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Vibration-based Structural Interrogation and Health Monitoring Based on Nonlinear Signal Analysis

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Summary. Vibration-based structural interrogation and health monitoring is a field which is concerned with the estimation of the current state of a structure or a component from its vibration response with regards to its ability to perform its intended function appropriately. This study suggests using the concept of signal cross-correlation for the purposes of vibration-based health monitoring. A nonlinear alternative of the cross-correlation, the mutual information between two signals measured on the structure, regarded as an input and an output, is used to develop a damage metric and a damage index. The application of the suggested methodology is shown on a composite beam test set using experimental measurements.

Introduction

Maintenance and operation costs are usually among the largest expenditures for most structures - civil, aerospace, and military. An ageing structure may reduce profits with increased maintenance costs and down time and it can become a hazard for its users. The ability to access the integrity of a structure and discover a fault at a rather early stage, before it has developed so that it can cause damage to the structure, can significantly reduce these costs. A large class of the structural health monitoring (SHM) methods are vibration-based methods where the state of the structure is assessed using its vibration response. Among the most common features are the ones extracted from the modal properties, like resonant frequencies, damping and mode shapes. All of them have their advantages and disadvantages, some of the main problems being lack of sensitivity to damage, and difficulties to estimate from measured data. Another large group of monitoring methods, the model-based methods assume and use a model for the structure under interrogation. Most of these methods use a linear structural model. Monitoring methods based on the time-domain vibration signatures represent a relatively new paradigm in SHM [1-3]. These methods are mostly based on non-linear dynamics tools and signal analysis and most of them utilise statistical characteristics. They represent a very attractive alternative since they do not assume any model or linearity of the structure under interrogation and they only require the measured structural vibration signals in the current and possibly in a baseline (undamaged) state. One such damage assessment method based on a novel concept for the comparison and namely the mutual information of two signals measured on a structure is presented here.

The main idea of the method.

The damage assessment method proposed is based on the measured time domain vibration response in two different points on the structure [3]. These could be accelerations, or displacements or velocities. The mutual information here is suggested as a nonlinear alternative of the cross-correlation between two signals. The main idea behind the method is that for e.g. an ideal linear system the two signals, considered as an input and an output, will be highly correlated and thus will be able to "learn" from each other . If there is damage in the structural member then this will affect the correlation between the two signals because the system will no longer be neither linear nor ideal. Accordingly for a damaged system the information learned by the signals is expected to go down. The mutual information between two sets of signals $\mathbf{a}=\{a_i\}_{i=1,\dots,n}$ (measured in the point A on the structure) and signals $\mathbf{b}=\{b_j\}_{j=1,\dots,m}$ (measured in a point B) is the amount "learned" by a_i from b_j, which is expressed in bits as:

$$I(a_i,b_j)=\frac{\log_2 P_{ab}(a_i,b_j)}{P_a(aj)P_b(bj)} \tag{1}$$

where $P_{ab}(a_i, b_j)$ is the joint probability density for signals **a** and **b** and $P_a(a_i)$ and $P_b(b_j)$ are their individual probability densities respectively. If the measurements are completely independent then the amount of information between them, the mutual information, is zero. The average mutual information (AMI) between the signal sets **a** and **b** is given by the average over all measurements a_i and b_j:

$$I_{ab}=\sum_{a_i,b_j} P_{ab}(a_i,b_j).\log_2\frac{P_{ab}(a_i,b_j)}{P_a(a_i).P_b(b_j)} \tag{2}$$

Our assumption is that this amount of information, the AMI between **a** and **b** for an intact structure will be different from the AMI between the same sets of signals for a damaged structure. The explanation is that the signals from an intact structure will be more correlated (in a nonlinear sense) and thus will learn more from each other as compared to the signals for the case of damaged structure [4]. The two signals for a damaged structure will be more independent and thus will learn less from each other and consequently the AMI will go down for a damaged structure.

Application of the method for damage/delamination detection in a composite beam.

Below a delamination index based on the AMI is introduced which represents the relative percentage change in the AMI between the baseline (undamaged) condition and a current possibly damaged condition:

$$i_{ab} = \frac{I_{ab}^{in} - I_{ab}^{dam}}{I_{ab}^{in}}.100 \tag{3}$$

The method suggested is applied for delamination detection in a beam with dimensions 1x0.06x0.008 metres made of composite laminate with ten layers. Figure 1 shows the beam and the measurement points for the two signals. The beam is clamped at both sides. Delamination is introduced in the middle of the beam (0.5 m from left end) in three different position along the beam height namely between layers 1 and 2 (upper) between layers 5 and 6 (middle) and between layers 9 and 10 (lower) delamination, and in three different sizes, namely 0.01m (small), 0.02m (medium) and 0.03m (large).

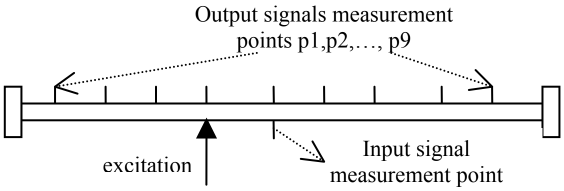

Figure 1. The beam and the signal measurement points

By using different random Gaussian excitation signals and different measurement points for the output signal (Fig.1) it is first shown that the metric suggested is robust with respect to changes in the excitation signal and to the measurement points. Our results show that the mean values of the AMI remain very much the same for changes in the measurement points as well as in the excitation signal with rather small standard deviations less that 3%.

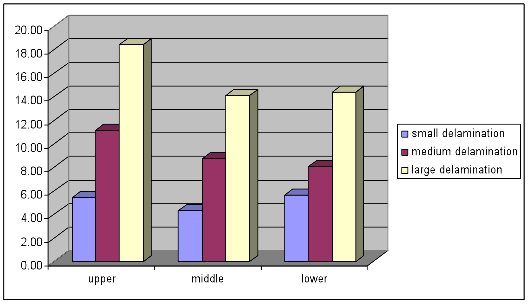

Figure 2. Damage index for different delamination sizes and positions

It is then shown that the suggested delamination index changes when delamination is introduced and it is sensitive to the size of the delamination. Figure 2 shows the delamination index (3) for different delamination sizes and positions. It can be observed that the suggested index changes with different delamination sizes. It definitely can be used for delamination detection since even for the case of small delamination it is about 5%. It can be applied also to judge for the delamination size as well since it can be seen from Figure 2 that it changes quite a lot for different delamination sizes.

Conclusions and discussion

This study suggests a novel concept for structural health monitoring based on nonlinear signal correlation namely the average mutual information. The AMI is a measure for the overall average dependence between two signals measured on a vibrating structure. The AMI is a better alternative to use for structures with well expressed nonlinear dynamic behaviour when the measured signals are nonlinear as well. A method for damage detection is developed based on damage index which represents the relative percentage change in the AMI between the baseline and the current structural state. The method is based on the time domain measured structural response and only requires two sets of signals (or two long enough signals) measured in two different points on the structure. Another attractive feature of the method is that it is developed and can be used for the case of ambient excitation when the force(s) applied to the structure are not measurable. In this study the method is demonstrated for a composite laminate beam which is known to demonstrate nonlinear behaviour.

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