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Operational Strain Modal Analysis and Wavelet Analysis for Damage Detection in Glass Beams

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ABSTRACT
Operational Strain Modal Analysis (OSMA) holds significant potential for Structural Health Monitoring (SHM), requiring only strain responses from the structure under investigation. Due to their high sensitivity, Strain Mode Shapes (SMS) can serve as a robust alternative for detecting and locating structural damage. This study presents a cost-effective damage detection method using seven strain gauges installed on a glass beam. Strain responses were processed to derive SMS, which were then compared to mode shapes obtained through traditional operational modal analysis (OMA), showing strong agreement. The work experimentally demonstrates the accurate detection and localization of small damages in a glass beam by combining OSMA with Continuous Wavelet Transform (CWT). This approach highlights the capability of OSMA to detect subtle damage patterns efficiently. Furthermore, the low-cost nature of the presented method makes it a promising alternative for various SHM applications, such as monitoring wind turbine blades or other critical structures. By leveraging OSMA, this work aims to contribute to the development of affordable and practical SHM techniques for field applications.

Keywords: Operational Strain Modal Analysis, Structural Health Monitoring, Strain-based detection, Damage Detection, Wavelet Transform

1. INTRODUCTION

1.1. General information

Structural Health Monitoring (SHM) plays a critical role in assessing the condition and ensuring the safety of engineering structures [1]. SHM helps maintain the safety, reliability, and longevity of structures, especially in critical applications such as wind turbines, bridges, and civil infrastructures. Modal analysis is a key tool for evaluating civil structures subjected to dynamic loading. Modal parameters, natural frequencies, mode shapes, and damping serve as a dynamic fingerprint, offering valuable insights into the dynamic behavior of a structure [2]. In the context of SHM, changes in these modal parameters can often be associated with the presence of structural damage [3].

The most common SHM techniques based on operational modal analysis (OMA) rely on displacement, velocity, or acceleration measurements. These methods are advantageous because they do not require prior knowledge or measurement of the excitation forces applied to the structure and their ability to characterize global dynamic behavior. However, modal analysis can also be applied to measured strains, enabling the estimation of Strain Mode Shapes (SMS) in a similar manner to how it is often applied to acceleration or displacement signals [2]. Operational Strain Modal Analysis (OSMA) has emerged as a promising alternative that requires only strain responses for modal analysis [4]. SMS are highly sensitive to structural changes, making them a robust tool for damage detection [5]. Despite their potential, the practical application of OSMA for damage detection remains relatively underexplored, particularly with respect to its feasibility as a cost-effective SHM solution in real-world scenarios.

This work aims to address this gap by presenting a novel, low-cost damage detection method based on OSMA. The proposed approach uses strain responses collected from seven strategically placed strain gauges on a glass beam. SMS derived from OSMA are compared with traditional mode shapes obtained through OMA, demonstrating strong agreement. To enhance the detection of subtle damage patterns, the continuous wavelet transform (CWT) is applied to the SMS, drawing inspiration from the work of [6]. This provides a robust framework for the detection and localization of damage.

The experimental results highlight the ability of the proposed OSMA-based methodology to detect and locate small damages accurately. The cost-effectiveness of this method underscores its potential for widespread SHM applications, including monitoring critical structures such as wind turbine blades, where early damage detection is essential. Using the inherent advantages of OSMA, this work contributes to the development of affordable and practical SHM techniques for various engineering domains.

The remainder of this paper is organized as follows. Section 2 presents the fundamentals of OSMA, SMS extraction, and damage detection methodology. Section 3 describes the experimental setup. Section 4 discusses the results and provides a comparative analysis. Finally, Section 5 concludes with key findings and future research directions.

2. METHODOLOGY

2.1. Operational Strain Modal Analysis

The detailed methodology of strain modal analysis can be found in [7] and is summarized below. The Strain Frequency Response Function (SFRF) of a continuous system can be expressed as [8]:

$$H_{il}^{\epsilon} = \sum_{r=1}^{M} \frac{\psi_{ir}^{\epsilon}\phi_{lr}}{k_r - \omega^2 m_r + j\omega c_r} \quad (i = 1, 2 \cdots N_0; l = 1, 2 \cdots N_i) \tag{1}$$

where N_o, N_i, M denote the number of outputs, inputs and modes respectively. And ψ_{ir}^{ϵ} is the rth order strain mode shape (SMS) at the *i*th point, and ϕ_{lr} indicates the *r*th order Displacement Mode Shape (DMS) at the *l*th point.

The strain response spectrum matrix can be expressed as [9]:

$$[G_{\epsilon\epsilon}] = [H_{\epsilon}]^{*}[G_{FF}][H_{\epsilon}]^{T} \tag{2}$$

Here, G_{FF} and $G_{\epsilon\epsilon}$ represent the excitation force spectrum matrix and the strain response spectrum matrix, respectively. When the excitation force exhibits a flat spectrum, such as those generated by impulsive forces or random excitations [10], over the frequency range of interest, G_{FF} can be simplified to a real constant diagonal matrix.

For lightly damped structures, performing singular value decomposition (SVD) on the strain response spectrum matrix at each spectral line yields [9]:

$$[G_{\epsilon\epsilon}]^T = [U][\Sigma][U]^H \tag{3}$$

where U is a unitary matrix containing the singular vectors corresponding to the strain mode shapes, and Σ is a diagonal matrix containing the real singular values, which are inversely proportional to the distance between the frequency point and the location of the pole. Similarly to operational modal analysis (OMA), where acceleration measurements are utilized, OSMA uses strain signals acquired at different positions along the structure as input. These strain signals enable the estimation of Strain Mode Shapes (SMS) and facilitate structural damage detection through modal analysis.

2.2. Damage detection

The natural frequencies and strain mode shapes are obtained using the OSMA method described in Section 2.1.. This methodology employs an extension of the measured strain mode shape to mitigate edge effects caused by the unstable behavior of the wavelet coefficients at the extremes of the analyzed signal [6]. The isomorphism method is applied, which involves replicating the measured modes on both sides of the current measurements of the physical structure. The extended signal is defined as [6]:

$$\psi_r(x) = [\psi_m(2a - x); \psi_m(x); \psi_m(2b - x)] \tag{4}$$

where the subscript m represents the actual strain mode shapes measured with n strain gauges installed on the structure. The parameters a and b correspond to the edge locations at the beginning and end of the measured SMS.

The extended SMS is then interpolated using splines to a length five times larger than the extended signal. This interpolation is necessary because of limitations in the number of sensors that can be installed in the experimental configuration. In this study, the MATLAB command interp1 was used to generate the interpolated modes.

The next step in the proposed methodology involves calculating the Continuous Wavelet Transform (CWT) of the interpolated extended modes $\psi_{int,r}$:

$$CWT^{u,d}_{\psi_{int,r}}(v, s) = \frac{1}{\sqrt{s}} \int_a^b \psi^{u,d}_{int,r} \varphi(\frac{x - v}{s})\, dx \tag{5}$$

where v is the translation parameter, s is the scale parameter and φ is the mother wavelet. In this work, the Gaussian wavelet gauss2 was used. The superscripts u and d denote information from the un-damaged and damaged structures, respectively.

The difference between the CWT of the damaged and undamaged structures is then squared:

$$d_2 = (CWT^d_{\psi_{int,r}}(v, s) - CWT^u_{\psi_{int,r}}(v, s))^2 \tag{6}$$

Finally, the proposed damage metric is defined as:

$$m_d = (\sum_{r=1}^{N} d_2)^2 \tag{7}$$

3. EXPERIMENTAL SETUP

The structure used in this study is a laminated glass beam with dimensions of 845 mm × 100 mm × 6.38 mm, with two layers of three millimeters and the thickness of the inter-layer of 0.38 mm. The structure was clamped at both ends between rubbery band in a glass standard impact frame [11]. Seven strain gauges were installed on the beam, consisting of six gauges with a resistance of 350 Ω and a gauge factor (GF) of 2.04 and one ICP 740B2 gauge (G4) with a sensitivity of 45 $mV/\mu\epsilon$.

The strain gauges were placed at the following locations along the beam Table 1 and the experimental setup is shown in figure 1:

Table 1: Strain gauge positions along the beam (in mm).

G1	G2	G3	G4	G5	G6	G7
100	190	280	370	490	615	730

For data acquisition, a National Instruments DAQ-9174 module was used, and LabView was employed for data recording. All measurements were conducted at a sampling frequency of 1800 Hz, data acquisitions were performed for 5 minutes, and the excitation force was applied stochastically in both time and space using a modal hammer. A quarter-bridge configuration was used for all strain gauges.

Figure 1: Experimental setup,

4. RESULTS AND DISCUSSION

Experimental mode shapes and experimental strain mode shapes

A comparative analysis was conducted between the experimental mode shapes obtained using Operational Strain Modal Analysis (OSMA), described in Section 2.1., and those obtained from Operational Modal Analysis (OMA). Modal parameters were estimated in the frequency domain using ARTEMIS Modal Pro software. The strain responses were measured using seven strain gauges positioned as detailed in Table 1. These experimental Strain Mode Shapes (SMS) were compared with the traditional mode shapes derived from acceleration measurements at the same positions using the well-established OMA technique. Although a comprehensive description of OMA falls outside the scope of this paper, further details can be found in [6, 12].

Figure 2 illustrates the comparative plot of the mode shapes obtained using OMA and OSMA. The continuous lines represent the SMS obtained through OSMA, while the dashed lines correspond to the mode shapes obtained from OMA. To facilitate a clear comparison, both sets of mode shapes are plotted on the same scale. As depicted, there is a strong agreement between the experimental mode shapes obtained through both methods. This concordance demonstrates that SMS can serve as a reliable alternative for damage detection in structural health monitoring applications, particularly when only strain measurements are available.

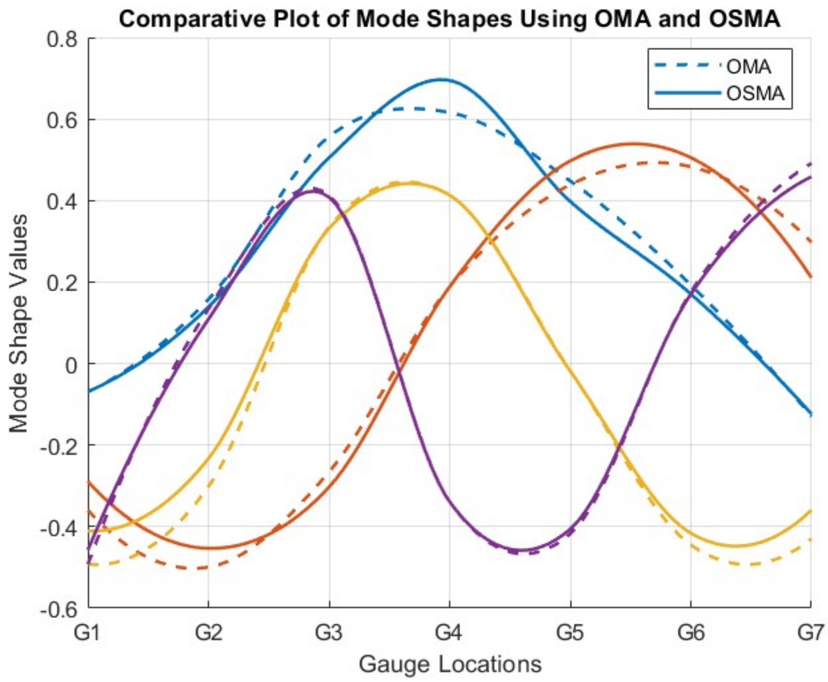

Figure 2: Comparative Plot of Mode Shapes Using OMA and OSMA

Damage detection

In this study, damage was simulated by attaching a 148g mass between strain gauges G3 and G4. First, experimental Strain Mode Shapes (SMS) were obtained for the structure in both its undamaged (without the mass) and damaged (with the mass) conditions. Following the damage detection methodology described in Section 2.2., the metric md from Eq. (7) was applied to identify the presence and location of the damage.

Figure 3 presents the resulting scalogram for md metric, where the x-axis corresponds to the strain gauge positions, and the y-axis represents the scales used in the Continuous Wavelet Transform (CWT). The color intensity indicates the energy distribution, with yellow regions signifying areas of higher energy concentration. These high-energy zones are indicative of the damage location.

Despite some noise around the damage region, the scalogram clearly highlights the area between strain gauges G3 and G4 as the predominant energy zone. This confirms the effectiveness of the proposed method in accurately detecting and localizing structural damage. The visual information provided by the scalogram demonstrates the robustness of the approach and its potential applicability in real-world structural health monitoring scenarios.

Practical Implementation Considerations

To enhance the practical applicability of the proposed OSMA-based damage detection methodology, several real-world implementation challenges must be considered. The durability of the strain gauge can be affected by long-term exposure to environmental conditions, adhesive degradation, and repeated mechanical loading; thus, protective coatings and periodic calibration are recommended to ensure reliable measurements. In addition, signal noise resulting from ambient vibrations, electrical interference, or sensor misalignment can degrade the quality of acquired data but can be mitigated through appropriate filtering techniques and proper installation practices. Environmental effects, such as temperature fluctuations and humidity, can introduce measurement drift or bias, which can be addressed through compensation strategies, such as differential configurations, or temperature-insensitive materials. Taking these factors into account, the proposed methodology can be applied more robustly in field conditions, supporting its potential for real-world structural health monitoring applications.

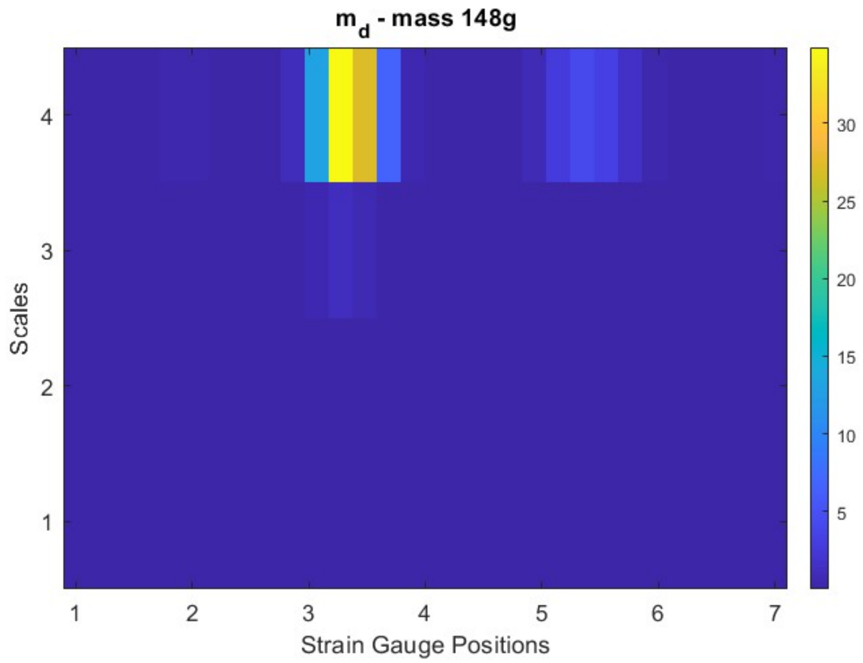

Figure 3: Damage detection with m_d metric

5. CONCLUSIONS

This study presents a novel approach to structural damage detection using Operational Strain Modal Analysis (OSMA) combined with Continuous Wavelet Transform (CWT). The methodology was experimentally validated on a glass beam, where damage was simulated by attaching a 148 g mass to the structure. A comparative analysis of Strain Mode Shapes (SMS) derived from OSMA and traditional modal shapes from Operational Modal Analysis (OMA) demonstrated strong agreement, confirming the reliability of SMS for dynamic characterization.

This finding underscores the potential of OSMA for practical SHM scenarios where traditional modal analysis may not be feasible due to sensor or data acquisition constraints. The demonstrated accuracy in capturing modal behavior using SMS highlights the method's robustness and versatility, making it a promising tool for real-world structural monitoring. The results suggest that OSMA, in combination with advanced signal processing techniques like CWT, offers a cost-effective and accurate solution for structural health monitoring. This method is particularly valuable for scenarios where traditional displacement or acceleration-based modal analysis may not be feasible. Future work will focus on extending this methodology to more complex structural systems and exploring its performance under varying environmental conditions.

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