PROBABILITY OF DETECTION OF DAMAGE FOR AN ELECTROMECHANICAL IMPEDANCE BASED SHM SYSTEM

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Summary

The paper presents the assessment results of probability of detection for damages in mechanical structures conducted with a Structural Health Monitoring (SHM) system based on the measurements of electromechanical impedance. The research was carried out with both numerical models and real-life mechanical components. The results of laboratory tests performed in operational conditions for a bolted pipeline connection confirmed usefulness of both the applied monitoring method and the SHM system. The *hit/miss* and *signal response* statistical approaches were employed to gain insight into the specific SHM system reliability.

Keywords: probability of detection, SHM, electromechanical impedance, system reliability.

ANALIZA PRAWDOBODOBIEŃSTWA WYKRYCIA USZKODZEŃ DLA SYSTEMU MONITOROWANIA STANU TECHNICZNEGO KONSTRUKCJI OPARTEGO O POMIAR IMPEDANCJI ELEKTROMECHNICZNEJ

Streszczenie

W artykule przedstawiono wyniki oceny prawdopodobieństwa wykrycia uszkodzeń w konstrukcjach mechanicznych dla systemu monitorowania stanu technicznego opartego o pomiary impedancji elektromechanicznej. Badania przeprowadzono zarówno dla modeli numerycznych jak i rzeczywistej konstrukcji mechanicznej, której stan techniczny monitorowano z zastosowaniem opracowanego systemu. Wyniki laboratoryjnych testów działania sytemu uzyskane dla monitorowanego połączenia kołnierzowego części rurociągu potwierdziły przydatność zarówno zastosowanej metody jak i zbudowanego systemu w obszarze monitorowania stanu technicznego konstrukcji mechanicznych. Do oceny prawdopodobieństwa wykrycia uszkodzeń zastosowano techniki statystyczne *hit/miss* data oraz *signal response data*.

Słowa kluczowe: prawdopodobieństwo wykrycia uszkodzeń, monitorowanie stanu technicznego, impedancja elektromechaniczna.

1. INTRODUCTION

Structural Health Monitoring (SHM) methods based on the measurement of the electromechanical impedance are widely used for continuous monitoring of the state of mechanical constructions [1-3]. Electromechanical impedance based SHM systems enable to detect local damage by means of arrays of piezoelectric transducers (PZT)s. PZTs are permanently installed on the monitored structure and act as both actuators and sensors. The integrity of the structure is assessed by applying local vibrations with frequency ranging from 10 kHz to 500 kHz. The excitation is present in proximity of the transducers [1, 4, 5]. Electromechanical coupling in the PZTs gives necessary information to infer on the presence of damage in the structure. Measured frequency characteristics and established damage indexes are used to track the local perturbations of mechanical properties resulting from the incipient and growing damage. Moreover, there are recently published works on the assessment of efficiency of the electromechanical impedance based SHM systems considering the influence of operational conditions, including temperature and contact effects [6-8].

The paper focuses on the assessment of the effectiveness of electromechanical impedance based SHM system through the calculation of probability of detection (POD) of a damage. Two application cases are examined. First a physical prototype of a bolted section of a pipeline is studied. Second, a computer simulation framework is built for the analysis of a simple beam.

The paper is structured as follows. In section 2 a description of the electromechanical impedance based SHM technique is given along with the definition of the damage index. In sections 3 and 4 the reliability assessment resulting from both numerical simulations and experimental tests of the SHM system is discussed. Section 5 provides a summary of the work with important conclusions.

The presented results were obtained with a SHM system developed and tested at the AGH University of Science and Technology, Department of Robotics and Mechatronics [9,10].

2. ELECTROMECHANICAL IMPEDANCE BASED SHM

2.1. Measurement of electromechanical impedance

Two types of the electromechanical impedance frequency characteristics allow for the assessment of a technical state of the monitored structure [1,9-11]:

- point Frequency Response Function (FRF)
- transfer FRF

A point FRF of the electromechanical impedance can be measured with the scheme shown in Fig. 1a. A single PZT is applied in order to generate vibrations in monitored structure and measure its response. Obtaining both the voltage and the indirectly measured current the electromechanical impedance can be found with the following formula:

$$Z = R\left(V_{IN} - V_{OUT}\right)/V_{OUT} \tag{1}$$

In case of a transfer FRF two electrically isolated PZTs are separately used for generating and sensing mechanical vibrations as presented in Fig 1b. The input voltage in the first circuit and the output current from the second one are applied to find the electromechanical impedance:

$$Z = RV_{IN}/V_{OUT} \tag{2}$$

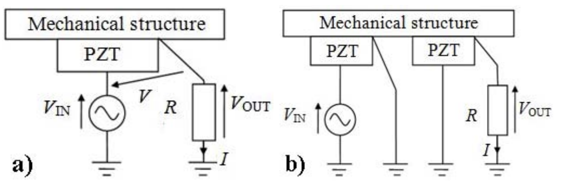

Fig. 1. Measurement of point FRF (a), and transfer FRF (b) of electromechanical impedance

For both mentioned above measurement techniques any significant changes of mechanical properties in the vicinity of mounted PZT transducers influence the determined frequency characteristics. The disadvantage of the first solution is a difficulty of choosing a PZT that could optimally act as both an actuator and a sensor. In the second case, however, the cost of the installed hardware grows resulting from an additional transducer and a more complicated electronic circuit. The second circuit also characterizes a higher efficiency in energy transformation resulting in the increased energy of generated vibrations and improved sensitivity to growing damage.

2.2. Definition of damage index

The impedance based SHM is a reference based technique. The inference on the presence and growth of a damage is performed with use of a baseline FRF. The baseline characteristics are gathered for a healthy system or after its repair and define a nominal condition with no damage.

To assess the size of damage the statistical metric was used as its effectiveness for damage detection had been previously confirmed [10]. The damage index DI is defined as follows [1]:

$$DI = 1 - \frac{\sum_{i=1}^{n}\left(\left(\mathrm{Re}\left(Z_{0,i}\right) - \mathrm{Re}\left(\bar{Z}_0\right)\right)\left(\mathrm{Re}\left(Z_i\right) - \mathrm{Re}\left(\bar{Z}\right)\right)\right)}{(n-1)s_0 s} \tag{3}$$

where $Z_{0,i}$, Z_i are baseline (referential) and current electromechanical impedances for i-th frequency, $\bar{Z}_0$, $\bar{Z}$ are mean values of those impedances, s_0, s are standard deviations of real parts of impedances, n is the number of frequency steps. Only real parts of FRFs are taken into consideration, because of their higher sensitivity to the changes of mechanical properties in the system with mounted PZTs [12]. Imaginary parts are mostly applied for testing the properties of PZTs since they represent a significant contribution of reactance in the resultant impedance (a PZT behaves as a capacitor in an electrical circuit).

3. EXPERIMENTAL TESTS

For experimental verification of the method a test bed was set up consisting of a bolted pipeline section and the elaborated measurement unit for acquiring characteristics of the electromechanical impedance for selected frequency ranges.

3.1. Laboratory test bed

The laboratory test bed is shown in Fig. 2. A bolt loosening at a selected localization was assumed to represent a damage in the pipeline. The measurements were performed using Data Acquisition Unit shown in Fig. 3. Monitored bolts were equipped with metal sleeves which enabled a proper placement of the PZTs. Mounted piezoelectric transducers were used to measure both point (PZT1 shown in Fig. 2) and transfer (PZT2 and PZT3) FRFs of the electromechanical impedance. In the following, only the transfer FRFs were employed for the probability assessment. For the nominal case, i.e. for the healthy pipeline component, all tightening torques were set to 50 Nm. Accurate values of the torques were obtained with use of torque wrench.

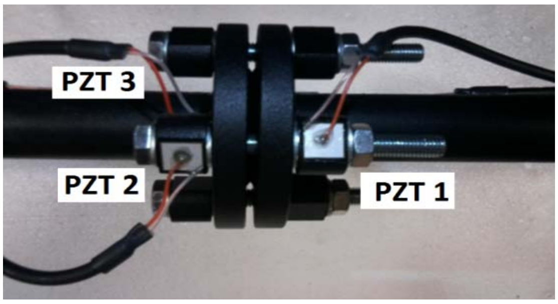

Fig. 2. Monitored pipeline section

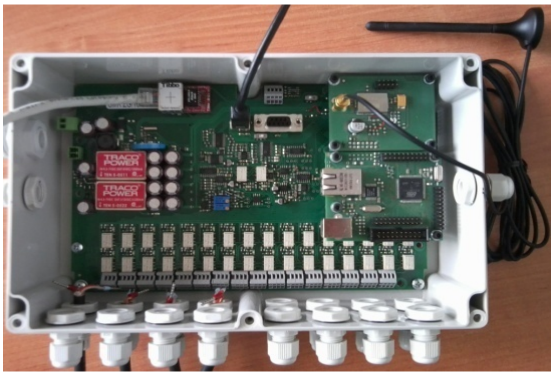

Fig. 3. Developed Data Acquisition Unit

3.2. Electromechanical impedance measurements

After the calibration of the analog measurement system a series of transfer FRFs were determined for different amounts of loosening the selected bolt. The measurements were performed for the frequency interval from 28 kHz up to 44 kHz. For each value of the torque the impedance measurements were repeated 10 times. Fig. 4 presents groups of the FRFs for given fastening torques.

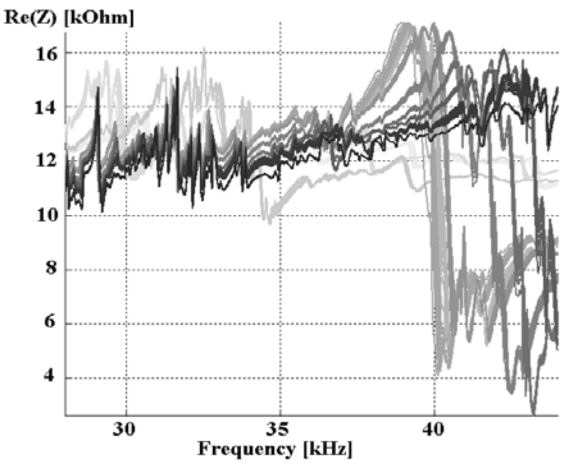

Fig. 4. FRFs for real parts of electromechanical impedance (black curve refers to the nominal healthy state)

Lighter colors are used for smaller values of the fastening torque. The black curves in Fig. 4 refer to the undamaged state of the pipeline section, i.e. with the fastening torque equal 50 Nm. The mean of the 10 black curves defines the nominal curve. The group of 10 curves with the lightest color corresponds to the state with fastening torque of 10.67 Nm, i.e. applying a loosening torque of 39.33 Nm. Additionally, the measurements were carried out in an ambient temperature varying from 24°C up to 36°C. The presence of damage is conveniently pointed out by changes of the FRFs with respect to the nominal curve. These changes comprise both amplitudes and frequencies of the resonances and confirm the considerable influence of the torque variations on the mechanical properties of the structure, also recognizable in presence of temperature variation.

3.3. Damage index

The damage index was calculated by comparing the current FRF with the nominal FRF (characterizing the fastening torque 50 Nm). For this purpose, as already mentioned, only the real parts of the FRFs were taken into consideration, because of their high sensitivity. Fig. 5 presents the results given by different loosening torques within the interval 0Nm - 39.33 Nm. Here, it is possible to observe the monotonic relationship existing between the loosening torque and the damage index. For the nominal case, i.e. for the group of the first 10 characteristics, the maximum value of the damage index equals 0.0023. Gradual increase of the bolt loosing caused sudden increase of the damage index.

Moreover, it was found that for torque reduction (or fastening) up to 11.7 Nm the range of metric was always significantly lower than 0.1. Then, after a fast growth of the damage index for increasing loosening torque, the damage index became much less sensitive to the loosening torque for values equal or higher than 2 Nm.

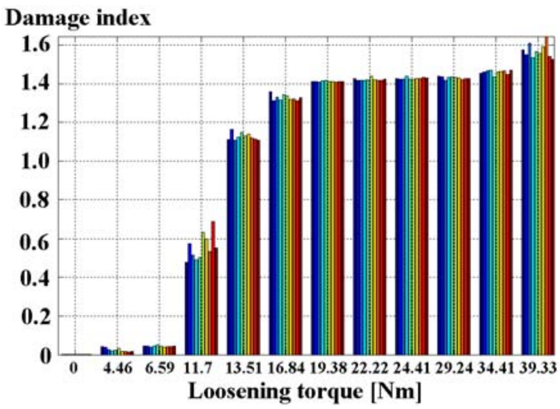

Fig. 5. Relationship between the loosening torque and the damage index

3.4. Hit/miss approach for probability of detection

The POD of the SHM system has been computed using a hit/miss analysis. All damage cases were ordered into a binary vector where 0 identifies a damage not detected (missed) and 1 refers to a damage detected (hit). Decision upon the presence of damage is made according to an established threshold level for the damage index [13-15].

Fig. 6 shows the resultant vector yielded from a threshold level equal to 0.04. The POD curve along with its lower confidence bound calculated for a significance levels equal 0.05 is shown in Fig.7. The lower confidence bound relates to the 95% probability that, repeating POD measurements with different datasets, the resultant mean curves will not stay below the obtained bound.

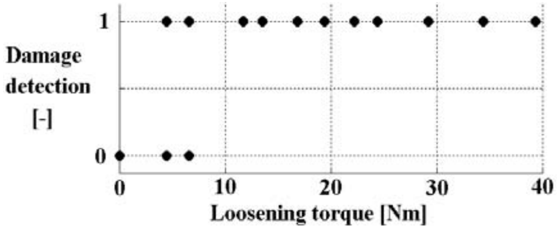

Fig. 6. Ordered damage cases

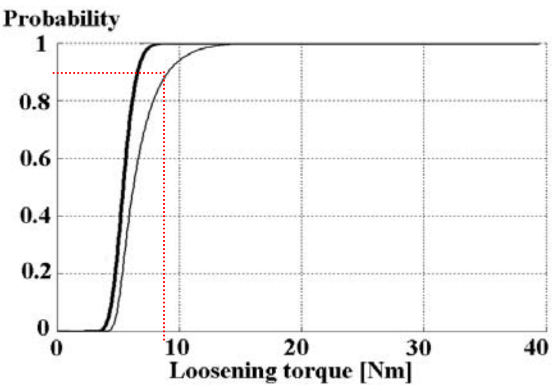

Fig. 7. Probability of detection

A quantity that is commonly considered as a valid summary of the system reliability is given by the damage size 90/95. This represents the damage size for which it exists a probability of 90% to detect damage with a confidence of 95%. In the present case, the 90/95 damage size corresponds to a loosening torque of about 8.5 Nm.

4. NUMERICAL TESTS

Recently, the adoption of detailed computer models simulating the SHM measurement process has been proposed as a way to alleviate the experimental burden. This procedure is known in literature as model-assisted POD (MAPOD) [16]. This section describes a second application case where MAPOD technique is employed for electromechanical impedance-based SHM system reliability assessment.

In order to further verify the reliability of the SHM technique presented in section 2, a FE model of a thin beam with attached a PZT was created in ANSYS/Multiphysics. The model calculates the FRFs of the electromechanical impedance for different flaw sizes introduced in the beam.

4.1. FE model

The FE model represents an aluminum beam with sizes 100 mm x 16 mm x 1 mm and free-free boundary conditions, as depicted in Fig. 8.

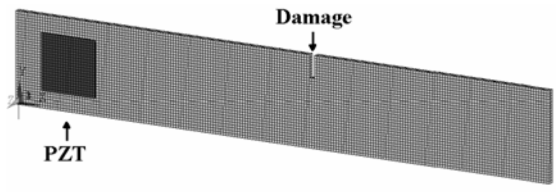

Fig. 8. FE model of the beam

The point FRFs were found with the use of one PZT. A transverse notch of 1mm width and depth varying from 0 mm up to 4 mm was considered as a damage introduced into the beam. The damage was located 55 mm away from the left edge of the beam. The PZT of size 10 mm x 10 mm x 0.3 mm was placed 5mm and 3mm away from the vertical and horizontal edges of the beam, respectively. The material of the PZT was assumed to be a PIC151 (PI Ceramic). A 0.05 mm thick epoxy-based glue adhesive layer was modeled between the PZT and the beam as it influences the dynamical response of the structure. The model was composed of 20-node SOLID95 FEs for the beam and the adhesive and SOLID226 FEs for the PZT. The maximum element's length was equal to 0.5 mm. The model considered an electromotive force of amplitude equal to 1 V. Finally, a 100 Ohm resistor was included in the circuit for the indirect evaluation of the current.

4.2. Evaluated electromechanical impedance

Harmonic analyses were conducted and the resultant FRFs are presented in Fig. 9 for all 80 different damage sizes. In the diagram only the real part of the electromechanical impedance is plotted, as required for Eqn. (3). The black curve marks the baseline solution for an undamaged beam. For the remaining ones the gray intensity determines the notch depth (the lighter the color, the deeper the notch). The presence of the crack is conveniently evidenced by both resonance frequency and resonance amplitude changes with respect to the baseline.

4.3. Damage index

The damage index is determined by Eqn. (3) for all point FRFs. Fig. 10 shows the results obtained for growing notch. Gained results justify the effectiveness of the process of damage detection aided with the electromechanical impedance measurements conducted for the FE models with a notch.

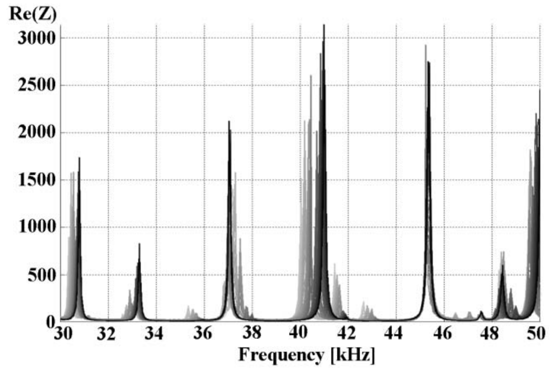

Fig. 9. Point FRFs for growing damage size (black curve refers to the nominal FE model)

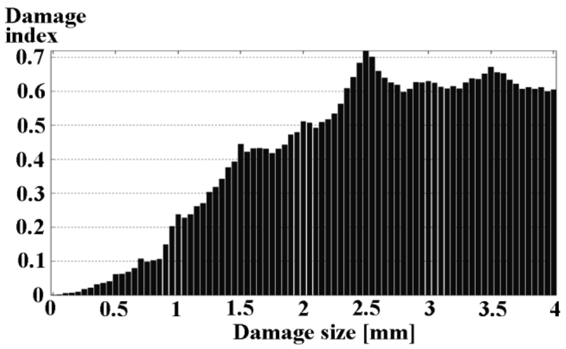

Fig. 10. Relationship between notch depth and damage index

Unquestionable correlation between the size of damage and the value of damage index can be seen, especially for the region with small and moderate crack sizes where the correlation is strictly positive. For larger damage sizes the monotonic trend is lost. However, from a practical point of view this may happen when a damage has been already detected far in advance.

4.4. Signal response data for probability of detection

In this case, the POD curves are computed using the 80 available damage indices and a signal response approach, as documented in [13, 14]. Signal response technique uses in a more efficient way the available information than the hit/miss analysis. It treats the outcome from the system as a continuous signal correlated with the damage size. For this reason the confidence bounds are usually closer to the mean curve.

Fig. 11 presents the obtained POD mean curve along with the lower confidence interval bound calculated for a significance level of 0.05. The evaluated 90/95 damage size corresponds to a notch depth equal 0.6 mm.

This analysis, carried out within a computer framework, was less costly than the previous one in terms of time. The total amount of variability affecting real SHM system measurement was included into the model by adding a random noise to the FRF numerical responses. In this study, the noise properties were assigned according to the signal variability resulting from preliminary experiments.

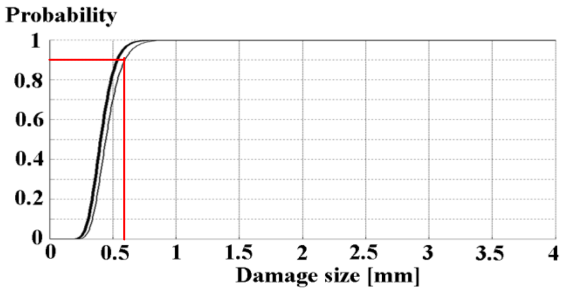

Fig. 11. Probability of damage detection and related confidence interval

5. SUMMARY AND REMARKS

The work presents the results of the POD assessment performed for the electromechanical impedance-based damage detection method. The study considers the evaluation of the electromechanical impedance while formulating the assessment of the construction condition. For the calculations of the POD there were applied two known statistical techniques: the signal response data and the hit/miss approach.

The results confirmed the usability of SHM based on the measurements of electromechanical impedance. For the considered instances damages could be detected at their initial stage of growth.

However, it should be mentioned that POD analysis has important limitations when performed for SHM systems. Since in SHM systems the sensors are permanently mounted on the structure, the factors that play a major role in the system reliability are, for instance, mounting conditions, environmental conditions, aging factors, etc. If ones wants to take into account all these parameters an infeasible amount of experimental tests would be required. This issue is well known in the scientific committee, see e.g. [14]. For this reason the analysis presented in the paper is intended to give only a rough idea of the detection performances of the SHM system. Moreover, this assessment is valid, and may be helpful, only for a very specific class of systems represented by the developed system considered for the present study and based on the electromechanical impedance measurements for a bolted pipeline section.

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