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Experimental validation of a novel pseudo-modal approach for damage detection

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Abstract

Damage detection and localization in structural systems is experimentally studied. A novel pseudo-modal approach, recently proposed by some of the authors, is adopted. It is based on the comparison between free vibrations of the undamaged and damaged states, and aims to maximize the damage signature embedded in the data by exploiting the energy content of the vibration signals. Towards this goal, the latter signals are analyzed by means of the Orthogonal Empirical Mode Decomposition (OEMD) technique in order to derive a data-driven damage index, the so called Pseudo Modal Index (PMI). In this paper the results of an experimental campaign on a small-scale shear type steel frame structure are presented and discussed. The tested structure is modeled as a four degree-of-freedom dynamical system and the damage is represented by a localized stiffness reduction. A filtering technique applied to the Intrinsic Mode Functions is also proposed in order to tackle the presence of noise polluted data.

Keywords:
damage identification, pseudo-modal approach, pseudo modal index, frame structure, laboratory test

1. Introduction

The identification of damages in structural systems is nowadays a crucial target. Within this topic, dynamic approaches have been proven reliable and effective and several techniques can be found in the technical literature [1,4]. Nevertheless, real-life structures are liable to *worst* conditions which may limit the practical application of the latter techniques. First of all, the solvability of the identification problem must be considered, looking at the analytical position of the relevant inverse problem [7]; this issue can be tackled properly choosing the excitation system and the acquisition network (through, for example, a preliminary analysis of the structure dynamics).

Afterwards, the acquired data must be treated resorting at first to the classical signal processing techniques (filtering, windowing, and so on), and then to the chosen identification technique. Focusing on the last point, which is the main topic of this contribution, the analysis can be performed both in time domain and in frequency domain; moreover, physical properties (mass, stiffness, damping) or modal properties (natural frequencies, mode shapes, modal damping) or signal processing features (e.g., power spectral density) can be used as signs for the damage identification [3].

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Under the hypothesis of a well-posed and determined inverse problem, the use of a particular domain, as well as, the use of one of the structural properties, do not affect the goodness of the identification. Unfortunately, real cases are far from these hypothetical conditions, hence one would like to extract as much information as possible from the vibration signals.

Starting from the last remark, a novel technique has been recently proposed by some of the authors [8]. The free vibrations of the undamaged and damaged states of a structural system are decomposed through the Orthogonal Empirical Mode Decomposition (OEMD). The energy content of these data-driven oscillations is then used to search the signature of the damage, by means of the so-called Pseudo Modal Index (PMI). Basically, the technique tries to maximize the extraction of the information from the signals, looking at the same time to the benefits of the modal properties based techniques (ease in interpreting the results, direct correlation between the damage and its effects) and to the advantages of the technique based on the signal processing (direct and accurate tracking of changes in signals, flexibility in updating the results). The PMI has been numerically tested under several conditions [9–11], resulting as an effective and reliable tool for the damage identification; this contribution poses the first experimental validation. To this aim, a steel frame structure, small-scale and shear type, has been tested in the laboratory of Univ. "La Sapienza" of Rome (Italy). The paper is organized as follows: section 2 summarizes the pseudo-modal approach, section 3 shows the experimental setup and results, section 4 highlights the main conclusions of the work.

2. Pseudo-modal approach

The Pseudo Modal Index is a output-only index based on the Orthogonal version (OEMD) of the Empirical Mode Decomposition (EMD).

2.1. Orthogonal version of the Empirical Mode Decomposition

The EMD [5] is a sifting process, which decomposes a given signal $y(t)$ in a set of n sub-signals called IMFs, Intrinsic Mode Functions, plus the residue $r_n(t)$:

$$y(t) = \sum_{i=1}^{n} \mathrm{IMF}_i + r_n(t) \tag{1}$$

Several versions of the EMD have been proposed in the literature, changing the interpolation rule and the local and global stopping criteria. Here, a cubic spline is adopted as interpolation rule, and dummy maxima and minima are added asymmetrically on both edges of the signal to reduce the spectral leakage. As stopping criterion, a tolerance value of 0.2 on the standard deviation between two consecutive iterations is assumed as local criterion, whereas for the global one the number of IMFs is fixed equal to 15 (a large number, considering that the laboratory prototype to be tested behaves approximately like a four degree-of-freedom system, see section 3.1).

Differently from the usual decomposition into harmonics, the IMFs provide a data-driven and self-adaptive basis. Moreover, these sub-signals are localized both in time and frequency, and hence are more suitable for the analysis of non-linear or non-stationary signals. On the other hand, while an harmonic signal can be easily linked to a physical model, the interpretation of the IMFs is in general tricky, due to mode-mixing phenomena, which yield to multi-frequency signals. It must be stressed, however, how this is not a real issue for the purposes of the PMI because it belongs to the class of the output-only model-independent indices; as a matter of fact, these interaction phenomena are the main difference among the modal approaches and the one proposed by the authors. On the contrary, since the PMI will pivot on energetic measures, it is necessary to turn the set of IMFs into an orthogonal basis; the Gram-Schmidt orthogonalization method can be implemented to this aim, obtaining the so-called OEMD, Orthogonal Empirical Mode Decomposition [6]. Analogously, the OIMFs are the Orthogonal Intrinsic Mode Functions.

2.2. Pseudo-Mode Index

To evaluate the PMI of a structural system, at first the IMFs of free response signals (displacements or velocities or accelerations) are required for both undamaged and damaged structure. Then, a cut-off rule [10] must be applied in order to reduce the boundary effects:

$$n_s = \frac{f_s}{2 f_{min}} \tag{2}$$

being f_s the sampling frequency , f_{min} the lowest frequency expected in the signal and n_s the samples that must be rejected at both the edges of the IMFs; applying the Gram-Schmidt method to the truncated IMFs, a consistent set of OIMFs can be obtained. Afterwards, a set of M experimental shapes with N components is extracted for both states as:

$$\varphi_{ij} = \sqrt{P_{ij}} \qquad i = 1, \ldots, N \qquad j = 1, \ldots, M \tag{3}$$

being N the number of measuring points (sensors or nodes), M the number of OIMFs plus the residue (modes), and P_{ij} the mean power of the relevant OIMF during the time of recording t_r:

$$P_{ij} = \frac{1}{t_r} \int_0^{t_r} \mathrm{OIMF}_{ij}(t)^2 \, dt \tag{4}$$

These experimental curves, based on the RMS values of the sub-signals, are called pseudo-modes (pseudo modal shapes) since it can be demonstrate that these coincide with the mode shapes only when the OIMFs are mono-frequency. Lastly, the PMI is defined as the comparison between undamaged (apex ^{u}) and damaged (apex ^{d}) pseudo-modes:

$$\mathrm{PMI}(i) = \frac{|\, \varphi^d_{iJ} - \varphi^u_{iJ} \,|}{\varphi^u_{iJ}} \tag{5}$$

where J is the pseudo-mode which exhibits the maximum variation of power after the damage:

$$J = \arg\max \Delta P(j), \ \text{where: } \Delta P(j) = \left| \sum\nolimits_{i=1}^{N} P^d_{ij} - \sum\nolimits_{i=1}^{N} P^u_{ij} \right| \tag{6}$$

The damage is then located at the peak of the function PMI(i), explaining that if the number of IMFs was set *a priori* and the selected pseudo-mode J is the residue, then the number of IMFs must be increased. A constant value of the function indicates that the structure remains intact, since φ^u_{iJ} and φ^d_{iJ} are just scaled.

However, while this framework properly works for numerical examples (see, for instance, [10,11]), when one deals with real-life applications, the Eq. (6) needs to be generalized in the following:

$$J = \arg\max \Delta P(j), \ \text{where: } \Delta P(j) = \left| \sum\nolimits_{i=1}^{N} \frac{P^d_{ij}}{\sum_{j=1}^{M} \sum_{i=1}^{N} P^d_{ij}} - \sum\nolimits_{i=1}^{N} \frac{P^u_{ij}}{\sum_{j=1}^{M} \sum_{i=1}^{N} P^u_{ij}} \right| \tag{7}$$

where the maximum variation of power is related to the power input, which can be easily set as a constant in numerical tests, but can significantly change from one experiment to the other.

3. Case study

A small-scale structure is used to verify the reliability and the applicability of the PMI as damage identification tool. The tests have been performed at the "Laboratory of materials and structures" of Univ. "La Sapienza" of Rome (Italy). Section 3.1 shows the experimental setup, whereas section 3.2 summarizes the results of the campaign.

3.1. Experimental setup

The structure is a shear type steel frame (steel class: S235), one-bay and four-story, see Fig. 1. Dimensions have been set aiming to hold structural frequencies ranging in the typical field of interest of ordinary civil structures (10 ∼ 100 Hz): the overall height is 800 mm (interstorey of 200 mm), the plan is squared with edge of 300 mm, the columns have a rectangular cross-section of 50 x 4 mm, while the beams have a L-shaped cross-section 50 x 50 x 4 mm. All the beam-column joints are bolted and full moment connections; the columns are mounted on a shaking table through base plates, welded to the columns and bolted to the table.

The use of *stiff* beams is related to the choice of a shear type frame; the use of thin plates for the columns aims to decouple the motion of the structure along the two horizontal axes, that is, the behavior of the frame is practically planar, where the plan is identified by the vertical axis z and by an axis x orthogonal to the columns plates. In other words, the structure approximately behaves like a four degree-of-freedom system (one for each floor).

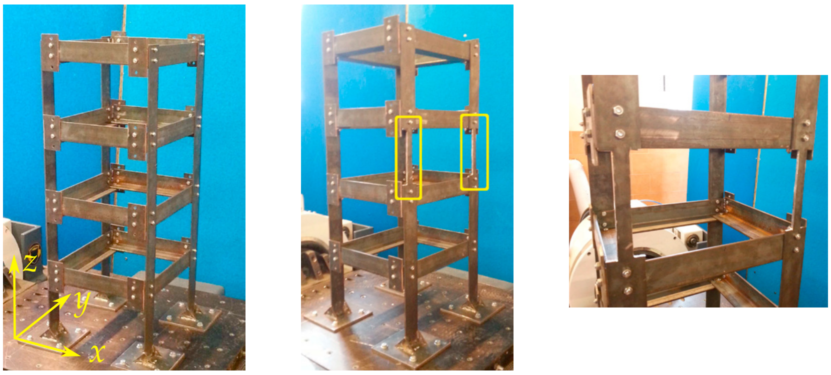

Fig. 1. The small-scale steel structure: undamaged state (left), damaged state (middle) and zoom on the damage (right).

The structural damage is artificially introduced bringing down the stiffness of the third floor (see again Fig. 1): the cross-sections of two columns are reduced from the original dimension of 50 x 4 mm to 20 x 4 mm; the two columns are chosen so to not affect the symmetry of the structure with respect to the plane $x - z$.

Two kind of excitations are applied: impulsive loadings at the top floor and base random vibrations. The former excitation is provided by an instrumented hammer PCB 086C03: sensitivity 2.28 mV/N, maximum load 2224 N, mass 160 g, resonant frequency 22 kHz. The base excitation is applied by the shacker on which the steel frame is mounted; the shaker, one-dimensional and electrodynamic, is the DONGLING GT700M, with the following properties: slip plate dimension 700 x 700 x 45 mm, dynamic range ± 10.3 g, moving mass 58 kg, frequency range 5~2000 Hz.

The acquisition system consists of 6 channels, one of which acquires the output of the instrumented hammer, while the other 5 record the lateral accelerations of each floor plus the base. The accelerometers used in the campaign are piezoelectric PCB 393B04: sensitivity 1000 mV/g, dynamic range ± 5 g, mass 50 g, frequency range 0.06~450 Hz; these devices are connected to the structure by means of small metal plates (bolted on the accelerometers) and tiny magnets (linking the plates with the structure). All the cables used in the experiments are low-noise coaxial cables.

The campaign is so scheduled: 3 impulsive loadings of about 80 N and duration close to 2 ∼ 3 ms, 3 base random excitations with a constant PSD of 105 g^2/Hz and a duration of 180 s.

3.2. Results

Before proceeding with the evaluation of the PMI, the modal properties of the (both undamaged and damaged) structure are discussed; for the purpose, the Peak Picking technique [2] is used to detect the first four frequencies and mode-shapes of the structures. Tab. 1 shows a comparison among the experimental frequencies of the undamaged and damaged structure, being μ the mean value, σ the standard deviation, CV the coefficient of variation and Δ the percentage difference among the mean values.

Table 1. Experimental frequencies.

Mode	Undamaged			Damaged			Δ, %
	μ, Hz	σ, Hz	CV, %	μ, Hz	σ, Hz	CV, %	
1	16.22	0.015	0.09	15.79	0.022	0.14	-2.65
2	47.58	0.013	0.03	45.31	0.046	0.10	-4.77
3	73.29	0.084	0.11	72.84	0.037	0.05	-0.61
4	90.73	0.046	0.05	86.33	0.072	0.08	-4.85

The small values of the coefficient of variation CV (always less than the 2 ‰) testify the high accuracy of the measures; the percentage differences Δ show that damaged frequencies are smaller than the healthy ones by a percentage ranging from the 0.61 % (third mode) up to the 4.85 % (fourth mode). Fig. 2 shows also the unit-mass normalized (mean) mode-shapes of the two states of the structure, under the hypothesis of masses localized at each floor: the damaged shapes are very close to the relevant healthy ones, suggesting that the identification problem is not so straightforward.

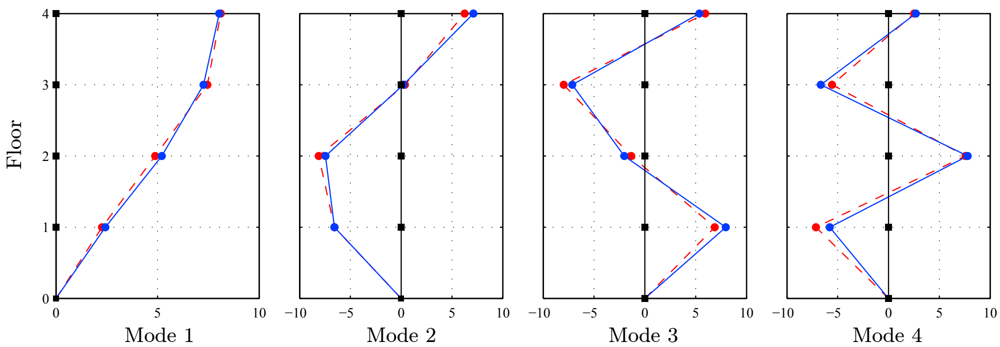

Fig. 2. Mode-shapes (unit-mass normalized): the blue solid lines and the red dashed lines stand for, respectively, the undamaged and the damaged structure.

The power distributions of the OIMFs obtained in two impulsive tests performed on the undamaged and damaged structure are displayed in Fig. 3. The two plots on the top show the distributions of the power as it is: from these results it appears how the first OIMFs are fast oscillations with low averaged power, that can be well ascribed to the noise corruption of the signals (this is not surprising, noting that the EMD sifts a signal from the fastest oscillation to the slowest one). From this consideration, a simple filtering scheme can be outlined: all the first OIMFs must be neglected until a clear *jump* appears in the power distribution. For example, accordingly to this criterion, the first two OIMFs are neglected for the acceleration of the first floor of the undamaged structure. The distribution of the power in the filtered OIMFs is displayed in Fig. 3 in the two plots on the bottom.

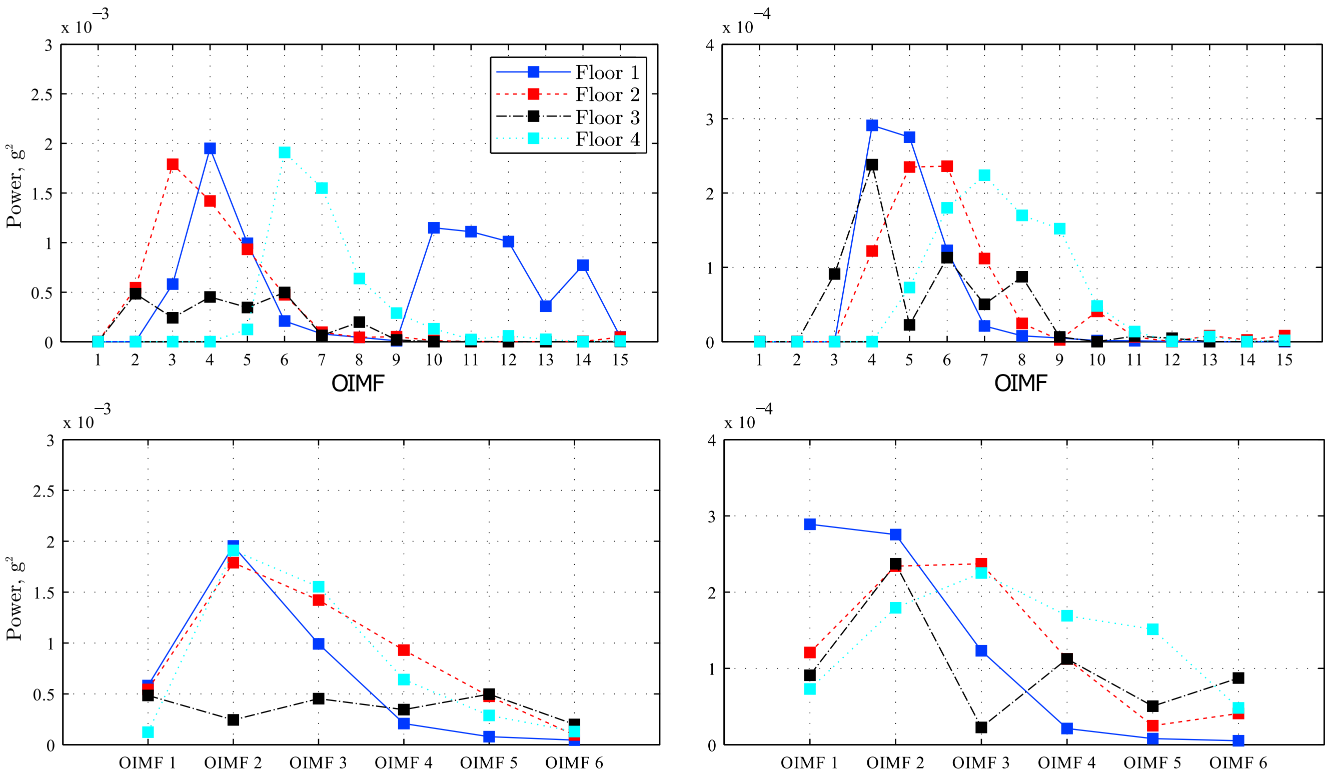

Fig. 3. Distribution of the power in the OIMFs: unfiltered (top) and filtered (bottom) sub-signals, undamaged (left) and damaged (right) structure.

Lastly, the damage identification scheme is sketched in Fig. 4. The first plot shows the PMI values for first six (filtered, that is, noise-free) OIMFs, while the last two contain the PMI curves obtained for the OIMF selected by (6) ($J = 2$, plot in the middle) and by (7) ($J = 3$, plot on the right). The results prove that the technique properly works if the selection criterion takes into account for the input energy, indeed, the PMI curve on the right is characterised by a single peak located on the sensor closest to damage (the third one from the base).

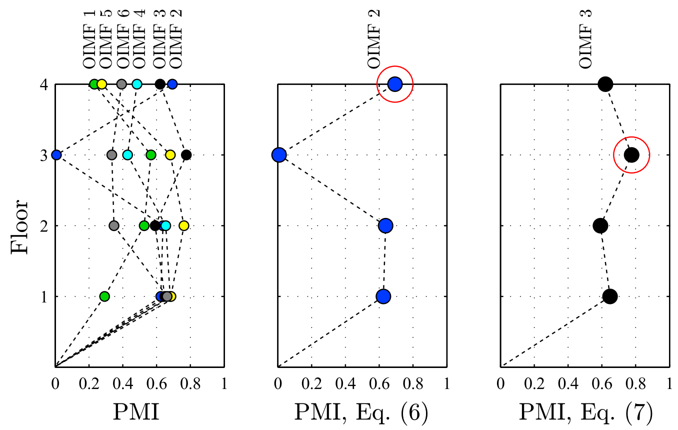

Fig. 4. Damage identification: PMI values for the first six OIMFs (left), PMI curve for the OIMF selected by (6) (middle) and (7) (right).

4. Conclusions

The paper dealt with dynamic damage identification, focusing on a pseudo-modal approach recently introduced by some of the authors. This contribution showed the first experimental validation, which involved a small-scale steel frame, artificially damaged at the third floor, with a precision cutting. Two main contributions turned out from the experimental campaign: first, the noise corruption can be easily avoided looking at fast oscillations with low averaged power; second, the energetic selection criterion provided in the previous works (Eq. (6)) needs to be updated (Eq. (7)) to properly work when input energy is likely to change. Applying the latter remarks, the results here presented corroborate the previous (numerical) findings and thus the goodness of the proposed method; further experimental tests are in progress.

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