PROPOSAL OF A SOLID STATE SWITCHING AND SIGNAL CONDITIONING SYSTEM FOR STRUCTURAL HEALTH MONITORING BASED ON PIEZOELECTRIC SENSORS/ACTUATORS

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Abstract. The Structural Health Monitoring – SHM method based on electrical impedance has been developed as a promising tool for structure failure identification in real time and is considered a novel non-destructive evaluation method. The piezoelectric - PZT impedance can be directly associated to the structure’s mechanical impedance where de PZT is bonded. Assuming that the mechanical PZT properties do not change over the monitoring time, the electrical PZT impedance can be used for monitoring structural health. The use of each PZT as both sensor and actuator reduces the total number of sensor and wires connecting them to the switching circuit. The technique consists in obtaining Frequency Response Functions - FRF, with the related signal modification, periodically. Modifications in the FRF of each PZT would indicate structural changes and, therefore, a possible failure. The required number of PZTs will be determined by the dimensions of the monitored structure and the precision required for locating a possible failure. To obtain the FRF of the entire monitored structure it is used a switching and signal conditioning system that continuously activate and deactivate each PZT. This paper proposes a solid state, low power, small sized and low signal distortion switching system. The system is quite modular and each module can manage 16 PZTs. It is possible to expand the sensing net by interconnecting a non limited number of modules. Descriptions of the working principles, circuits used and experimental results are presented.

Keywords: Structural Health Monitoring, PZT, Piezoceramic material, Switching System.

1. INTRODUCTION

The development of a real-time in-service structural health monitoring and damage detection technique has attracted a large number of academic and industrial researchers. The main goal is to monitor the structure integrity while still in operation and during its working life. The reduction of maintenance costs by minimizing explicit preemptory maintenance and prevention of catastrophic failures are expected.

Nondestructive methods (NDE) are used in cases where the monitored structure is still in service. Sun et al. (1995) proposed a NDE method based on the electromechanical coupling property of piezoceramic materials. Basically, the method identifies damage by monitoring the structure mechanical impedance that will present variations in the presence of structural damage. Since the structure mechanical impedance is difficult to obtain, a PZT patch bonded to the monitored structure can be used as a sensor-actuator device. The electric impedance of the PZT is directly related to the mechanical impedance of the host structure (Park, G. and Inman, D.J., 2001). Figure 1 shows a one-dimensional model representation of an mechanical system containing an integrated sensor-actuator piezoelectric patch (Raju, 1997).

![Figure 1. One-dimensional electro-mechanical coupling model.](image-url)

The solution of the wave equation for the PZT patch connected to the structure leads to Eq. (1), for a frequency-dependent electrical admittance (Liang et al. 1994):

$$Y(\omega) = i\omega \alpha \frac{\varepsilon_{33}}{Z_s(\omega) + Z_0(\omega)} d_{3x}^2 \frac{\varepsilon_{33}^\prime}{Z_s(\omega) + Z_0(\omega)}$$

(1)

In Eq. (1), $Y$ is the electrical admittance (inverse of electrical impedance), $Z_s$ and $Z_0$ are the PZT material and the structure mechanical impedances, respectively, $Y_{\text{Young}}^\alpha$ is the complex Young’s modulus of the PZT with zero electric field, $d_{3x}$ is the piezoelectric coupling constant in the arbitrary $x$ direction at zero stress, $\varepsilon_{33}^\prime$ is the dielectric constant at zero
stress, $\delta$ is the dielectric loss tangent of the piezoelectric patch, and $a$ is a geometric constant of the PZT. This equation indicates that the electrical impedance of the PZT bonded onto the structure is directly related to the mechanical impedance of the host structure. The variation in the PZT electrical impedance over a range of frequencies is analogous to that of the frequency response function (FRF) of a structure, which contains vital information regarding the health of the structure.

Damage causes direct changes in the structural stiffness and/or damping and alters the local dynamic characteristics of the system. In other words, the mechanical impedance is modified by structural damage. Since all other PZT properties remain constant, it is $Z_s$, the external structure impedance that uniquely determines the overall admittance. Therefore, any change in the electrical impedance signature is considered as an indication of a change in the structural integrity.

Through monitoring the measured electrical impedance and comparing it to a baseline measurement, one can qualitatively determine that structural damage has occurred or is imminent to occur. The sensitivity of the NDE technique in detecting damage is closely related to the frequency band selected in the excitation signal of the PZT. Usually, the PZT is excited with a sinusoidal waveform (1 volt) at frequencies varying from 30 kHz to 250 kHz (Stokes and Cloud, 1993) and (Raju, 1997). The specific range for a given structure can be determined by a trial and error method (Sun, et al., 1995).

Structural Health Monitoring (SHM) could play a considerable role in maintaining safety of “in-service structures”. The development of an integrated sensory system able to monitor, collect, and deliver the structural health information is of major importance. One of the proposed approaches is to utilize arrays of PZT patches attached to the surface of a metallic structure or embedded in a composite material. When attached to the structure and connected to the electronics, these PZT patches become active sensors that can act as both actuators and sensors of elastic waves in the structure. The high-frequency response is not affected by the global structural modes and environmental conditions such as ambient vibrations (Giurgiutiu and Zagrai, 2005). Thus, the impedance method allows monitoring incipient local damage, like cracks, which produces only imperceptible and hardly noticeable changes to the large-scale dynamics of the entire structure. For this reason, the high-frequency impedance method can detect localized small damage that is otherwise undetectable with conventional vibration testing.

Each FRF, obtained from each PZT, must be processed to better locate and identify possible damage in the structure. A Fast Fourier Transform (FRF) is used to process the resulting FRF and to obtain the PZT impedance. While the impedance response plots provide a qualitative approach for damage identification, the quantitative assessment of damage is traditionally made by using a scalar damage metric, Eq. (2). In an earlier work (Sun et al., 1995), a simple statistical algorithm, which is based on frequency-by-frequency comparisons, referred to as ‘Root Mean Square Deviation’ (RMSD), is used to quantify damage. $M$ represents the damage metric, $Z_{i,1}$ is the impedance of the PZT measured under healthy conditions and $Z_{i,t}$ is the impedance for the comparison with the baseline measurement at frequency interval $t$.

$$M = \sum_{i=1}^{15} \left[ \frac{|\text{Re}(Z_{i,1}) - \text{Re}(Z_{i,t})|^2}{|\text{Re}(Z_{i,1})|^2} \right]$$

Eq. (2)

Temperature changes, among all other ambient conditions, significantly affect the electric impedance signatures measured by a PZT. Only the imaginary part of this impedance is very dependent of temperature changes. (Park et al. 1999) use a modified RMSD metric, which compensates for horizontal and vertical shifts of the impedance in order to minimize the impedance signature drifts caused by the temperature or normal variations. Other possibility is to discard the imaginary part of the PZT impedance and work only with the real part.

Experimental implementation of the impedance-based structural health monitoring technique has been successfully conducted on several complex structures: a four bay space truss (Sun et al. 1995), an aircraft structure (Chaudhry et al. 1995), complex precision parts (Lalande et al. 1996), temperature varying applications (Park et al. 1999), a spot-welded structural joints (Giurgiutiu et al. 1999), civil structural components (Park et al., 2000), a reinforced concrete bridge (Soh et al. 2000) and civil pipelines (Park et al. 2001a).

2. TRADITIONAL IMPEDANCE BASED SHM SYSTEMS

A typical impedance-based SHM system is illustrated in Fig. 2. A total of $N$ PZTs are bonded onto the monitored structure where each PZT patch is connected to a Switching and Signal Conditioning System (SSCS) that will control their activation/deactivation. There are only $N+1$ wires connecting the PZTs and the SSCS since all of them have the same reference. The activation sequence of the PZT array is determined by an external Digital Control (DC), which is working synchronized with a Digital Signal Analyzer (DSA) or a Computer with an incorporated Digital Acquisition System (DAQ). Each digital word from the DC, or a DAQ, activates only one specific PZT at a time and its response is sent to the DSA. The DSA may be either a computer with a data acquisition system or a dedicated equipment, such as the HP 4194 Impedance Analyzer that is able to control the SSCS and to store the FRFs of the structure for each PZT patch.

The SSCS can be implemented in many ways. Figures 3a and 3b present two possible implementations, which differ from each other on how the PZT are referenced to the electrical ground. Fig. 3a shows that the PZT patches are not connected to the circuit ground reference, which is done by the shunt resistor. The shunt resistor provides a sample of the PZT response in the form of its internal current. The conditioning circuit, implemented by the High Speed Precision Amplifier (HSPA), provides a conditioned sample of the PZT current by using a single operational amplifier. In Fig. 3b it is
possible to see that one end of each PZT is connected to the circuit ground reference. In this configuration it is necessary to use a High Speed Differential Precision Amplifier (HSDPA).

![Figure 2. Typical SHM system based on monitoring the electro-mechanical impedance, for many PZT patches.](image1)

![Figure 3. Block diagrams of two possible topologies for the SSCS. (3a) PZT floating ground reference configuration. (3b) PZT grounded reference configuration.](image2)

Some more operational characteristics can be outlined for both the topologies shown above:

- For both topologies, the DSA shall use FFT to analyze and calculate the PZT electrical impedance. Since only the real part of this impedance provides results invariant with temperature changes, the sampling rate of the DSA must be, at least, a hundred times higher than the excitation signal applied to the PZT. This will minimize harmonic and phase distortions sampled from the response signal and, therefore, errors on calculating the real part of the electrical PZT impedance.

- The excitation signal is pre-conditioned using a High Speed Voltage Follower (HSVF), which must present high input impedance, low total harmonic distortion and low output impedance, thus guaranteeing that the PZT response will not be affected by any limitations from the excitation source.

- An array of $N$ controlled switches is used to activate/deactivate each PZT patch at a time. It is very important that these switches do not add any distortions, in phase and amplitude, to the excitation signal. It is quite common to use “reed relays” to implement each switch, even at the expense of increased power consumption and slow operation speed.

- The digital word received from the digital control is decoded by a demultiplexer circuit. This circuit will decode the $x$ input bits into $2^x$ lines where each one will activate a switch in the array. It is quite common to use TTL or CMOS logic circuits to implement the demultiplexer.

DSA able to use FFT with sampling rates of tens of MSamples/s are quite expensive. In this paper a variation on topologies presented at Fig. 3, which does not requires a DSA with FFT and high sampling rate capabilities, is presented. The proposed hardware is described as follows.

### 3. THE PROPOSED SWITCHING AND SIGNAL CONDITIONING SYSTEM (SSCS)

To avoid the use of FFTs to analyze the response signal, the proposed SSCS works directly with phase vectors. A phase vector, or simply *phasor*, is a representation of a sine wave whose amplitude ($A$) and phase ($\theta$) are time-invariant at a given frequency ($\omega$). Figure 4.a illustrates how excitation and response can be expressed as *phasors*.

![Figure 4. Phasor representations at a given frequency: (4a) Excitation and response; (4b) Excitation and response with errors due to low sampling rate; (4c) PZT impedance representation (modulus and real part).](image3)
Each time a FFT is used on a DSA it generates a vector of phasors which describes the FRF of a monitored PZT. With both phasors the DSA can calculate the real part of the PZT impedance in the form presented at Fig. 4c. For that, a low distortion signal must be sampled at high sampling rates. Low sampling rates will generate phase and amplitude errors in each calculated phasor, as it can be seen in Fig. 4b.

The proposed SSCS can directly measure each phasor response at a given excitation frequency. In this way, there is no need to use neither a FFT capable DSA nor high sampling rates (only a few kSamples/s). Three more functional blocks are added to the original topology seen in Fig 3b, as it can be seen in Fig. 5.

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The Phase Detector Block is responsible to measure $\theta$. This block is implemented using two High Precision Digital Counters (HPDC) and two Zero Crossing Detectors (ZCD). If the DSA is a Digital Signal Processor (DSP) the HPDC is present as a DSP peripheral needing only the sync pulses provided by the ZCD. The new Response Block is implemented with a High Precision Full Way Rectifier (HPFWR) and a simple low pass filter to obtain the mean value of the response signal. The returned response will be the mean value of the PZT current.

The amplitude response represents the mean value of the PZT current and it is calculated accordingly Eq. (3) where $V_{\text{res}}$ is the phasor amplitude response provided by the SSCS and $K_{\text{HSDPA}}$ is the gain applied by the HSDPA. In Eq. (4), the impedance of the $n$-th PZT at the $i$-th applied excitation frequency is calculated. The real part of this complex impedance is obtained from Eq. (5).

\[
I_{\text{res}n_i} = \frac{V_{\text{res}n_i}}{0.635 \cdot R_{\text{shunt}} \cdot K_{\text{HSDPA}}} \tag{3}
\]

\[
Z_{n_i} = \frac{V_{\text{ex}} \cdot \theta_{i}}{I_{\text{res}n_i} \cdot \theta_{\text{res}n_i}} \tag{4}
\]

\[
Z_{\text{res}n_i} = Z_{n_i} \cdot \cos(\theta_{\text{res}n_i}) \tag{5}
\]

A prototype has been built in order to evaluate the proposed system and the results are presented at next section.

4. EXPERIMENTAL RESULTS

To evaluate the proposed SHM system, experimental tests were performed using the aircraft panel presented in Fig. 7a. Due to the size and complexity of the structure (0.8m x 0.8m) six PZT patches were used in the experiment. The positioning of the PZT patches was arbitrary (the position of the PZT patches was not optimized).

The experiment was conducted according to the following steps:

1 - Acquisition of FRFs for each PZT patch. These FRFs, called here as baselines, will represent the undamaged structure. A frequency ranging from 35 kHz to 45 kHz was arbitrarily chosen to be applied to all PZT patches.

2 - The rivet outlined in Fig. 7b was extracted and additional FRFs were obtained from each PZT patch. These new FRFs and the baseline are applied to Eq. (2) to quantify the damage. Not all the PZT patches detect the damage properly.

Ten measurements, for each PZT patch were taken for each case. A Matlab boxplot was used to quantify deviations on each group of measurements. On each boxplot, the central mark is the median, the edges of the box are the 25th and 75th
percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually.

Figure 8 presents the FRFs for each situation considered. Only the PZT patches numbered as 3, 4 and 5 detected the inserted damage and Fig. 9 presents their corresponding damage metrics.

![Figure 7. Aircraft panel used in the experiment: (7a) The structure with PZT patches; (7b) The SSCS connected to the monitored structure; (7c) Detail of the rivet that will be extracted to simulate a damage.](image)

![Figure 8. Impedance signatures for PZTs 3, 4 and 5.](image)

![Figure 9. RMSD metrics for PZTs 3, 4 and 5.](image)

The RMSD values for PZTs 1, 2 and 6 do not suggest the identification of damage due to the low difference between their values. A perceptual tolerance, of about 5%, shall be used to avoid false damage detection (false positive identification) due to electrical noise or incipient structural changes.

5. CONCLUSIONS

This paper presented the architecture of a Switching and Signal Conditioning System that is proposed to be used in SHM applications. The use of phasors made the proposed hardware simpler, not requiring FFT capable DSA or high sampling rates. It warrants an investment of less than $500, using a DSP microcontroller as DSA, which is much less than the hardware proposed by Bahalla et al. (2009), i.e., $2500.

A prototype was built and tested directly in an aircraft structure to validate its working principle, thus simulating real operational conditions. The results demonstrated the effectiveness of the system to detect a typical damage found in an aircraft panel.
6. ACKNOWLEDGEMENTS

The authors are thankful to FAPEMIG and CNPq (research agencies in Brazil) for providing financial support to this work through Proc. Nb. 574001/2008-5 - (INCT-EIE).

7. REFERENCES


8. RESPONSIBILITY NOTICE

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