Available online at www.eccomasproceedia.org
Eccomas Proceedia SMART (2025) 1060-1068

ECCOMAS Proceedia

XI ECCOMAS Thematic Conference on Smart Structures and Materials - SMART 2025
M. Krommer, M. Nader and M. Schagerl (Eds)

Received: 9 April 2025 / Revised: 5 September 2025 / Accepted: 7 September 2025

Damage Detection and Filtering of EOV Effects by Monitoring Piezoelectric Coupling

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Abstract. This paper describes an innovative structural health monitoring approach for smart structures where piezoelectric elements are present and connected to the primary system to be monitored. The approach requires to measure and monitor the piezoelectric coupling trend for different modes of the system. Indeed, this quantity is shown to be sensitive to damage presence and its location, lowly affected by environmental (mainly thermal) and operational variability (which is an important point in structural health monitoring applications), and easy to be estimated. This makes the proposed approach reliable, robust and less expensive compared to already available structural health monitoring methods based on the use of piezoelectric elements (e.g., electromechanical impedance approaches).

Numerical simulations are employed to highlight the capability of the newly proposed method to detect a damage and its location. Then, the final part of the paper proves the reliability of the approach by means of experimental tests on two different structures: a cantilever beam and a truss, using either piezoelectric patches or stacks. During the tests, particular attention was devoted to environmental variability effects, and the experimental activity confirms that the proposed structural health monitoring method shows larger sensitivity to damage presence than to environmental variability effects.

Key words: Structural health monitoring, Damage detection, Smart structure, Piezoelectric element, EOV, Piezoelectric shunt

1 INTRODUCTION

The use of piezoelectric elements in systems and structures can be exploited for many different purposes, such as vibration control (e.g., [1]), energy harvesting (e.g., [2]), micro positioning. Structures equipped with these materials (smart structures, e.g., [3, 4]) can thus show

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ISSN:3078-543X. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of SMART 2025.
doi: 10.7712/150125.13701.302001

specific advanced features which are possible because of the double piezoelectric effects: direct effect which implies that mechanical strain is converted in voltage at the electrodes of the piezoelectric element (used to build sensors), and inverse effect which implies that a voltage applied to the electrodes generates a mechanical strain (employed for designing actuators).

The aim of this paper is to show that the presence of this double effect can be exploited for developing a new approach for structural health monitoring (SHM) for smart structures based on piezoelectric elements.

The paper is structured as follows: Section 2 introduces the proposed damage feature and its advantages, as well as a related damage index, then Section 3 discusses some numerical simulations on a beam, and, finally, Section 4 presents experimental tests validating the newly proposed approach. The main aim of this paper is to summarise some of the most important results discussed in [5].

2 DAMAGE FEATURE AND INDEX

When piezoelectric elements (either patches or stacks) are connected to a structure, the dynamics of both the mechanical and electrical parts of the system can be described by means of modal coordinates [6, 7, 8]. These equations are function of a parameter named modal electromechanical coupling factor (MEMCF) k_i, which describes the efficiency of the energy transfer between the electrical part of the system (for the considered piezoelectric element) and the considered i-th mode and vice versa.

The value of k_i depends on different features of the coupled system, such as geometry, material properties, etc. However, the main parameter affecting the value of k_i is the trend of the mode shape at the boundaries of the piezoelectric element [9]. This means that a change of the $|k_i|$ value is expected in case a damage occurs in the structure and it is able to affect the corresponding mode shape at the boundaries of the considered piezoelectric element [5]. Therefore, $|k_i|$ can be seen as a damage feature, and here its main advantages are discussed. Before this, it is important to explain how the value of $|k_i|$ can be estimated. Even if analytical formulations exist for k_i as function of either physical [10] or modal [11] quantities, the easiest way to estimate $|k_i|$ is by using the following formulation:

$$|k_i| \simeq \sqrt{\frac{\hat{\omega}_i^2 - \omega_i^2}{\omega_i^2}} \tag{1}$$

where ω_i is the i-th eigenfrequency with the piezoelectric element short-circuited, while $\hat{\omega}_i$ is the i-th eigenfrequency with the piezoelectric element open-circuited. The value of $\hat{\omega}_i$ is always larger than that of ω_i because of a stiffening effect related to the electromechanical behaviour of the piezoelectric element [6]. When different piezoelectric element are present in the structure, ω_i and $\hat{\omega}_i$ for a given piezoelectric element are determined keeping all the other piezoelectric elements short-circuited. Thus, the value of $|k_i|$ can be obtained both numerically or experimentally by determining eigenfrequency values.

Therefore, if one performs two modal analyses (one with the considered piezoelectric element short-circuited and open-circuited for the other), the $|k_i|$ values of many modes can be estimated. Repeating this estimation at different times, the possible rise of a damage can be discovered. As a damage index, the following quantity s_p is proposed in [5]:

$$s_p = \sum_{i=h}^{q} |(|k_{i,p}| - |k_{i,p,\mathrm{u}}|)| \qquad (2)$$

where the subscript p indicates that the index is computed for the generic p-th piezoelectric element in the structure and $k_{i,p,\mathrm{u}}$ is related to the undamaged (or reference) structure condition. Furthermore, h and q indicate the generic h-th and q-th modes (with $h < q$), respectively.

The proposed approach allows using piezoelectric elements already present in the structure also for SHM purposes. Such an approach can be somehow categorized among SHM methods based on the estimation of mode shapes or related quantities (e.g., [12, 13]), but with the significant advantage that mode shape estimation can be avoided and substituted with eigenfrequency estimation which is a much simpler approach. Furthermore, this allows avoiding common problems in mode shape identification, such as noise effects and need for dense sensor mesh.

The use of $|k_i|$ as damage feature provides also another important advantage. Indeed, it has been demonstrated in [5] that it shows low sensitivity to environmental and operational variability (EOV). As for the robustness to environmental effects, this can be explained considering Eq. (1), where a ratio of eigenfrequencies is present. Even if ω_i and $\hat{\omega}_i$ change differently in response to environmental changes, their changes are expected to be close and this implies low sensitivity of the value of $|k_i|$ to environmental variations. Furthermore, operational changes (e.g., change of external excitation) are expected not to change the value of $|k_i|$ because eigenfrequency values are not related to operational conditions (unless significant non-linearity arises). This makes the proposed approach robust also to operational variability. The evidenced robustness to EOV makes the proposed method easier to be applied compared to other existing approaches based on piezoelectric elements (e.g., electromechanical impedance methods [14]).

A possible difficulty in using the proposed damage feature and index is related to uncertainty in estimations of small value of $|k_i|$ (i.e., when ω_i and $\hat{\omega}_i$ are close in frequency). This problem can be overcome by shunting a negative capacitance (since a negative capacitance does not exist in nature, it is built by using tailored electrical circuits [15]) to the considered piezoelectric element. Indeed, as explained in [5], this makes farther and farther the short- and open-circuit eigenfrequency, thus artificially increasing the value of $|k_i|$. The artificially increased MEMCF value is referred to as $\tilde{k}_i$, with $|\tilde{k}_i| > |k_i|$.

3 NUMERICAL SIMULATIONS

Here, some simulations are described in order to show that s_p is a reliable index for damage detection and that it is even able to provide information about damage location when more than one piezoelectric element are present on the structure. The considered structure is an aluminum clamped-clamped beam (length 770 mm, thickness 1 mm) equipped with five piezoelectric

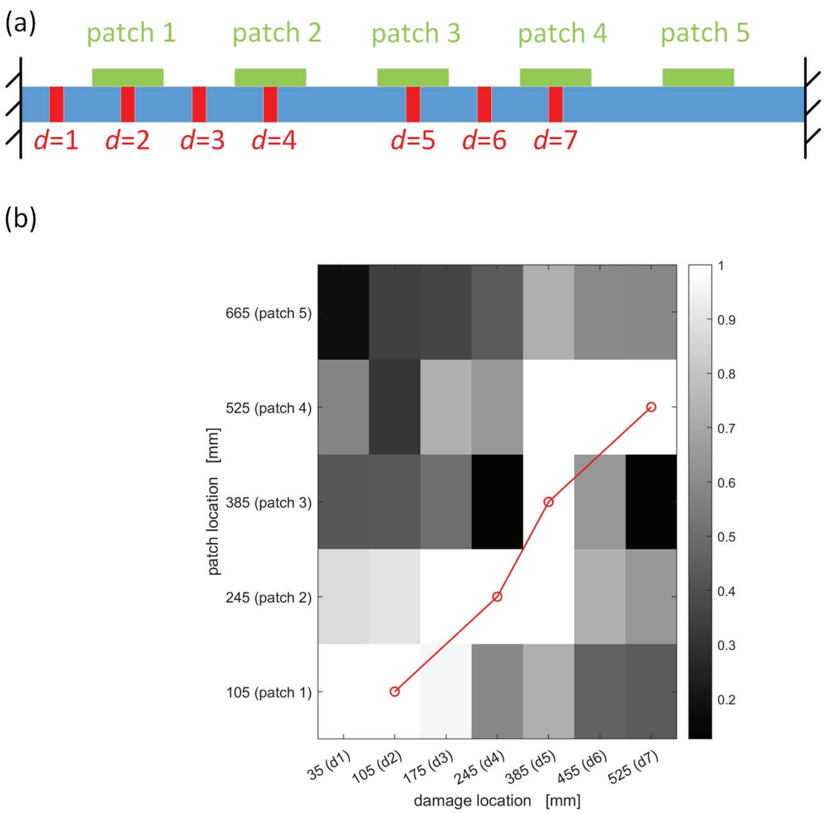

Figure 1: Schematic of the clamped-clamped beam with patch and damage locations (a) and value of $\bar{s}_p$ (b).

patches (material PIC151, length 70 mm, thickness 0.5 mm). Damage is simulated by decreasing of 70$\%$ the Young's modulus of the beam in five locations (see Fig. 1a). A single damage is considered in each simulation (i.e., damage is not present in more than one location in a given simulation). For each simulation, the s_p value is computed for all the patches considering the vertical bending modes from the fifth to the fifteenth.

Figure 1b shows the value of $\bar{s}_p$ ($\bar{s}_p$ is a normalised version of s_p such that it is equal to 1 for the patch having the highest s_p value for the considered damage location). It is evident that the value of $\bar{s}_p$ is able to evidence the presence of the damage and its value result high (i.e., close to 1) for the patches close to the considered damage, implying the capability of giving information about damage location. Many more simulations and details are available in [5].

4 EXPERIMENTAL TESTS

This section discusses some tests carried out on two different structures: (i) a cantilever aluminum beam equipped with piezoelectric patches and (ii) a truss structure equipped with

Table 1: Locations of the brick and of the patches.

	position of the center of the considered element from the constraint of the cantilever beam [mm]
patch 1	105.0
patch 2	385.0
brick location deA	47.5
brick location deB	105.0
brick location deD	302.5
brick location deE	347.5

piezoelectric stacks. Details about these structures can be found in [5].

Here, few tests are discussed. The reader can refer to [5] for many more tests.

4.1 Test with the beam

The cantilever beam is made from aluminum and has length of 700 mm and thickness of 1 mm. Two piezoelectric patches (material PIC151, length 70 mm and thickness 0.5 mm) are used for damage detection. The beam is excited with a non-contact electromagnetic actuator providing random disturbance and eigenfrequencies are identified with modified Ibrahim time-domain method [16] applied to response measurements (collected with a non-contact laser vibrometer). Here, two test types are presented.

The first is a test where it is shown that the effect of temperature slightly affect the $|k_i|$ values compared to damage. Damage is simulated here by adding a small brick bonded to the beam in different positions (see Fig. 2 and Table 1).

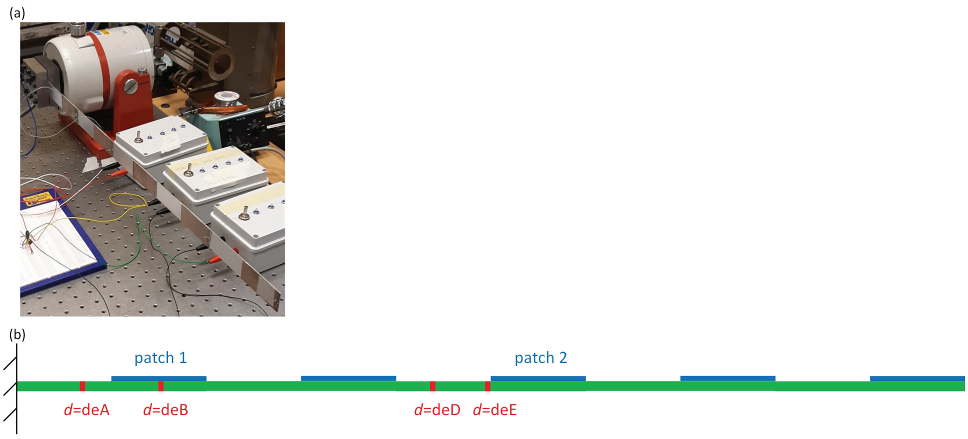

Figure 2: Picture (a) and schematic (b) of the cantilever beam with patches and brick locations.

The second is a test where s_p (considering five bending modes, excitation between 350 and 900 Hz approximately) is computed for the two patches. Since repetitions of calculation of s_p

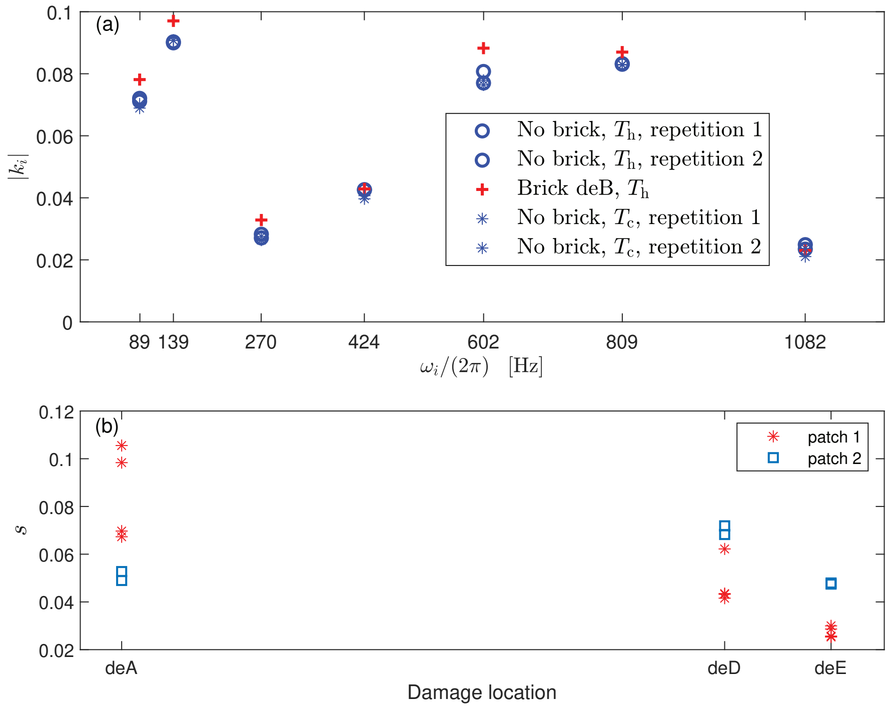

Figure 3: Trend of $|k_i|$ for patch 1 and for some modes defined through the corresponding eigenfrequency ω_i (with all the patches short-circuited) for different temperatures (T_h=300.15 K and T_c=288.15 K) and with brick in position deB (a) and s_p value (calculated on five bending modes) for the two patches as function of the position of the brick (b). See Table 1 for the locations of the brick and of the patches.

without damage showed values below 0.03 for both the patches, Figure 3b shows that damage is always detected at least by a patch for the three locations where the brick was bonded. Furthermore, the patch closest to the considered brick location always shows the largest s_p value, implying the possibility to give indications on damage location (see Table 1).

4.2 Test with the truss structure

Here, a steel truss structure (height of 1 m) with three main pillars is considered (see Fig. 4a). Two piezoelectric stacks are placed at the base of the truss. The truss is excited with a non-contact electromagnetic actuator providing random disturbance and eigenfrequencies are identified with modified Ibrahim time-domain method [16] applied to response measurements (collected with an accelerometer).

The damage is obtained making two small cuts on one of the main pillars approximately 20 cm far from the stacks. A negative capacitance was connected to both the stacks in order

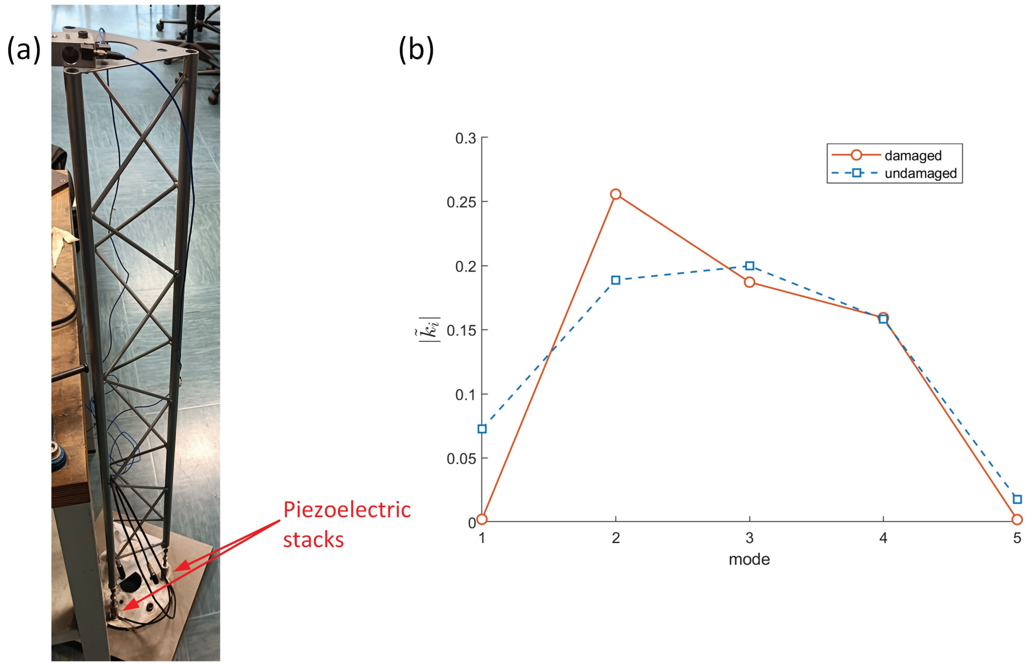

Figure 4: Truss set-up (a) and trend of $|\tilde{k}_i|$ for the considered modes with and without damage for one of the two stacks.

to increase the coupling values because of the initial small values of $|k_i|$ for various modes. The $|\tilde{k}_i|$ values of five bending modes (below 400 Hz) were estimated before and after the cuts. Figure 4b shows that it is easy to detect the damage (significant changes of the $|\tilde{k}_i|$ values of the first two monitored modes) also in a real condition with a real slight damage.

5 CONCLUSION

This paper has dealt with a new approach for damage detection in structures equipped with piezoelectric elements. The damage feature is the MEMCF, which measure the coupling between a given mode and the electrical part of the system. The use of MEMCF as damage feature allows for a low sensitivity to EOV and ease of estimation of the chosen damage index. The proposed approach has been tested on two different structures with good results, paving the way for further developments and opening to the use in the context of real structures.

ACKNOWLEDGMENTS

This research has been supported by the project ”CHIMERA? - is there a CHance that Indexes and Measurements of the energy conversion Efficiency Reveal system Alterations?” funded by the European Union – Next Generation EU, M4C2 I1.1, through Progetti di Rilevante Interesse Nazionale (PRIN) 2022, grant n. 20225PKHWJ (CUP: D53D23003060006).

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