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The use of piezoelectric coupling in structural monitoring as a feature robust to EOV

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Abstract. This paper introduces a new method for utilizing piezoelectric elements placed within a structure or system for structural health monitoring purposes. The novel damage feature suggested here is the piezoelectric coupling factor. It is proven to be sensitive to damage presence and its severity and it is not significantly affected by changes in environmental and operating conditions. The effectiveness of this new damage feature is evaluated through simulations and experiments.

Keywords: structural health monitoring, vibration, coupling factor, piezoelectric, piezoelectric shunt

1. Introduction

Structures and systems can deteriorate over time due to factors like, e.g., wear, which can lead to significant damage. When this occurs, it affects the current and future performance of the system. Therefore, it is crucial to detect any damage early to initiate timely maintenance operations. This is important not only for safety but also from an economic perspective.

The field of research dedicated to designing techniques and algorithms for automatically detecting damage is known as structural health monitoring (SHM) [1]. Relying on advanced sensing methods and technology for collecting, processing, and managing signals and data, these methods are primarily based on real data from the monitored system or structure. Since there are no sensors that directly measure damage, it is important to extract specific information from sensor data, referred to as damage-sensitive quantities or features, to identify any damage.

Vibration-based methods are widely employed for damage detection, as evidenced by numerous comprehensive review papers in the literature (see, e.g., [2–8]). These methods analyse the dynamic response of the monitored structure to identify features sensitive to damage. Techniques like modal analysis [9] and time series models [10–12] are commonly used for this purpose. The fundamental idea is simple: damage leads to alterations in

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structural properties, such as, e.g., stiffness and constraint features, resulting in changes in modal parameters like, e.g., eigenfrequencies and mode shapes [13]. Vibration-based methods offer two primary advantages. Firstly, they can detect damage even when the exact location is unknown beforehand. Secondly, they typically necessitate only a few sensors, and the needed equipment can be easily installed in the structure under observation (see, e.g., [14]). These practical benefits make vibration-based methods effective across various engineering domains, including civil, mechanical, aerospace, and industrial sectors.

Such techniques are particularly well-suited for lightweight structures, which are prone to significant vibration levels due to their specific characteristics. Piezoelectric elements are frequently integrated into these structures for various purposes, including vibration control, monitoring, energy harvesting, and precision positioning. In this context, this paper delves into the potential utility of the piezoelectric coupling factor for structural monitoring.

The paper is organized as follows: Section 2 introduces the piezoelectric coupling factor and outlines how its value can be estimated using an indirect approach. Section 3 examines the benefits of estimating the piezoelectric coupling factor as a damage-sensitive feature, along with the challenges associated with the estimation process. Section 4 employs simulations to demonstrate the sensitivity of the piezoelectric coupling factor to damages. Section 5 outlines two approaches aimed at enhancing the accuracy in estimating the piezoelectric coupling factor and, finally, Section 6 provides experimental results.

2. Coupled system model

Structures and systems integrating piezoelectric elements are typically termed as coupled structures/systems. The dynamics of these systems are often analyzed using a modal approach, as demonstrated in numerous existing studies. For simplicity, this paper focuses on a generic continuous system equipped with a single piezoelectric bender. Nonetheless, it is straightforward to extend this analysis to systems equipped with multiple piezoelectric elements, including stacks rather than benders.

Introducing modal coordinates ϑ_m, where m is the counter on modes (from 1 to M), the equations of motion of the coupled system can be written as [15]:

$$\ddot{\vartheta}_m + 2\xi_m\omega_m\dot{\vartheta}_m + \omega_m^2\vartheta_m - \chi_m V = F_m \qquad \forall\ m = 1, \dots, M$$

where ω_m is the m-th eigenfrequency of the coupled system with the piezoelectric transducer short-circuited, ξ_m indicates the corresponding non-dimensional damping ratio, V is the voltage between the piezoelectric bender electrodes (see Fig. 1a), F_m represents the modal force, and, finally, χ_m is a modal coupling coefficient for the m-th mode. Furthermore, the dynamics of the electrical part of the system is described by the following equation:

$$CV - Q + \sum_{m=1}^{M} \chi_m\vartheta_m = 0$$

where C is the capacitance of the bender at constant strain (which corresponds to the value at infinite frequency) and Q is the charge in one electrode. When the electrodes are connected to an external electric impedance Z_{sh} (Fig. 1b), the link between V and $\dot{Q}$ (i.e., the derivative of Q with respect to time, thus an electrical current), depends on Z_{sh}. This will be useful further in the manuscript.

In case of low modal density, a single-degree-of-freedom approximation can be carried out and, for $\Omega \simeq \omega_m$ (being Ω the angular frequency), the equation of motion has to be written only for the m-th mode, while the equation describing the dynamics of the electrical part of the system can be written as:

$$C_m V - Q + \chi_m\vartheta_m = 0$$

where C_m is the modal capacitance of the m-th mode and can be roughly seen as the value of the capacitance of the bender halfway between ω_m and ω_{m+1}. More details about the modal capacitance are available in the literature [16,17].

The value of χ_m can be normalised, deriving k_m [17]:

$$k_m = \frac{\vartheta_m}{\omega_m\sqrt{C_m}}, \quad |k_m| = \sqrt{\frac{\widehat{\omega}_m^2 - \omega_m^2}{\omega_m^2}}$$

being $\widehat{\omega}_m$ the m-th eigenfrequency of the coupled system with the bender open-circuited.

The $|k_m|$ value expresses the efficiency of the energy conversion between the m-th mode and the electrical part of the system. The larger this value is, the better the coupling between the bender and the structure/system at the m-th mode is. It will be shown further in the paper that $|k_m|$ is a damage-sensitive feature.

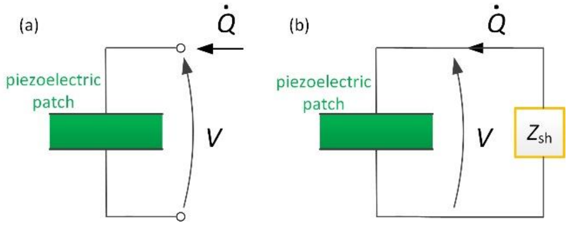

Fig. 1. Schematic of the piezoelectric element in the electrical domain (a) and shunt of the piezoelectric element with electric impedance $\boldsymbol{Z}_{\mathbf{sh}}$ (b).

3. The strengths of $|k_m|$ as a damage-sensitive feature

The fundamental concept of this paper is that the presence of a damage can alter the modal parameters of the coupled system, consequently affecting the value of $|k_m|$. The benefits of monitoring the value of $|k_m|$ to detect damage are outlined below.

One of the primary benefits of utilizing $|k_m|$ as a damage indicator is that its value can be indirectly determined by estimating two eigenfrequency values: ω_m and $\widehat{\omega}_m$ (see above the definition of $|\boldsymbol{k}_{\boldsymbol{m}}|$). This estimation process relies on straightforward modal analyses, focusing on the eigenfrequencies, which are the simplest quantities to extract. Moreover, operational modal analysis can be applied. Unlike traditional modal analysis, operational modal analysis does not require knowledge of external excitation acting on the coupled system, allowing for the utilization of environmental excitation. Additionally, in structures where piezoelectric elements are already employed for tasks such as vibration control, energy harvesting, or micro-positioning (e.g., [18,19]), they can be used for SHM when not actively used for their primary functions.

Apart to what mentioned above, the primary advantage of employing the value of $|k_m|$ as a damage feature lies in its robustness against environmental and operational variations (EOV). Considering robustness to environmental changes, this robustness is mainly due to the fact that the value of $|k_m|$ derives from the subtraction and normalization of two eigenfrequency values (see above), which mitigates the impact of temperature variations, especially when compared to other modal parameters, such as single eigenfrequencies. The main challenge in utilizing the $|k_m|$ value as a damage feature is its inherently low magnitude. In practical scenarios, its maximum value is expected to be around 0.3 [20]. Consequently, accurate estimation of $|k_m|$ may pose difficulties due to significant uncertainty, particularly when $|k_m|$ is smaller than a certain threshold, such as, e.g., 0.05.

Section 4 will initially establish the applicability of $|k_m|$ as a reliable damage feature for SHM, emphasizing its resilience to temperature fluctuations. Subsequently, Section 5 will detail strategies for improving the accuracy on $|k_m|$ estimates.

4. Simulations

A finite element model representing a clamped-clamped aluminium beam with five piezoelectric patches (as depicted in Fig. 2) is employed. Specifically, here, attention is focused on the first patch positioned on the left side for demonstration purposes.

Fig. 2. Structure used for the finite element simulations.

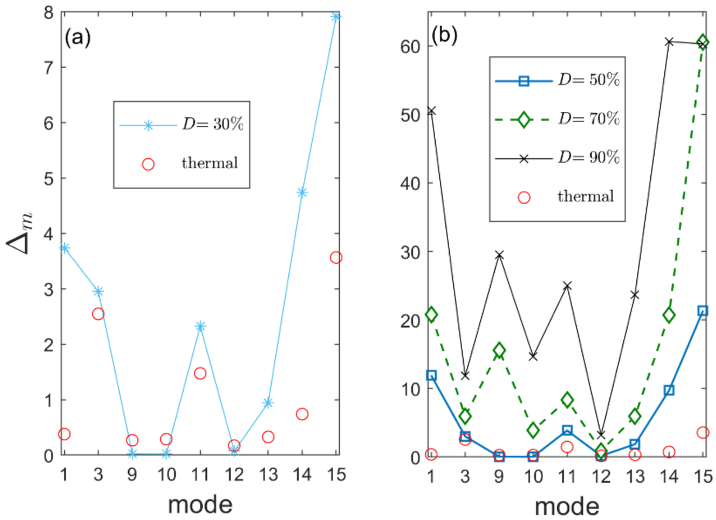

Fig. 3. Vaues of Δ_m for different bending modes and D values

The $|k_m|$ value across the first fifteen bending modes is calculated with and without introducing damage by reducing the Young's modulus in a defined section of the beam (as shown in Fig. 2) by varying percentages (D=30, 50, 70, and 90%). The length of the damaged section accounted for less than 0.7% of the total length of the considered beam. To ensure general applicability, the material (PIC151) and patch size were chosen without optimization. Instead, they were selected from available options offered by manufacturers.

The effect of the presence of damage is shown here through the index Δ_m:

$$\Delta_m = 100\left|\frac{|k_{m,\mathrm{d}}| - |k_m|}{|k_m|}\right|$$

where the subscript d indicates the presence of the damage. Figures 3a and b show the results for the different D values. The same figures also show, by means of red circles, the values of Δ_m when the beam is subject to a temperature shift of -40 K and no damage is present. The analysis of Fig. 3 evidences that, across multiple modes, larger values of D correspond to increased magnitudes of Δ_m, suggesting that changes in $|k_m|$ can effectively quantify the severity of damage. Additionally, in the majority of cases, the impact of beam alterations on the values of Δ_m surpasses that of thermal shifts, underscoring the robustness of $|k_m|$ to temperature fluctuations.

As mentioned earlier, a key challenge in adopting $|k_m|$ as a damage feature for practical applications stems from its low magnitude, which introduces the risk of considerable uncertainty in estimation. Section 5 presents two alternative approaches designed to improve the accuracy of estimation.

5. Approaches for lowering uncertainty on $|k_m|$ estimates

This section will present two methods for lowering the uncertainty associated to the estimates of $|k_m|$.

5.1 Approach 1

The piezoelectric bender is connected to a known inductance L (refer to Fig. 1b, where $Z_{sh} = j\Omega L$, with j representing the imaginary unit). When this connection is made, an additional resonance appears in the system, causing the original m-th resonance frequency to split into two frequencies (see, e.g., [15]). According to [16], these two new resonance frequencies are separated from each other by more than ω_m and $\widehat{\omega}_m$. This suggests that using them to estimate the value of $|k_m|$ would introduce less uncertainty into the final result. Referring to the two new frequencies as $\omega_{m,1}$ and $\omega_{m,2}$, $|k_m|$ can be estimated as [16]:

$$|k_m| = \sqrt{\frac{\omega_{m,2}^2+\omega_{m,1}^2}{\omega_m^2} - \frac{\omega_{m,2}^2\omega_{m,1}^2}{\omega_m^4} - 1}$$

In Fig. 4, it is possible to observe the theoretical trend of the ratio between the uncertainty u_{L} of the newly proposed method for estimating $|k_m|$ and the uncertainty u_{cl} of the traditional approach (based on the estimates of ω_m and $\widehat{\omega}_m$). This trend is plotted against normalized L values relative to a specific reference value L_{ref} (where$L_{\mathrm{ref}} = 1/(\omega_m^2 C_m)$ [16]). The graph unmistakably demonstrates a significant reduction in uncertainty with the adoption of the new approach (i.e., shunt of L). This suggests the potential effectiveness and feasibility of monitoring the trend of $|k_m|$ for SHM applications.

5.1 Approach 2

An alternative method involves connecting the bender to a negative capacitance $-C$ ($Z_{\mathrm{sh}} = -1/(\mathrm{j}\Omega C)$ in Fig. 1b). Adjusting the negative capacitance value can further distance ω_m and $\widehat{\omega}_m$, resulting in reduced uncertainty in estimating $|k_m|$. Techniques for creating negative capacitance, which is not present in nature, are described in different papers in the literature (e.g., [17]).

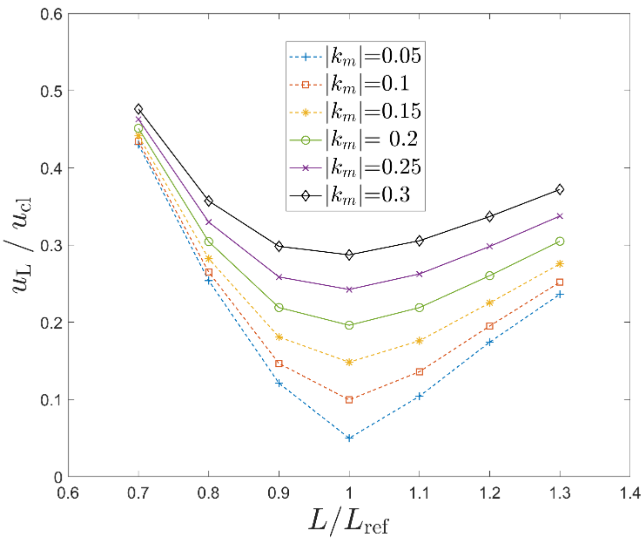

Fig. 4. Trend of u_L/u_{cl} as a function of L/L_{ref}.

6. Experimental tests

Initially, experiments were conducted to demonstrate that the methods outlined in Sections 5.1 and 5.2 effectively reduce the uncertainty in estimating $|k_m|$. As an example, Fig. 5 illustrates the resulting values of various estimation repetitions for the same $|k_m|$ value. In this case, the first mode (i.e., $m = 1$) was examined using a cantilever beam setup with a piezoelectric bender attached at the clamped end, as shown in Fig. 6a. The beam response was measured using a non-contact laser velocimeter, while excitation was provided by a non-contact magnetic actuator. The results clearly show a significant reduction in dispersion when a shunt inductance is employed. It is worth noting that synthetic inductors were used in these experiments to achieve the high inductance values required, implemented through Antoniou's circuit [15].

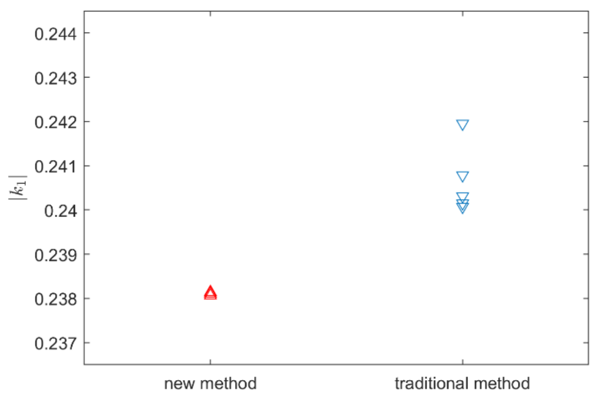

Fig. 5. $|k_1|$ results shunting L (new method) or using the traditional method for the set-up in Fig. 6a.

Subsequently, employing a different beam measuring 70 cm in length and featuring five piezoelectric patches arranged as shown in Figs. 6b and c, the effectiveness of utilizing $|k_m|$ as a damage feature is demonstrated. In this case, the beam response was monitored using a contactless laser velocimeter, while excitation was generated via an electro-dynamic shaker. The variation in $|k_m|$ (computed here using ω_m and $\widehat{\omega}_m$) throughout consecutive tests is depicted in Fig. 7. Certain tests involved no alterations to the beam, whereas others entailed affixing a small metallic brick at two distinct positions on the beam. The trend observed in $|k_m|$ reveals its sensitivity to both the presence of the added brick and its specific placement. Notably, despite a temperature shift of approximately 6 K occurring during the tests, the impact of the brick addition remained evident.

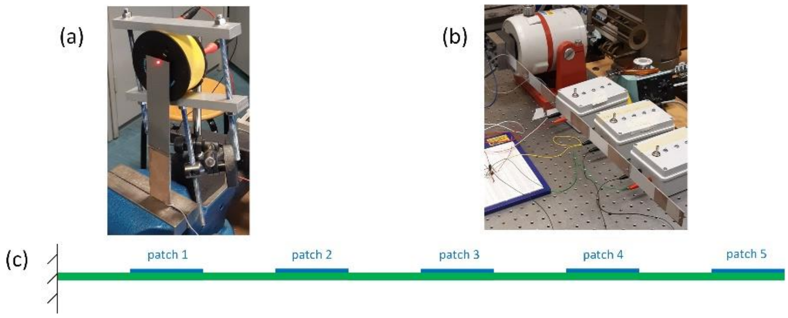

Fig. 6. Set-up used for demonstrating the benefits provided by the use of the shunt inductance when estimating the value of $|k_m|$ (a), set-up employed for demonstrating the possibility of using $|k_m|$ as a damage feature (b) and its schematic (c).

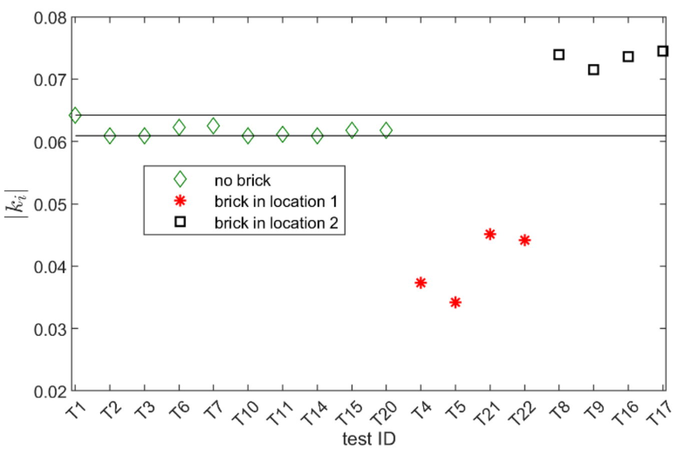

Fig. 7. $|k_m|$ values in different test repetitions for a bending mode at approximately 730 Hz and the first piezoelectric patch in Fig. 6c.

7. Conclusion

This paper has presented a new approach for exploiting piezoelectric elements embedded into a system/structure to the aim of SHM. The proposed damage feature is the piezoelectric coupling factor which can be easily estimated by means of simple modal analyses of the coupled system. The main advantage provided by the proposed damage feature is its robustness to temperature variations (and more generally to EOVs). Its effectiveness was demonstrated both through numerical simulations and experiments. Furthermore, two different methods are proposed to the aim of lowering the uncertainty on the coupling factor estimates.

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