FUZZY CLUSTERING TO DISTINGUISH STRUCTURAL DAMAGE FROM TEMPERATURE EFFECT

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Abstract. Structural Health Monitoring (SHM) denotes a system with the ability to detect and interpret adverse changes in a structure. Many companies invest large amount of money in SHM applications, since damage can lead to catastrophic and expensive failures. This paper is addressed to apply impedance technique for structural health monitoring. This technique is based on high frequency to monitor changes in the impedance signals. This can be done by using piezoelectric sensor/actuator that get measurements directly related with the mechanical impedance of the structure. When this approach is used for practical applications, it is very important to stand out the environmental influences, since it can interfere in the signal and could indicate a false damage diagnosis. In this work the influence of the temperature is evaluated to classify the impedance signals in clusters. A fuzzy clustering algorithm is used to organize the data in clusters with the aim of distinguish damage situation from structural changes caused by temperature variations. In the experimental application, an aluminum beam with one coupled piezoelectric ceramic was analyzed. A commercial system from National Instruments controlled by LabVIEW® software was used for input excitation and data acquisition. In all tests the beam was suspended horizontally to simulate a free-free boundary condition.

Keywords: Piezoelectric Material, Structural Health Monitoring, Electric Impedance Technique, Temperature Variation Effect, Fuzzy Clustering

1. INTRODUCTION

In recent years the Structural Health Monitoring (SHM) has been an increasing sector with featured in bigger enterprises, mainly in aviation. The SHM operate in many important factors to development of it. Among this factors we can quote more security of humans, less rich in environmental disasters, less tempo spend with maintenance and consequently less waste financial.

The impedance-based health monitoring technique has been developed as a promising tool for detecting structural damage in real time and is considered to be a method for non-destructive evaluation. Through monitoring the impedance signature and comparison with a baseline impedance measurement the structural damage can be qualitatively determine. This is possible due the change generated by damage in the mechanical impedance of the structure. Due to the electromechanical coupling, this change causes a change in the electrical impedance of the piezoelectric sensor.

However, in the most real cases the structure that is being monitored is subject to environmental changes or operational conditions that can cause changes impedance of system coupled. The temperature variation is one of the most that can cause changes in impedance signature. Thus, the success in SHM procedure is to decide correctly whether damage is present or not. The partitioning of the damage-sensitive feature to separate the healthy and damaged conditions is traditionally conducted in frequency-domain by different indexes.

In order to overcome some practical drawbacks found in SHM procedures based on electromechanical impedance, this paper proposes to evaluate the effect of the temperature variation in impedance-based structural health monitoring system. This study uses a fuzzy clustering algorithm to classify the impedance signals in clusters and to distinguish damage situation from structural changes caused by temperature variations. The experimental tests, an aluminum beam with one coupled piezoelectric ceramic (PZT) was analyzed. A commercial system from National Instruments controlled by LabVIEW® software was used for input excitation and data acquisition.
2. PRINCIPLE OF IMPEDANCE-BASED NON-DESTRUCTIVE EVALUATION TECHNIQUE

The Impedance-based Structural Health Monitoring method uses the two piezoelectric effects (direct and inverse) simultaneously to obtain the impedance signature. The electromechanical interaction between PZT and host structure can be described by a simple impedance model. Figure 1 shows the schematic representation of this model. The PZT is normally bonded directly to the surface of the structure and in considered how a thin bar undergoing axial vibration due to the applied alternating voltage. One end of the bar is considered fixed and the other id connected to the structure (Inman et al., 2005).

\[ Y(\omega) = i\omega a \left( \varepsilon_3^T (1 - i\delta) \frac{Z_S(\omega)}{Z_S(\omega) - Z_a(\omega)} d_{33}^x \hat{Y}_E \right) \]

in which \( Y(\omega) \) is the electrical admittance (inverse of impedance), \( \omega \) is the frequency, \( a \) is the geometric constant of the PZT, \( \varepsilon_3^T \) is the dielectric constant at zero stress, \( \delta \) is the dielectric loss tangent of the PZT, \( d_{33}^x \) is the piezoelectric coupling constant in the direction \( x \) at zero stress, \( \hat{Y}_E \) is the complex Young’s modulus of PZT to electric field equal zero, \( i \) represents the imaginary number, \( Z_S(\omega) \) and \( Z_a(\omega) \) are the mechanical impedance of structure and PZT, respectively.

It is well known that the real part is more vulnerable to structural changes, i.e., is the most indicated for damages detections. The real part is the resistive part of electric impedance and the imaginary part represents the reactive part. For the damage detection cases the imaginary part remains unchanged or changed a little, the changes in this portion is more due to change in boundary conditions such as loading effects, temperature changes and length of test wire (Park et al., 1999).

2.1. Damage assessment

The RMSD index is presented here in the following form, (Lopes Jr. et al., 2000):

\[ M = \sum_{i=1}^{n} \left[ \frac{\left( Z_{i,1} \right) - \left( Z_{i,2} \right)}{\left( Z_{i,1} \right)} \right]^2 \]

where \( Z_{i,1} \) is the electrical impedance of the baseline condition, or healthy structure, of the PZT sensor and \( Z_{i,2} \) is the signal in the same PZT in unknown structural conditions at frequency interval \( i \).

3. FUZZY CLUSTERING

The goals of clustering methods are the classification of objects according to the similarity between them, and organization of data into groups. In others words, the goal is to identify a finite number of clusters to describe one dataset. In these methods, the membership of a data point in a cluster is a fuzzy decision. Few studies have been made with the use of fuzzy clustering for SHM. In this work the method of fuzzy classifiers used is the fuzzy c-means.
3.1. Fuzzy c-means

The fuzzy c-means (FCM) is one of the most used algorithms for fuzzy clustering. It is a problem of minimizing, where the cost function to be minimized is given by (Silva et al., 2008):

$$\min_{f_j, C_i} \sum_{j=1}^{N} \sum_{i=1}^{c} f_{ij}^{m} \| x_j - C_i \|^2$$

subject to \(0 \leq f_{ij} \leq 1\)

$$\sum_{i=1}^{c} f_{ij} = 1 \quad \forall j \in \{1, 2, ..., N\},$$

$$0 < \sum_{j=1}^{N} f_{ij} < N \quad \forall i \in \{1, 2, ..., c\},$$

where \( f_{ij} \) is a function associated with the \( j \)-th object of the \( i \)-th cluster, \( C_i \) is the centroid of the \( i \)-th cluster, \( c \) is the number of clusters, and \( m > 1 \) is a constant that determines the relative positions of the clusters (\( m \) is normally chosen to be 2, and is the value used here), \( x_j \) is the representative feature, which here is set to RMSD index, and \( N \) is the number of objects (tested cases) that depends on the number of datasets (in this paper \( N = 18 \), the number of cases studied).

The distance norm can be written as:

$$D_{\text{fA}}^2 = \| x_j - C_i \|^2 = (x_j - C_i)^T A (x_j - C_i),$$

where \( A \) is known as a norm-inducing matrix. In FCM, \( A \) is usually the identity matrix. Hence, one can only detect clusters with the same shape and orientation due to use the same norm-inducing matrix for all clusters. The solution of the optimization problem described by Eq.(4) comes from the optimality equations via Lagrange multipliers. Details about this procedure can be found in Bezdek and Pal, 1992.

4. EXPERIMENTAL SETUP

This section describes the tests that were conducted in order to verify the proposed methodology. The experiments were done in a smart aluminum beam. In all tests tests the beam was suspended horizontally to simulate a free-free boundary condition. One PZT element was bonded on the beam surface. This element is called Buzzer. Table 1 shows the geometric properties of the PZT patch and of the beam.

All input excitations for testing were a chirp signal within +/- 0.5 V saturation limits and 0-50kHz frequency range. The schematic diagram of the measurement network with the positions of damages is shown in Fig. 2.

The input-output data acquisition was controlled using the LabView with a National Instruments card board, model NI-USB 6211, 16 bits. The signals were stored with a sample rate of 250 kHz and 65536 samples were recorded in each channel. The schematic diagram of the measurement network with the positions of damages is shown in Fig. 2.

The signals were analyzed in three different temperatures, for each temperature three conditions were simulated: without damage, with damage 1 and with damage 2. For the two damages conditions were used a gimp and a little magnet to simulate the damages. The damage 1 was a grimp with 1.1g and the damage 2 was 4.1g, Fig. 3. All tests were performed inside a heater with controlled temperature. For each case studied the signal was collected twice. Then, 18 cases in healthy or damaged conditions were investigated.
5. RESULTS

Table 2 indicates the characteristics of each test. Figure 4 shows the impedance module of the signals obtained (without damage) and their temperatures respectively. Observing these signs is remarkable the region of greatest sensitivity (greatest number of peaks) corresponding to 6800-8500Hz range.
Due the impedance real part is more sensitive to structural changes and the imaginary part most sensitive to changes caused by temperature variation we working with these two signals to calculate the indexes (indicators). Below is observed the distribution in plan of these two indicators, were the index calculate used the signal of real part is called Index 1 and the index relative the imaginary part is called Index 2. By simple observation of this plot, it is possible to separate the data into three groups corresponding the three temperatures examined. In point of practical view could be difficult to define exactly the number of clusters. To implement the FCM it was used the toolbox of Matlab®. In the same figure the centers of clusters calculated with this procedure and the division of groups by color is showed.

Observing the Fig. 6 is possible to identify visually what are the situations of damage (where the Index 1 varies more than Index 2). Figure 7 shows the percentage of Membership in each cluster.
6. CONCLUSIONS

For the case studied in the present paper was possible to separate the data index in the correct temperature where the test was performed. It was not possible to give the diagnostic of the health structure in the same moment of the diagnostic of the temperature. However, in a posteriori analysis it could be detect the damage without problem. In others words, if the data were divide in temperature clusters end each cluster has its own baseline, the structural state of the system can be monitored. Once the large increase in temperature between the tests still cannot extend this approach to any situation. Some tests are still needed for this methodology can be implemented.

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8. REFERENCES


9. RESPONSIBILITY NOTICE

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