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# Fuzzy Similarity Classifier as damage index: Temperature effect and compensation

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## Abstract

The effects of ambient operational temperature variability on the measured dynamics response of structures have been addressed in several studies. It is intuitive that temperature variation may change the material/geometric properties or boundary conditions of a structure and therefore may affect the damage detection performance. Then we consider the ability of a Fuzzy similarity classifier as a feature when the temperature is changing; it will be shown that temperature change might have more significant effect rather than the simulated damage on this feature, which leads to false positive decisions. Therefore, it is vital to compensate the effect of temperature to achieve a desirable result. To do this, the temperature effect is compensated and it is shown the compensation increases the performance of damage detection using the Fuzzy similarity index. To support claims mentioned above, this work involves experiments with composite plate equipped with PZT transducers. To simulate the effect of temperature the specimen is subjected to temperature change between  $-25^{\circ}\text{C}$  and  $60^{\circ}\text{C}$ .

**Keywords:** Damage detection, Temperature compensation

## 1 Introduction

Structural Health Monitoring (SHM) is a non-destructive method which aims to give, at every moment during the life of a structure, a diagnosis of the “state” of the constituent materials, the different parts and the full assembly of these parts constituting the structure as a whole. SHM takes the advantage of different methods such as pattern recognition, neural network, genetic algorithms, statistical method etc. This work applies another technique called Similarity Classifier.

The concept of similarity is a basic concept in human cognition. Some of the earliest speculations of ancient Greek philosophers were based on similarity arguments. For instance, it seems likely that one of the first uses of a similarity notion was the adoption of an equivalence relation to classify all matter in the world into four basic elements: air, earth, fire, and water [1]. There are a wide range

for concept of similarity and there does not exist a valid, general purpose definition of similarity. According to Zadeh [2] "Formulation of a valid, general-purpose definition of similarity is a challenging problem". The concept of similarity is used in various areas such as Anthropology (similarity of peoples and nations), Music (similarity of different compositions), Geology (mineral resource appraisal) and Zoology (mammalian similarity studies). Similarity has also got many different specific usages in engineering and statistics fields such as cluster analysis, Fuzzy similarity, image processing, pattern recognition and diagnostics [3, 4]. There are many aspects of the concept of similarity that have eluded formalization.

In this work, the effect of temperature change on a new damage index is considered and compensated. The proposed index is based on fuzzy similarity and Łukasiewicz-Structure. The index is utilized in a damage detection strategy that uses Principal Component Analysis (PCA) as dimension reduction and feature selection tool. The efficiency of the proposed index and the effect of temperature is experimentally evaluated on a carbon fiber-reinforced plastic (CFRP) plate.

## 2 Damage detection based on Fuzzy similarity

### 2.1 Fuzzy Similarity based on Łukasiewicz structure

The concept of similarity is of fundamental importance in different fields and it can be considered as a many valued generalization of the classical notation of equivalence. For instance, similarity plays an essential role in taxonomy, recognition, case-based reasoning and many other fields. Fuzzy similarity is an equivalence relation that can be used to classify multivalued objects. To define the Fuzzy similarity we previous need to consider some definitions.

**Definition 1** *In generalized Łukasiewicz structure, the equivalence relation can be defined as*

$$a \leftrightarrow b = 1 - |a^p - b^p|^{1/p}$$

*Here  $p$  is an arbitrary fixed natural number.*

Readers are recommended to read [5] for more information about Łukasiewicz structure. Let  $X_{n \times m}$  be a set of  $n$  objects each of which having  $m$  features (variable). If we know the similarity value of the features  $f_1, \dots, f_m$  between the objects, it is possible to choose the objects that have the highest similarity value. To achieve this goal, PCA is applied to reduce the dimension of the original data  $X_{n \times m}$  to a score matrix  $T$  by finding matrix of eigenvalues and eigenvectors of the covariance matrix, using singular value decomposition as follows:

$$X = P\Sigma V^T \quad (1)$$

$$T = XP \quad (2)$$

After that the similarity is calculated. The formula of the similarity based on the generalized mean and the generalized Łukasiewicz structure attains the following form [6]:

$$S\langle x_1, x_2 \rangle = \left[ \frac{1}{m} \sum_{i=1}^m W_i \left( \sqrt[p]{1 - |(x_1(f_i))^p - (x_2(f_i))^p|} \right)^m \right]^{1/m} \quad (3)$$

where  $x_1, x_2 \in X$ ,  $i \in 1, \dots, m$  and  $p$  is an arbitrary value. This formulation above is used as a new damage detector index to compute the similarity between features from any observation captured from current status of structure (probably damaged) and the pristine structure (Baseline). The features are selected using PCA and are fed to the formulation above.

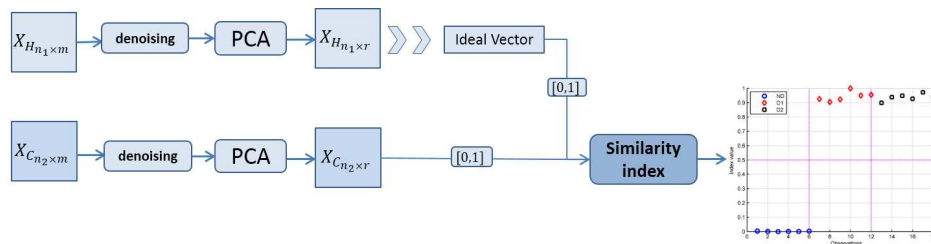


Figure 1: Damage detection algorithm

The proposed damage detection algorithm can be described as follows (see Figure 1). In the first stage (training), experiments are performed for the structure in a healthy status. Recorded data from sensors are stored in a matrix  $X_{H_{n_1 \times m}}$ , where  $n_1$  is the number of observations and  $m$  is the number of variables. After dimension reduction and feature selection using PCA, all selected features are scaled between  $[0, 1]$  to fulfill the requirement of the methodology presented in section 2.1. Data from pristine structure are used to calculate the representative features of the structure called *ideal vector* in healthy condition. This could be done by calculating the average of all the set of learning data in pristine condition or any other representatives such as median etc. In the second stage (diagnosis), similar experiment is performed for the structure in a current status (healthy or damaged). Data matrix  $X_{C_{n_2 \times m}}$  follows a similar track (see Figure 1). All data features of any observation from the current status of structure are compared with the ideal vector using similarity classifier measurement (Equation 3). The index value of similarity for any observation is calculated. This quantity is used as a novelty index to distinguish between healthy and non healthy status. This means that the similarity value between the ideal vector and any observation belong to the healthy status of the structure is supposed to be different from the similarity value between the ideal vector and any other observation that may be affected by existence of damage in structure.

### 3 Experimental Setup

This case study is performed on a composite plate with the dimension of  $305 \times 305 \times 2mm$ , which is equipped with PZT ceramics. PZTs are located in  $20cm$  distance from each other and  $5cm$  from each edge of the structure. Figure 2 shows the schematic, sensor location and a snapshot of the specimen.

Damages are simulated on 4 different locations by adding appropriate mass (circular magnets with  $10mm$  diameter). Figure 2-b and 2-d shows the schematic and a snapshot of damages on the specimen surface.

Signals are recorded in different frequencies such as 150, 200, 300, 350 and 400KHz. Switching makes it possible to scan all routes between transducers.

All actuation signals are generated by a National Instruments *PCI – 6110* DAQ card and routed through a Krohn-Hite 7602 wideband power amplifier. Then the received waveforms are digitized with acquisition card on the same chassis with the sampling rate of 2.5 MHz.

This study employs a thermal chamber to test the effect of temperature fluctuation on wave propagation as well as the efficiency of the proposed damage feature to detect damages while temperature is changing.

To simulate the environmental effect, the temperature is increased from  $25^\circ C$  to  $60^\circ C$  and then is decreased to  $-20^\circ C$  with the resolution of  $5^\circ C$ . Using a thermocouple, the ambient temperature is measured constantly. Signal is repeated 10 times and averaged to reduce the noise effect and 3 observations are recorded per each temperature.

Each observation is recorded by averaging of 10 excitations and finally 50 observations are recorded

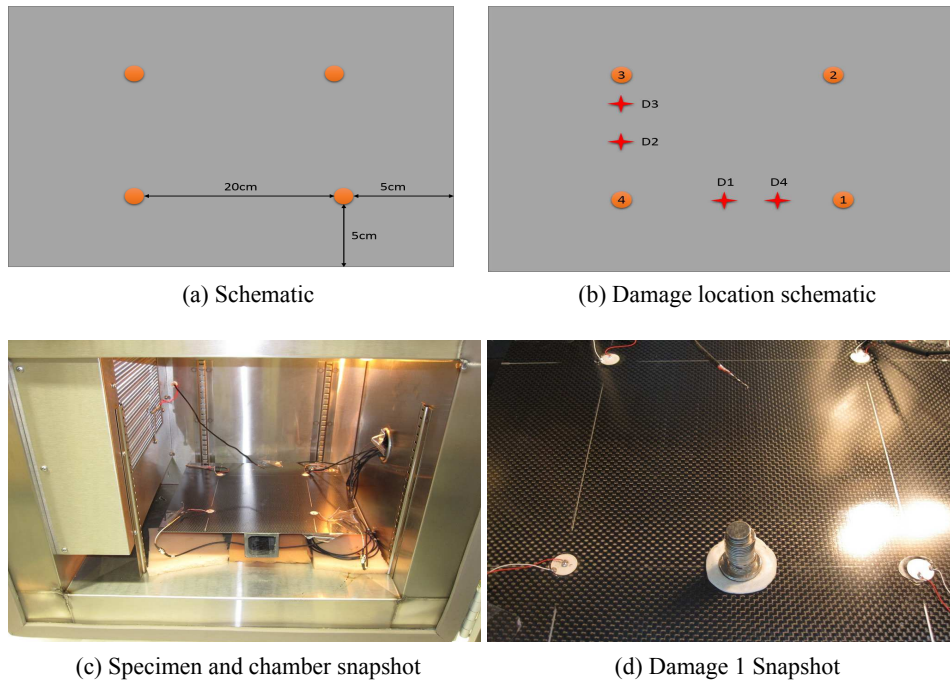


Figure 2: Composite plate with PZT, UCSH SHM Lab. USA

for healthy structure and 25 per each damage.

#### 4 Temperature effect and compensation on Similarity classifier method

In this section, the effect of temperature on similarity classifier method is considered. To check this effect, the analysis is performed on 350KHz for the route 3 → 4 where the damage 2 is simulated. As it could be seen in Figure 3, temperature has a clear effect on the index but it does not mask the effect of damage. In other words, the damage is still distinguishable from the other status.

To achieve better analysis, data captured from the structure are analyzed for all temperatures when damage 2 is simulated for different frequencies. Figure 4 shows the result of this analysis. As it is depicted, the same result is achieved for other frequencies. For instance, for 400KHz the damage effect dominate the effect of temperature. The same result is achieved for 300KHz, 350KHz and 400KHz.

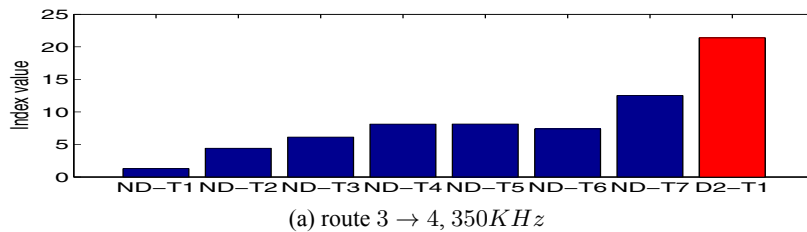


Figure 3: Temperature effect on similarity classifier

The same method is applied on the structure when damage 3 is simulated. As it is described in Section 3, this damage is located on route between the first and third transducer. The analysis is performed on different frequencies. The result is presented in Figure 5. The same outcome is obtained

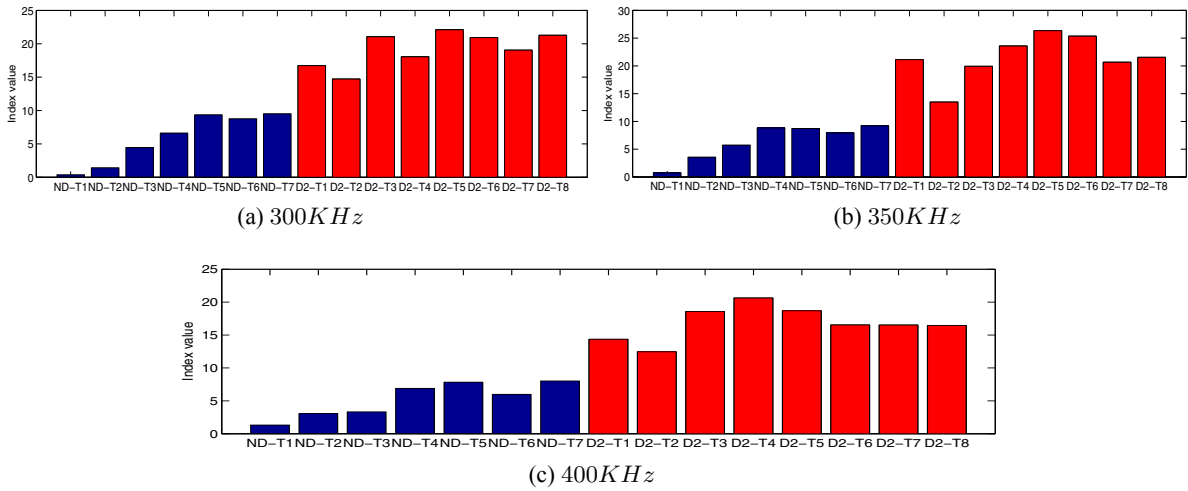


Figure 4: Temperature effect on similarity classifier, route 3 → 4, with D2, different frequencies

in this analysis as could be seen, the damage effect is still distinguishable from the temperature effect but not so clearly.

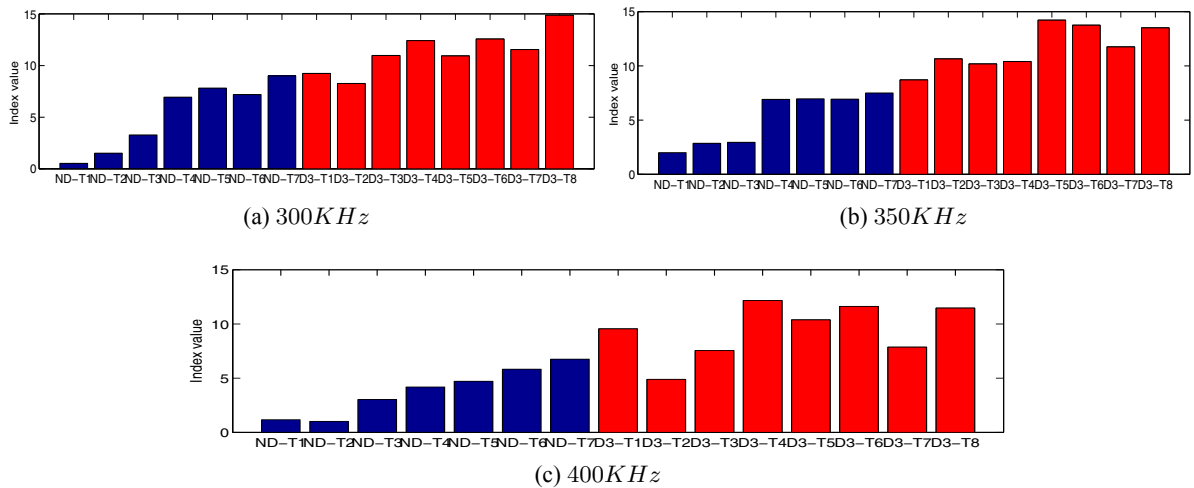


Figure 5: Temperature effect on similarity classifier, route 1 → 3, with D3, different frequencies

### 4.1 Temperature compensation techniques

Due to the effect of temperature fluctuation mentioned above, a simple baseline comparison methods are unable to distinguish damage from environmental and operational effects.

Different methodologies are proposed to compensate the effect of temperature such as interpolation and extrapolation of baseline [7], baseline signal stretch (BSS) [8] or optimal baseline selection (OBS) [9, 10].

In OBS technique (See Figure 6), to discriminate the effects of damage from those of environmental changes, a “bank” of baseline signals acquired at the various temperatures ( $T_1, T_2, \dots, T_n$ ) and later the response data (from unknown status) is compared with baseline database to find the closest

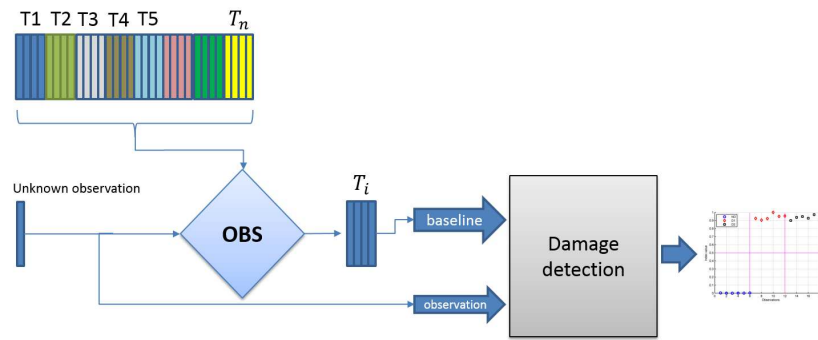


Figure 6: Schematic of OBS temperature compensation technique

match ( $T_i$ ). The selected baseline is used as the data representing pristine structure in this temperature. Unlike BSS, that technique does not change the time-trace but simply reduces the temperature difference seen. To achieve the highest performance, the baseline database should be formed at number of temperatures spanning the expected service range. In the next step, the best baseline signal is selected using appropriate measurement distance. Michaels [9] suggests three differential features which calculate the difference between the signal and the baseline. The first feature is the normalized squared error between the signal and baseline,

$$E_1 = \frac{\int_0^T [y(t) - x(t)]^2 dt}{\int_0^T x(t)^2 dt} \tag{4}$$

Here  $y(t)$  is the signal and  $x(t)$  is the baseline and  $T$  is the time window over which the signal are compared.

The result of applying OBS technique is demonstrated for different frequencies (300KHz, 350KHz and 400KHz) in Figure 7. This figure shows the analysis applied on the case study on the route 3 → 4. As it can be seen from the figure, applying OBS mitigates the effect of temperature and makes the damage effect more separable.

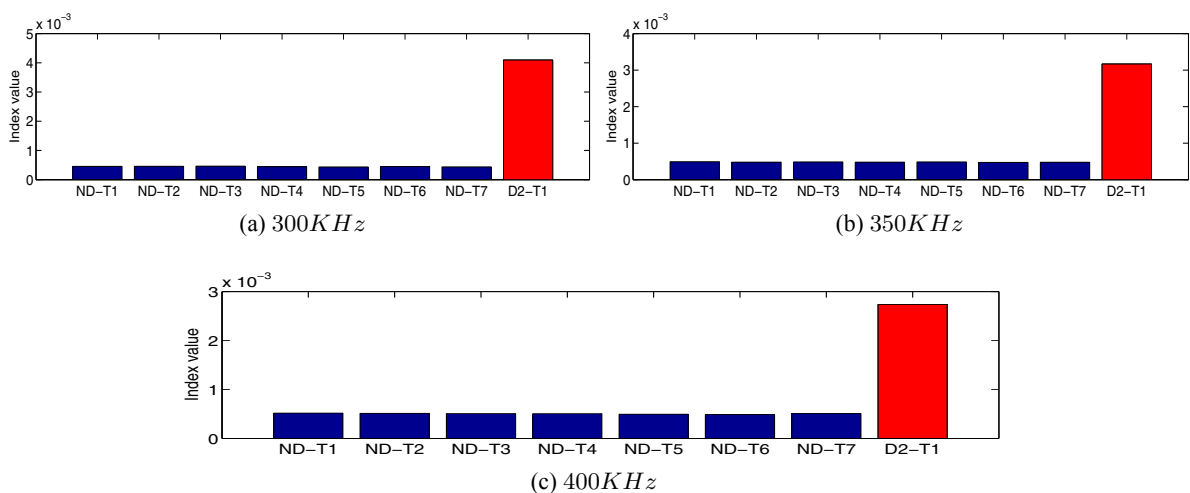


Figure 7: Temperature compensation: similarity classifier, route 3 → 4, with  $D_2$ , different frequencies

The same analysis is applied on route 1  $\rightarrow$  3 where damage 3 is applied. Results are shown in Figure 8. The same description is valid for this result.

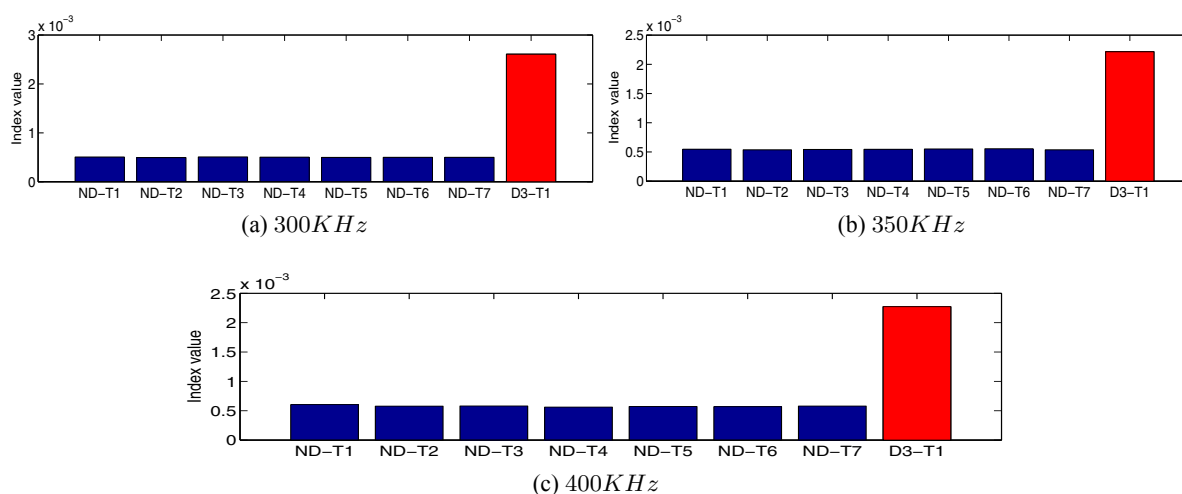


Figure 8: Temperature compensation: similarity classifier, route 1  $\rightarrow$  3, with  $D3$ , different frequencies

## 5 Conclusion

This work is dedicated to analyze the effect of temperature fluctuation on a new damage index based on Fuzzy Similarity. First it is shown that temperature change has adverse effect on the performance of this index. Therefore, simple baseline comparison is not able to achieve the complete goal of damage detection. To increase the performance of the technique and mitigate the adverse effect temperature change, Optimal Baseline Selection method is applied. Results show that applying this method increase the performance of damage detection and decrease the false alarms.

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