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An assessment framework for sensor-based detection of critical structural conditions with consideration of load uncertainty

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ABSTRACT

The assessment of the condition of structures subjected to ageing and extreme loading conditions becomes increasingly important. Highly accurate sensor technologies and advanced structural identification methods can help to detect critical structural conditions and thus prevent collapse. The paper presents a general methodology for the evaluation of the measurement quality of sensor setups based on the identification of target structural properties like section forces, deflections or stresses. The target quantities that are relevant for the structural assessment will be identified from readily measurable deformation quantities such as inclinations. The proposed framework includes considerations of uncertainty in load pattern and uses mathematical optimisation techniques to relate the measured quantities to the range of target properties and thus to the ability of identifying critical structural conditions. The methods are applied to sample structures and the effect of uncertainty in the loading and uncertainty in the measurement process are studied for an inclinometer-based monitoring system. The quality of competing sensor setups will be evaluated for a single target quantity and expanded to multiple target properties. The methodology developed can be used for optimising sensor setups in the context of detection systems.

1. Introduction

Any structure is subject to ageing over the course of its service life, affecting its load bearing behaviour and — more importantly — capacity. In recent years, attention has also shifted to more extreme climatic conditions potentially subjecting structures to loads well beyond those that the structure has been initially designed to. Therefore, it is becoming ever more important to develop methods for assessing the state of a structure, which may be coupled to warning systems that ensure the safety of users in case of the structure reaching a critical condition.

The advent of cost-effective digital sensing solutions has led to the development of manifold systems for measuring structural parameters in order to facilitate condition assessment, which is the subject of the field of Structural Health Monitoring (SHM) and has been applied to a wide range of problems ranging from aerospace to civil engineering [8]. In the field of civil engineering, SHM encompasses system identification, model updating and damage detection among other fields. A general overview of Structural Health Monitoring is given in [7] and [28]. Sohn et al. [21] and Li et al. [12] provide an extensive overview of past and current literature on the subject. Specific applications to damage identification and prognosis are described in [4] and [6]. In the past years wavelet analysis has been applied for vibration-based damage detection and localization within different structures [22,23] such as steel frames [17,18]. Recent examples of implemented monitoring systems include [29] on bridges and [10] on wind turbines. The challenge of detecting critical conditions on the basis of data associated with uncertainty has given rise to a class of methods entitled Signal Detection Theory [19,27].

Sensor-based SHM systems measure physical responses on structures and record the corresponding data. The characteristics of sensor systems are introduced in detail in the extensive available literature related to the process of measurement e.g. [3] and [26]. Whilst piezoelectric sensors are the most commonly used in SHM systems, MEMS (Microelectromechanical Systems) based sensors are growing in popularity because they are small, inexpensive and easy to include in embedded systems, cheap wireless networks and smartphones [2,14].

A fundamental problem in SHM is that the physical quantities measured are typically different from the quantities of interest. That is because those quantities relevant for the assessment of structural condition and integrity such as stress distributions, crack widths or deflections are different from those readily measurable by standard sensors and measurement devices. An example are accelerometers, which many systems employ for sensing structural behaviour. Acceleration time histories of a dynamic response can be used to compute natural

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frequencies of the structure by spectral analysis and by detecting changes in frequencies it may be possible to infer changes in stiffness, which in turn may be a manifestation of damage or deterioration of the structure. The inverse analysis problem solved hereby is termed system identification, because system parameters are computed from response quantities by using some knowledge of the system [13,16,20,24].

Within this paper, the response quantities will be referred to as measured or observed quantities while the quantities inferred will be named target quantities or quantities of interest. These quantities of interest could be broadly divided into those relating to structural condition and behaviour and those relating to the performance under actions such as static loads or temperature effects. The first category would include deterioration effects whilst the second would include stresses or deflections. This paper concentrates on the identification of target quantities of the second category in the context of the optimisation of sensor systems employed for detection of critical loading conditions.

The motivation arises from the emergence of a class of modern accelerometer sensors that can very accurately measure slowly varying inclinations. The accuracy of those small and cost-effective MEMS-based sensors is shown in Section 2. When attached to structural components, the local rotation under load can be measured and assuming that the mechanical behaviour of the structure is known, other target quantities can be computed. Thus, the concept constitutes an identification problem wherein bending moments, deflections or stresses can be inferred from measured rotations. Whilst the structural behaviour may be known from the design stage of the structure or can be obtained from a calibration process, e.g. a load test where a defined loading is applied, a practical problem arises from the uncertainty in the loading. It is obvious, that in most cases an unknown magnitude of a known load pattern can be determined from a single rotation measurement. However, typically the load pattern itself will be subject to uncertainty.

The uncertainty in loading leads to uncertainties in the identified structural parameters. As will be shown, a range within which the target quantity must be, can be computed and this will form a critical component in the framework presented here.

If the sensor system is to be used for detecting a critical structural state, then this requires the expression of this state in terms of a target quantity that is identifiable, such as a critical stress or deflection. If the identification of this target quantity is subject to uncertainty, this will have to be accounted for in the assessment. Basically, the larger the uncertainty, the more early an alarm system would have to be set of – or, in other words, the larger the distance from the actual critical state may be.

This uncertainty is herein used to quantify the quality of a measurement system used for detection of the critical state. It is shown, that it depends on the sensor setup and that it can be used for optimising the setup such as to minimise the likelihood of a false alarm.

2. Motivation and problem definition

This section will outline the basic concepts employed in using inclination measurements to determine mechanical target parameters in structures. It forms the foundation of the assessment procedures introduced later.

2.1. Inclination measurements

To illustrate the background to the studies and the potential benefit of such sensor systems, a laboratory test on the accuracy of a novel MEMS-based accelerometer is presented. This sensor is specifically geared towards high-resolution measurement of absolute inclinations, specifically of angles against the direction of gravity action. Because it senses accelerations, a rotation with respect to gravity can be measured when the sensor is stationary. Special modifications and signal processing methods are employed in this type of sensor to maximise its accuracy. Whilst the description of the device is beyond the scope of this paper, the results of a test conducted to assess the accuracy of the sensor for measuring rotations are reported here in order to highlight the potential of such sensors in combination with the identification methods that are the main subject of this paper. In the experiment, the sensor was subjected to very small changes of inclinations. As a reference system a total station Zeiss Elta S10 was used, which allows to set inclinations with an accuracy of 0.3 m° [25]. After removing the collimator the sensing device was mounted on top of the telescope. The experimental setup is shown in Fig. 1. The sampling rate was set to 100 Hz and the sensor was configured to a full range of ± 5 °. Measurements were taken for 10 s each and data was recorded using the hard- and software supplied by the manufacturer. The inclination of the telescope was changed incrementally in steps of 1 m°.

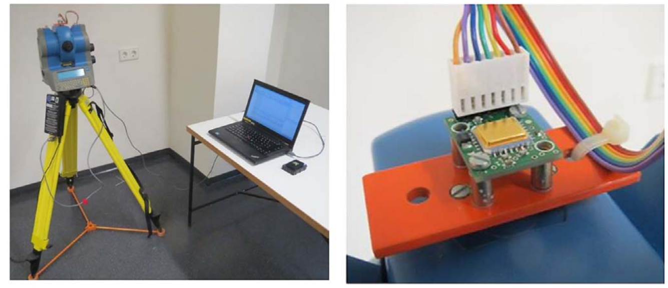

Fig. 1. Experimental setup of the laboratory test to investigate the accuracy of the novel MEMS-based accelerometer: total station Zeiss Elta S10 on tripod with inclinometer mounted to the telescope.

External vibrations impaired in the recorded data were filtered and the mean was computed. The average inclinations were then compared to the adjusted inclinations as shown in Fig. 2. The agreement between applied and measured rotations based on the linear regression coefficient is very good with errors being well below 1 %. In this respect it should be noted that the sensor was not encapsulated, a temperature-correction was not considered and impairment of the measurement process cannot be precluded due to the presence of lab personnel. Even though a more intensive investigation with a wider range of rotations, longer measurements and a study of the aforementioned effects are required to assess the accuracy of the sensor, the results of the preliminary test show that the inclinometer is capable of detecting very small changes due to its high sensitivity.

2.2. Identification concept

In order to outline the devised concept of system identification, we shall first study the load bearing behaviour of a mechanical system, which can be expressed by the a differential equation of linear elastic beam bending without shear deformations:

$$w''(x) = -\frac{M(x)}{EI(x)}, \tag{1}$$

wherein w is the vertical displacement, M is the bending moment, EI is the bending stiffness and ($'$) denotes d/dx. Combining this with the differential equation of section forces in beam bending

$$M''(x) = V'(x) = -q(x), \tag{2}$$