An approach to damage detection based on PZT sensors and Transfer Impedance method

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Abstract

One of the ideas for structural health monitoring (SHM) systems built is based on analysis of small displacements propagation excited in the element by a network of PZT piezoelectric actuators. Structural damage can result in observable changes of the signal generated by the network sensors, due to elastic wave interaction with damage. There are two approaches how to utilize PZT sensors for SHM purposes. One of the approaches follows closely classical ultrasonic testing. In that case, short pulse excitation of PZT transducers is used, thus guided wave packets can be scattered on different elements of structure, eventually also on the damage itself. The disturbance of the scattered wave field is the basis of damage detection and evaluation. In the different approach, the so called electromechanical impedance (EMI) method, harmonic excitation of PZT is used, thus steady elastic waves are excited in the structure. As in guided waves approach, the signal can be gather in the pulse echo scheme, i.e. when single transducer is used both as a actuator and the receiver of waves, as well in the pitch – catch scheme, when a pair of transducers, the generator and the sensor, are used. For the latter EMI approach, the term Transfer Impedance Approach is sometimes used. In the paper, an approach for damage detection and localization with use of network of PZT sensors excited with harmonic signals in broad frequency spectrum is presented. In particular, some signal characteristics – called Damage Indices (DI’s) used for structure assessment are proposed and their properties are discussed. The DI’s have the property to maintain all of the information about the signals. That property manifests the robustness of the proposed approach, in the sense that if a damage is detectable by PZT sensors, then it should be revealed by the proposed DIs.

1. Introduction

One of the popular methods of PZT sensors application for Structural Health Monitoring is Electro-Mechanical Impedance (EMI) method [1]. The principle of this method is illustrated in Figure 1. Piezoelectric transducer integrated with monitored structure is supplied with a sinusoidal voltage \( v(t) \) at frequency \( \omega \) introducing harmonic deformation of structure. Forced body vibration depends on local elastic properties of the material and affects the amplitude and phase of the current \( i(t) \) in the circuit. Similarly classical eddy current method, impedance \( Z \) of PZT transducer coupled with a structure can be used for structure assessment.
The EMI techniques measure the electrical impedance in wide range of frequencies. Plots of real or imaginary parts of the impedance profiles can be used for damage detection or sensor self-diagnostics, e.g. strength of bonding with the structure. Typical frequencies profile of impedance of PZT sensor coupled with a structure are quite complex. As damage is introduced in the plate, resonant frequency shifts, peaks splitting, and the appearance of new resonances can be noticed. Detection of changes in impedance profiles can be used as damage indicators in the case of EMI technique.

EMI method was applied to monitoring of:
- bolt and bolt connections [1, 2];
- glued and welded joints [3];
- delaminations and debondings in composite materials [4–6];
- reinforced concrete structures [7];

2. The approach

2.1 Approach description

For classical EMI approach single PZT sensor is used for structure monitoring. If pair of transducers are applied, a variant of EMI approach, called Transfer Impedance method can be used. For Transfer Impedance (TI) approach, the voltage induced on PZT sensor used as the receiver of elastic waves can be considered as the response signal – proper for the structure assessment. Figure 2 shows an example of voltage signals obtained for three different PZT sensors receiving elastic waves excited by an actuator sourced with sinusoidal voltage. Due to Linear Time Invariant (LTI) systems theory, if a sinusoidal voltage $U_{in}$ is applied to PZT actuator, then the voltage signal $U_{out}$ on the receiver, induced by elastic waves, is also sinusoidal and has the same frequency as $U_{in}$. Therefore the ratio, called the transfer function:

$$TF = \frac{U_{out}}{U_{in}}$$

(1)

does not depend on time. It can be written in complex form as:
\[ TF(\omega) = \frac{U_{out}}{U_{in}} = \left| \frac{U_{out}}{U_{in}} e^{j\omega t + \phi(\omega)} \right| = \left| TF(\omega) e^{j\phi(\omega)} \right|, \]

where \( |TF(\omega)| \), \( \phi(\omega) \) denote respectively – the amplitude ratio and the phase difference between output and input signals for a given frequency.

Figure 2. Example of a sinusoidal steady state excitation of PZT sensors (a) PZT network; (b) Output voltages acquired on PZT sensors.

Transfer function is invariant with respect to small disturbances of the voltage source used for PZT actuator excitation. In Figure 3 an example of the obtained transmission function is presented. Both components of TF carry the information about mechanical properties of the structure within the sensing range of a given pair of transducers, but can also depend on other factors, e.g. the properties of PZT sensors used or the distance between sensors.

Figure 3 Example of transfer function components: (a) amplitude ratio; (b) phase difference, between output and input signals

The dependence of the transfer function on the signal frequency can be quite complex (Figure 3), therefore its direct application for structure assessment is of limited usability. The state of the structure is usually determined by using signal characteristics, called the Damage Indices (DIs), which are based on comparison of the baseline signal – acquired
for pristine state of the structure with signal obtained for a given structure condition. Denoting as \(|TF_0(\omega)|\) and \(\phi_0(\omega)\) the components of the baseline transfer function \(TF_0(\omega)\), the DIs used in this paper are the following:

\[
DI(\omega) = \frac{TF(\omega)}{TF_0(\omega)} = \frac{|TF(\omega)|}{|TF_0(\omega)|} e^{i(\phi(\omega) - \phi_0(\omega))}
\]  

(3)

It is worth to be noticed, that almost all of the information of the signal is carried by the DIs. Assuming the baseline transfer function and input voltage are known, then the voltage on the receiver can be reconstructed from the DIs. Therefore all damage types having impact on the voltage induced on the receiver, should be detectable by the proposed method.

For structure assessment, it is not necessary to use a single DI calculated at a given frequency. DIs behavior obtained for a range of frequencies can be better suited for damage detection and classification. Figure 4 illustrates an example of DIs behavior obtained for a range of frequencies for undamaged structure and with damage presence. For undamaged structure, the DIs should be concentrated in the vicinity of the point 1+i0 in the complex plane, irrespectively of the frequency of the excitation. If damage is present, it can change the output voltage amplitude or its phase, therefore DIs diverge from the point 1+i0 (Figure 4). In this example all of the frequencies were influenced by a damage. It is possible, that only for limited frequency range there will be response of a signal to a damage. In this case two groups of data would be formed for damaged structure: the DIs obtained for frequencies not sensitive to damage would be close to the point 1+i0, whereas DIs influenced by damage would be separated from it. In this way optimal range of frequencies for the purpose of damage detection could be established.

![Figure 4 Example of DIs obtained for the pristine state of the structure and when a damage is present](image)

Also it is possible that different kind of damage occupy different regions of the complex plane. If it was the case it would be possible to classify damage based in DIs.
behavior, by using statistical data classification methods, like nearest neighbor algorithm or linear discriminant classifier. A necessary condition for those methods to work properly is repeatability of indications under similar conditions. In order to achieve, that DIs should be located at the same region of the complex plane when comparable damage is present near a sensing path.

2.2 Approach implementation

The TI method is direct and easy to implement, an example conception of measurement system based on this method was shown in Figure 5. Excitation of the guided wave in the structure takes place through the PZT piezoelectric transducer integrated with the monitored structure, to which signal from the signal generator and the amplifier unit is applied. The structure response is recorded by another PZT transducer, which acts as a guided wave receiver - a local vibration sensor structure. The electrical signal generated by the sensor is registered using an oscilloscope. The control of the measurement instruments and the acquisition of data is made by control computer operating under application control which algorithm is shown in Figure 6.

![Figure 5 An example conception of measurement system based on EMI method](image)

The application starts working from establishing a connection with the signal generator and the oscilloscope. Then, the input parameters such as voltage, start frequency, frequency step, end frequency, shape of output signal from the generator and the oscilloscope channel ranges are set. The measurements start at generate signal with a given amplitude value and initial frequency causing a extraction of the guided waves. In the next step, the signal is recorded on all channels of the oscilloscope. If the current
frequency of the signal triggered by the signal generator is different from the end frequency set by the user, the current frequency of the signal is incremented by the frequency step declared before. The procedure of excitation of the guided wave and acquisition of the signal is repeated until reaching the final frequency and take measurements in the whole set frequency spectrum.

Figure 6 Example algorithm of the measurement management application
3. Conclusions

In the paper, a method of structure monitoring based on PZT sensors was proposed. It is based on the so called Electromechanical Impedance approach to SHM. For the purpose of structure monitoring a bundle of Damage Indices was defined, from which almost entire information about raw signals can be reconstructed. That property manifests the robustness of the proposed approach, in the sense that if a damage is detectable by a given PZT network, it should be revealed by the proposed DIs. A possible method of the proposed approach implementation was also delivered.

References