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PORTABLE SOLUTIONS FOR MEASURING DYNAMIC STRESS AND CURVATURE OF BUILDING STRUCTURES

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Abstract: *For ambient vibration measurements on building structures, a strain gauge displacement sensor has been developed alongside two accessories that enable local relative deformations and/or curvatures of a structure to be measured at very low levels. With a resolution below 0.01 microns, the sensor has been tested in the 0–100 Hz frequency range, making it suitable for frequency measurements as well. The sensor can be mounted on the structure using magnets quickly and easily. This article presents two application examples that demonstrate the device's advantages and sensitivity. The device is intended for diagnosing damage in building structures, as relative deformations and curvatures directly reflect stresses within the structure.*

Keywords: Dynamic measurements, Strains, Curvatures, Portable transducer, SHM

1. Introduction

Ambient vibrations of building structures are typically measured using accelerometers or geophones. If we do not want to wait for windy conditions or other sources of external excitation, sensitive sensors are required. However, measured accelerations and velocities are not directly related to stresses in structures. In the case of low frequencies (i.e. under 1 Hz), the conditions for applying accelerometers are even less favourable (Ewins, 1984).

Although displacement and strain measurements are more convenient for assessing low frequencies, the sensitivity of conventional strain gauges is insufficient for measuring stresses caused by ambient vibrations. Furthermore, strain gauges cannot compete with accelerometers in terms of durability and ease of mounting (Rytter, 1993). Additionally, strain and curvature measurements are of interest as they have been proven to be good indicators of local damage (Padney, 1995; Maeck, 1999; Reynders, 2010).

When it comes to assessing or monitoring the condition of large building structures, measuring ambient vibrations is often the most widely used and cost-effective solution (An, 2019). In this context, the relationship between stresses and deformations is crucial, but requires the measurement of both ambient deformations and corresponding strains. New technologies, such as the interrogation units of fibre Bragg grating (FBG) sensors, which offer similar parameters (Anastasopoulos, 2025), are relatively costly.

Recently, the need to measure local deformations in the vicinity of impact loads has led to the displacement sensor being adapted for measuring curvatures, too. The remarkable properties of the device are demonstrated by practical examples of both applications of the sensor, taken from measurements.

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2. Displacement Transducer and Accessories

The sensor operates using standard Wheatstone bridge amplifiers. Its sensitive component is a clamped steel frame, in which horizontal displacement is linearly proportional to stress near the clamped supports, which are equipped with strain gauges. The forces required to displace the sensitive upper part of the frame are negligible compared to those acting due to vibrations in massive building structures. Therefore, the stresses measured at the clamped end are proportional to the displacements at the sensor's touch point. However, the transducer exhibits slight nonlinearity due to various factors, including the applied semiconductor strain gauges. When measuring at lower levels, it is recommended that the sensor is calibrated near the zero position to allow for a higher resolution, where the nonlinearity is negligible. The transducer was calibrated using an Instron Extensometer Calibrator with a resolution of 1 µm. Another possibility for calibration could be the use of a sine wave shaker.

The sensor is easy to apply due to its neodymium magnetic connections. Using magnets at the touch point also means that the measuring frame does not need to be pre-stressed in order to measure both negative and positive displacements. The gauge can be fixed to the structure quickly and easily.

The displacement transducer has a measurement range of ±0.5 mm, which corresponds to stresses of approximately ±200 MPa at the inner sensing part that is equipped with strain gauges. The characteristic relationship between internal strain and measured displacement is 1.9 m^{-1}. Both arrangements were tested in the 0–100 Hz frequency range. The accessories have a measurement base of 20 cm, with the option of a 10 cm base for strain measurements.

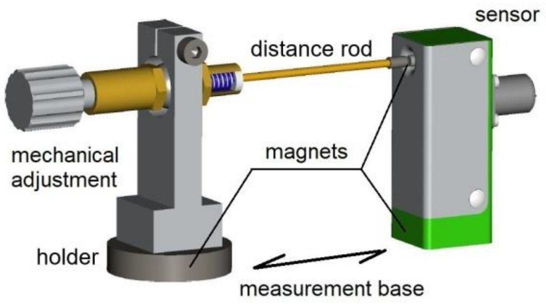

Fig. 1: Measuring arrangement for strain measurements (portable strain gauge)

When measuring strains (see Fig. 1), a reference part with fine adjustment is connected to the sensor via a distance rod. This setup enables the measurement of strains (i.e. relative displacements between the holder and the sensor divided by the measuring base length) in parallel with the connecting rod (i.e. the distance element).

Another accessory allows for measuring curvatures, with the transducer being mounted on an aluminium beam that has an opening at its centre, allowing the sensor to be connected to the structure using a connecting rod that is perpendicular to the surface of the structure. With this setup, the difference in vertical displacement is measured between the supports of the aluminium beam and the midpoint between them. This measurement setup allows for the detection of very low stresses in building structures caused by ambient vibrations, which will be demonstrated in the next section.

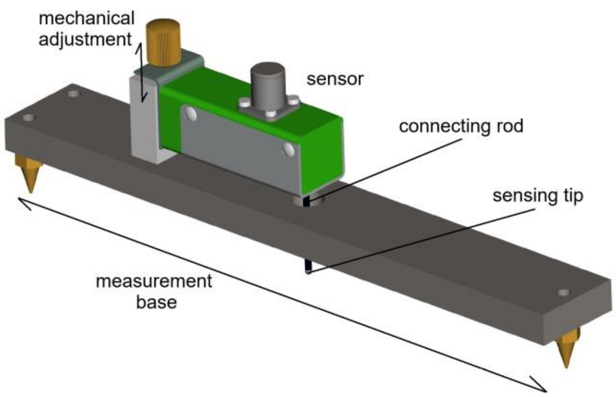

Fig. 2: Measuring arrangement for curvature measurements (deformeter)

This equipment was designed to measure dynamic stresses because a temperature change of 1°C can cause a relative displacement of 2.4 µm at the 20 cm base of common materials. Therefore, the transducer's sensitivity can only be used for static applications during very short measurements or when compensating for natural temperature drift. In dynamic applications, the pseudo-static part caused by temperature drift can easily be filtered out using a high-pass filter.

3. Experiments

3.1. Measuring the vibrations of the Cukrák Tower at its foundation

An experiment was conducted at the 195-metre-high Cukrák TV Tower, which is made of steel and has a 6-millimetre-thick outer coating and hollow vertical ribs. The tower's diameter at its base is 16 metres, and its first natural frequency is 0.29 Hz.

It should be noted that vibrations cannot be measured at the top of the tower due to the strong electromagnetic field surrounding it. However, accelerations can be measured without issue up to approximately half the tower's height using standard equipment.

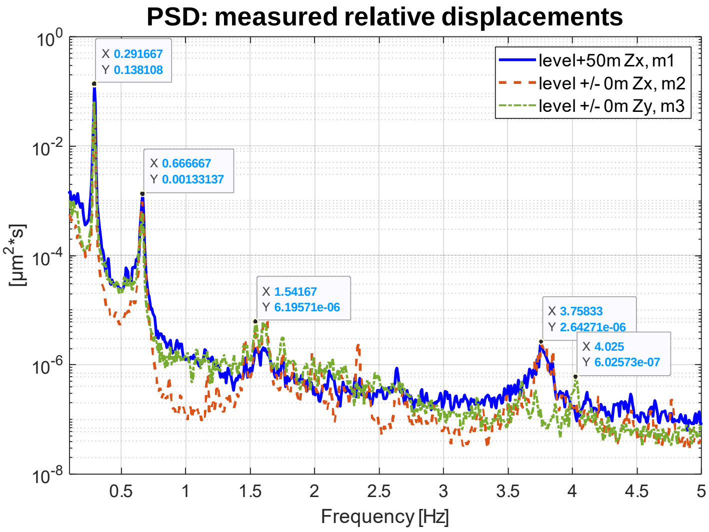

Fig. 3: Measured relative displacements using arrangement from Fig.1

Measurements were taken at two levels: +50 m and ±0 m on the ground floor. Mounting the sensor vertically to measure the dominant stresses on the steel ribs, along with the necessary mechanical and electrical adjustments, took no more than five minutes using a 20 cm measurement base. The sensor was successively placed on both levels (+50 m in the Zx plane and ±0 m in the Zx and Zy planes). To validate the measurements, a pair of sensitive accelerometers (Wilcoxon Research Model 731A) were used horizontally at the +50 m level. The signals were recorded using a DEWETRON measurement rack.

The new sensor provided a clear signal at both levels (see Fig. 4). The power spectral density (PSD) displacement spectra from the basement show that there is sufficient resolution and a clear signal even below 10^{-9} m using approximately 60 averages over one hour with a resolution of under 0.1 Hz. For instance, at a frequency of 4 Hz, an RMS strain of $3.9 \cdot 10^{-3}$ µε was measured, which corresponds to a stress of 0.8 kPa. Comparing with measured acceleration spectra confirmed the same position of dominant frequency peaks.

3.2. Measuring impact-induced local deformations on a steel beam

In connection with research on moving impact loads, it was necessary to measure the local response to a force impulse on a 4 m long, simply supported steel U-profile beam (210x50x5 mm). For this purpose, the curvature accessory was used. The impulse was applied using a 0.5 kg Brüel & Kjær impact hammer (type 8202).

Figure 4 shows the measured responses close to the midpoint (2.08 m) and near the support (3.74 m). Note that the double amplitude measured one second after impact was 0.054 µm (corresponding to a curvature of 5.4*10-10), and after 20 seconds the decay was still 0.007 µm, demonstrating a remarkable signal-to-noise ratio.

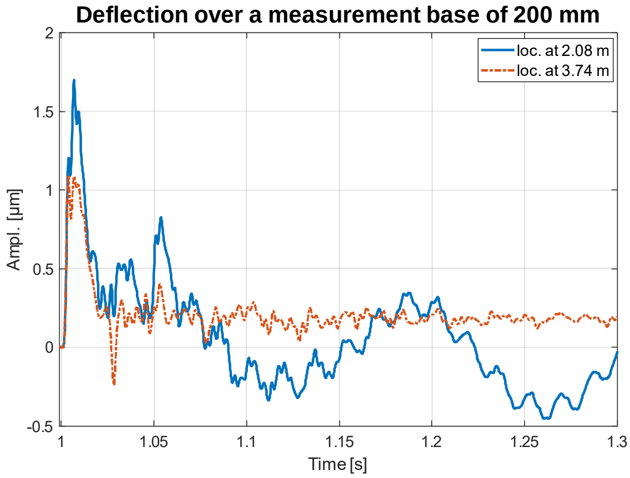

Fig. 4: Measured deflection over a meas. base of 200 mm due to impulse loading

4. Conclusions

A prototype of a new, portable relative displacement sensor has been introduced, along with two accessories. The sensor can be quickly and easily mounted on a structure. The sensor can measure dynamic displacements, as well as dynamic strains and curvatures, at ambient vibration levels. This cost-effective solution offers extremely high sensitivity, making it ideal for measuring natural frequencies and stress amplitudes.

The measurement approach presented here can be used to investigate wind-induced vibrations in tall, slender structures, where low-frequency responses and stress-related quantities play a dominant role. Notably, the capacity to measure dynamic strains and curvatures at ambient vibration levels establishes a robust foundation for the experimental analysis of aeroelastic phenomena, including galloping, flutter, and vortex-induced vibrations. The proposed measurement concept enables detailed observation of the structural response, which is often impossible with conventional acceleration-based measurements due to insufficient sensitivity. Therefore, the developed measurement methodology represents a promising experimental tool for future research focused on the interaction of wind-excited slender structures.

Further applications are anticipated, such as measuring crack activity in ageing historic structures and assessing the condition of civil engineering structures.

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