to as “terrestrial interferometric synthetic aperture radar (t-InSAR)”. With such systems the highly accurate determination of movements or change rates of local limited objects is possible and has been shown by PIERACCINI et al. (2006), RIEDEL et al. (2011) and RÖDELSPERGER (2011).

Since 2006 such a system called IBIS (Image by Interferometric Survey), developed by IDS (Ingegneria dei Sistemi), is available for the use in field of engineering geodesy. This system is available in different configurations. Beside the version for static monitoring (e.g. landslides, dams, etc.) a special version for the dynamic and static monitoring of structure vibrations exists, the IBIS-S which is depicted in *Figure 2* on the outer right.

The IBIS system that was used for the tests shown in this paper was bought by the Institute of Geodesy and Photogrammetry (igp) of the University of Technology Braunschweig in 2011.

The measurements with the IBIS-S system are done within the Ku-band (17.1 – 17.3 GHz) which results in a wavelength of 1.78 cm. Through the measurements the radar unit is sending a continuous wave with stepwise changing of the frequency (Continuous Wave - Stepped-Frequency, CW-SF-method), which is reflected by natural or artificial targets. A detailed description can be found in Pieraccini et al. (2004).

To detect a target the signal strength has to be higher than the surrounding noise. In the IBIS-S configuration the system is able to analyse signals in a distance up to 1000 m. To ensure a good reflection of the signal and to signalised points of the structure that are of interest, so called corner reflectors have to be present on the structure surface. Often the object already has parts on the surface that act like corner reflectors and the installation of artificial corner reflectors is not necessary. In *Figure **3*** on the outer left an example of such a structure is shown.

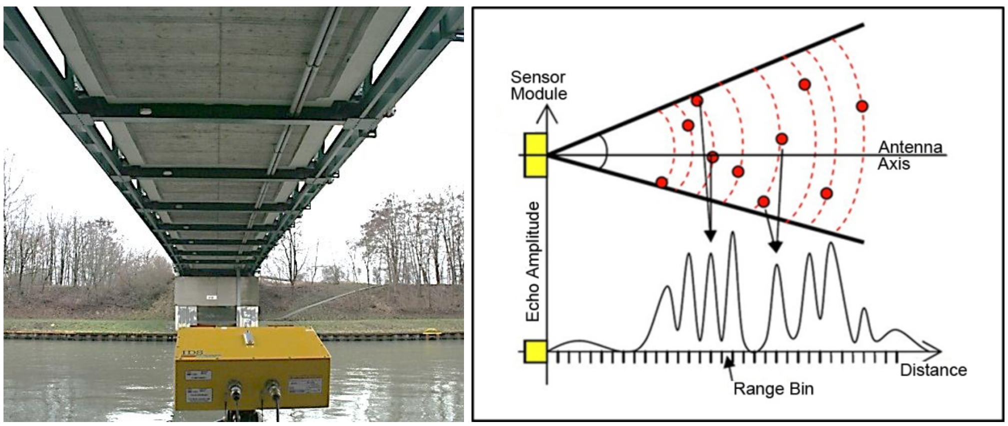

Figure 3. Example of a structure with "natural" corner reflectors (left) [Riedel and Lehmann 2012] and principle of signal detection (right) [Ricci 2009].

Caused by the CW-SF technique the measured distance is divided in so-called range-bins with a length of 75 cm. The detected signal of one range-bin is the sum of all signals that are reflected in this spatial area, see *Figure **3*** on the outer right . This also shows that the radar system (IBIS-S configuration) does not have an azimuthal resolution.

By repeating the measurements with a frequency up to 200 Hz the system is able to detect changes of the object by analysing the changes of the phase see,

Figure 4 with an accuracy of up to 0.01 mm.

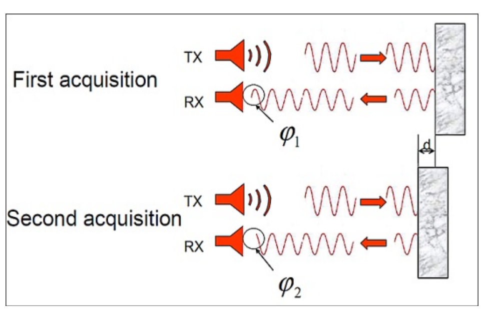

Figure 4. Principle of the interferometric determination of object changes [Ricci 2009].

The differences in the phase can be directly converted in the line of sight displacement component of changes of the structure. By taking the geometry of the acquisition into account, it is possible to calculate also the displacement component of the structure which is of interest. In the case of a measurement of a bridge this is the vertical component, see *Figure* ***5***.

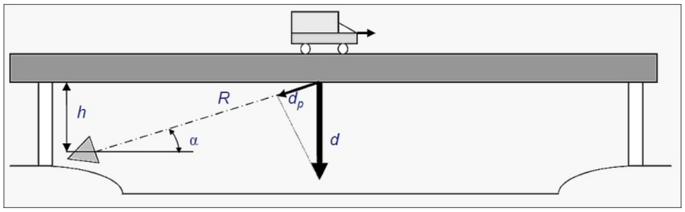

Figure 5. Example for the geometry of a measurement of a bridge and the single components of the displacement [RICCI 2009].

DATA ACQUISITION AND PREPERATION

The measurements are carried out during traffic and shall include sufficient evaluable measurements for subsequent modal analysis. In particular the sections of ambient vibrations, which occurred after excitation, are relevant for the determination of natural frequencies, damping coefficients and mode shapes that are called ambient windows. A detailed overview about ambient vibration monitoring can be found in e.g. WENZEL and PICHLER (2005).

Data processing

The single point accuracy of the used terrestrial laser scanner (TLS) Z+F Imager 5003 is technically not high enough to detect displacements smaller than a millimetre. The only way to detect such small displacements is to perform measurements with a high sampling rate and to average the measurements afterwards. Therefore a sampling rate of 7812 Hz was used in order to achieve a reasonable accuracy for the averaged distance measurements. The raw distance measurements of the TLS were pre-processed using a moving average filter with an optimal filter length of

$$2l = \frac{\text{Sampling rate}}{1^{\text{st}}\ \text{natural frequency}}. \tag{1}$$

Afterwards 100 filtered distance measurements were averaged which resulted in a theoretical sampling rate of 78.12 Hz for the TLS time series. Furthermore trend and offset were removed by subtracting an adjusted straight line from the post-processed TLS data as well as of the raw displacements obtained from IBIS-S and acceleration measurements. The resulting ambient window of the TLS measurements is depicted in *Figure* ***6***. The maximum amplitude of the oscillation is approximately 0.4 mm and shows a smooth behaviour for the first 15 seconds while the rest is noisier. The damping characteristic is visible with some deviations from a smooth damped harmonic oscillation.

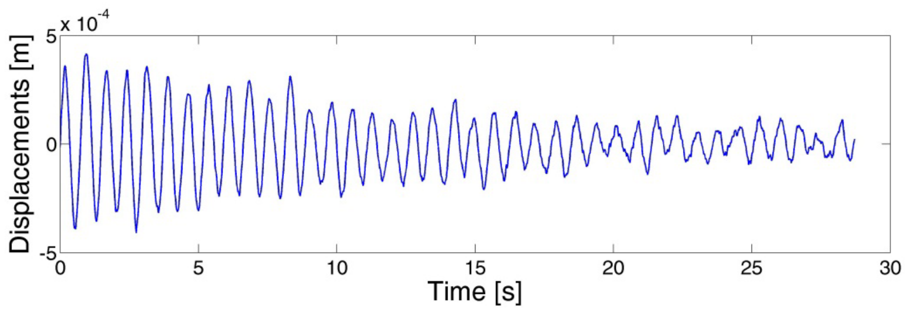

Figure 6. Ambient window derived from TLS.

The ambient window obtained from accelerometer measurements is shown in *Figure 7* where the vibration and damping characteristic of the bridge are clearly visible. Although in comparison to post-processed TLS or raw IBIS-S data the signal itself is much noisier.

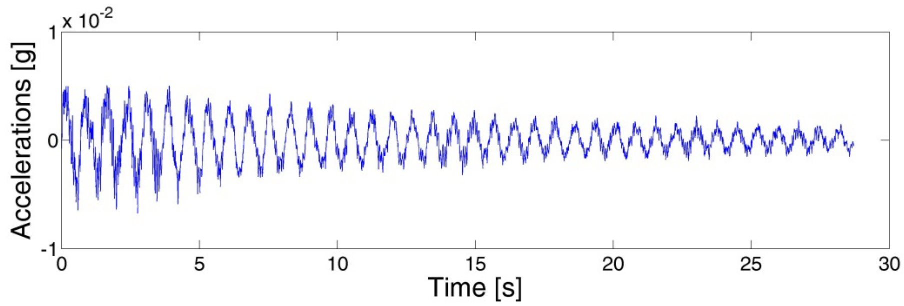

Figure 7. Ambient window obtained from accelerometer.

Due to the high accuracy of the IBIS-S measurements the observed oscillation with maximum amplitude of nearly 0.5 mm is very smooth and reveals an explicit damping characteristic, which can be seen in *Figure **8***.

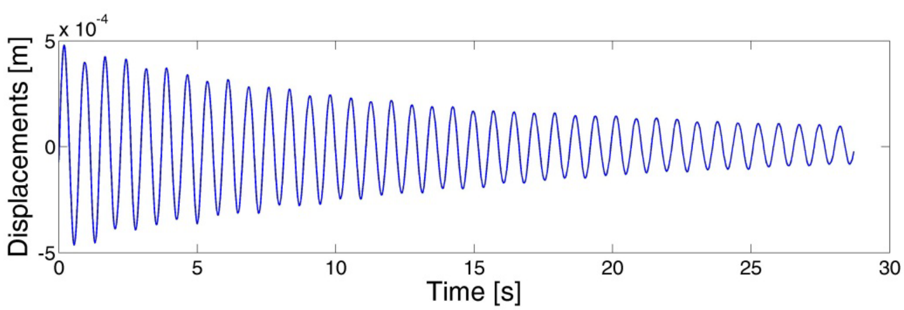

Figure 8. Ambient window obtained from IBIS-S.

Natural Frequency and damping coefficient

The ambient window obtained from each sensor were used to determine the first natural frequency and damping coefficient using least squares adjustment, see e.g. MIKHAIL (1976), with the functional model for a damped harmonic oscillation

$$y(t) = a\sin(2\pi ft + \varphi)\cdot \mathrm{e}^{-2\pi dt} \qquad (2)$$

including amplitude a, frequency f, phase shift φ and damping coefficient d as unknown parameters. The adjusted first natural frequency and damping coefficient as well as their standard deviations are listed in Table **1**.

Table 1. Adjusted natural frequency and damping coefficient.

	Acc.	σ_{Acc}	TLS	σ_{TLS}	IBIS	σ_{IBIS}
1st natural frequency [Hz]	1.3553	1.6e-4	1.3553	1.4e-4	1.3559	3.0e-5
Damping coefficient [%]	0.91	1.6e-2	1.12	1.4e-2	0.97	3.0e-3

The difference between the calculated first natural frequencies of all sensors is smaller than 0.6 mHz, also the damping coefficient derived from accelerometer and IBIS-S are nearly equal and differ by only 0.06 %. The damping coefficient determined from TLS measurements is remarkably different from those derived via accelerometer or IBIS-S measurements. The pre-processing of the TLS measurements hardly influenced the determination of the damping coefficient but on the natural frequency. The different damping coefficient needs to be clarified in further investigations.

The high accuracy of the IBIS-S is also reflected in the standard deviations of the first natural frequency and damping coefficient which is approximately five times smaller than the achieved value for the standard deviations using accelerometers or TLS. Hence it is justified to regard IBIS-S as a reference sensor.

Mode shape

In order to compare measurements of the three introduced sensors only a single point along the bridge was observed. Thus it is not possible to compare resulting mode shapes of each sensor directly. Instead only displacements of this single point will be compared which provides fundamental information about the suitability of the applied sensors for mode shape analysis.

TLS and IBIS-S directly provide displacements of the point whereas accelerations have to be double integrated and filtered before. A detailed description of the all necessary steps of data preparation for integrated accelerations can be found in NEITZEL et al. (2007). The resulting displacements are depicted in *Figure **9***.

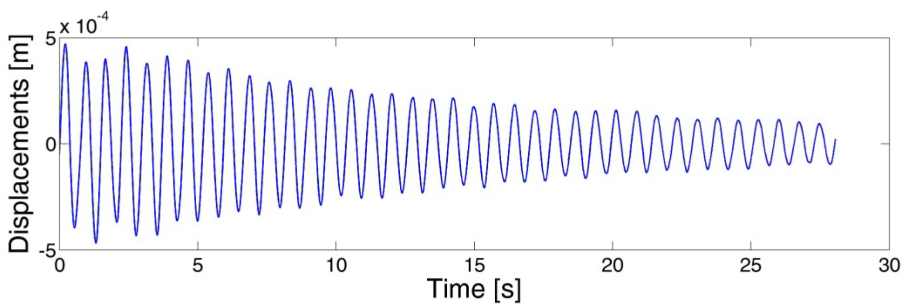

Figure 9. Double integrated, reduced and filtered accelerations.

The deviations of the displacements derived from accelerations and TLS with respect to IBIS-S as a reference sensor are depicted in *Figure **10***.

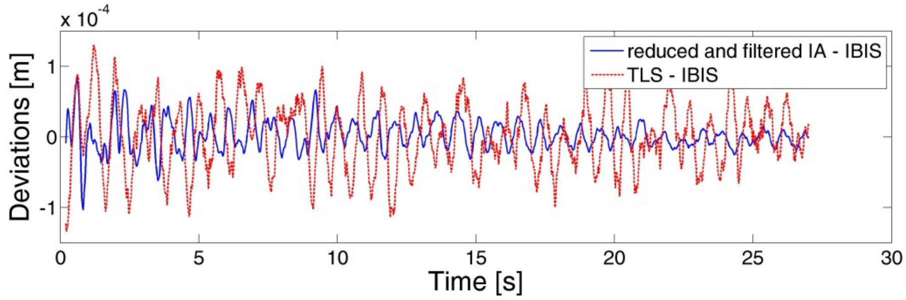

Figure 10. Deviations of displacements in comparison to IBIS-S.

In comparison to IBIS-S the observed displacements derived from integrated accelerations (IA) are more accurate than those derived from TLS. Applying appropriate filter techniques results in displacements with a standard deviation of $\sigma_{IA} = 2.1 \cdot 10^{-2}$ mm for accelerometer and $\sigma_{TLS} = 4.8 \cdot 10^{-2}$ mm for TLS measurements. However the resulting deviations are not only due to random errors. There are still some systematic effects left which were not taken into account during data analysis or may results from applied filters. Basically all three sensors have proven their suitability for modal analysis of structures.

CONCLUSION AND OUTLOOK

This contribution provides information about accuracy and reliability of modal parameters derived from low-cost accelerometer sensor system, TLS and IBIS-S under real measurement conditions. The used low-cost accelerometer sensor system is a suitable sensor for modal analysis of structures. Natural frequencies, damping coefficients as well as derived displacements could be determined with high accuracy.

Besides poor single point accuracy of TLS measurements such systems are revealing great potential for modal analysis of structures. A maximum sampling rate of 125 kHz could have been applied for the measurements using the presented TLS although a relatively small sampling rate of 7812 Hz was used which led to a standard deviation smaller than 0.05 mm for the obtained displacements. Increasing the sampling rate will lead to a more precise determination of natural frequencies and displacements while different results for damping coefficient still need to be clarified in further investigations. Furthermore some TLS are able to scan in a profile mode which enables the possibility to observe the whole length of a bridge at once with a sampling rate up to 50 Hz. The accuracy and reliability of derived modal parameters from TLS measurements scanning in profile mode still needs to be analysed.

For an upcoming dynamic deformation analysis of structures the correlation between measurements as well as the applicability of existing statistical tests on derived modal parameters needs to be determined.

The implementation of geodetic strategies for deformation analysis of a combined geometric and dynamic monitoring of structures will offer a much more significant and reliable tool for damage detection which will provide a substantial contribution to structural health monitoring.

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