Application of High-frequency EMI on Shell SHM with Diverse Radians

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Abstract. Exploring the application of electric-mechanical impedance (EMI) on structural health monitoring (SHM) of diverse systems or structures, especially the radian shell is very necessary to achieve the rapid online monitoring of structural damage. This paper studies the application of EMI on damage detection of shell structure with different radians. Using the piezoelectric equations of piezo-material lead zirconate titanate (PZT), the admittance values of aluminum shell before and after structural damage were got in a given frequency domain. Then by designing experiments based on Agilent 4294A instrument and analyzing the changes of admittance-frequency spectra before and after damage, it concluded the corresponding relationship between the sensitive detection frequency and the radian of the aluminum plate under given thickness; on the meantime, it is found that the damage index (DI) - root mean square deviation (RMSD) can be a judgment standard of damage by analyzing the data of special frequency band, which will has strong guiding significance for the selection of damage detection frequency and damage judging in arc structure hereafter.

1. Introduction
In view of the high requirements of the X-ray testing, magnetic particle testing, ultrasonic C-scan and other experimental methods on the operator, and the complexity of processing results, the EMI-based damage detection technology is used to detect structural changes in recent years [1]. In EMI there are many characteristics [2] such as damage sensitivity, large linear range, strong resistance to far-field damage. At the same time, the piezoelectric wafers used obtains the characteristics of light weight, high cost performance, and being online, which is very suitable for non-destructive testing (NDT) of military equipment like rockets, missiles, spaceships, and dunkers, and civil infrastructures like bridges, wind driven generator, oil and gas pipelines. Furthermore, the method adopted in this study is quite appropriate for other structural systems meeting the requirements of cylindrical wall and requiring real-time detection of various types of damages. Study about effect of curved surface structure i.e. shell with diverse radians on EMI signals is as significant as research on effect of plate thickness and density, which is the base of damage identification based on high-frequency EMI method.

Nowadays, there are many researches on the machine learning (ML) of the impedance curve, for example processing EMI signal with various artificial neural networks (ANNs) [3]. It is possible to input all the signals into the neural network for the classification learning of the structural characteristics and damage parameters, and also to extract only few signal features for classification identification and clustering analysis. However, one of the problems of ML is that a large amount of data are needed to train and validate the model, which is difficult to be realized in many situations and make ML not easy to apply as a traditional statistical index.
2. Health detection principle of structural damage based on EMI

The EMI method for SHM and NDT is a new technique for detecting structural local damage using global-based vibration. The basic principle is [4]: ① the piezoelectric wafer is attached onto the shell to be tested, and the mechanical impedance of the shell will change when a certain damage occurs; ② however, the mechanical impedance is difficult to be obtained by direct testing, so the electro-mechanical coupling effect of the piezoelectric material is utilized subtly; ③ when an alternating electric field is applied to the piezoelectric wafer bonded to the shell, the piezoelectric material generates mechanical vibration due to the inverse piezoelectric effect as shown in Equation 1, and meanwhile the main structure also starts to vibrate together; ④ then the mechanical vibration of the shell is transmitted to the piezoelectric material, and the piezoelectric wafer generates an electrical response through the positive piezoelectric effect shown in Equation (1) of Reference [5], which is expressed as a change of electrical impedance/admittance (reciprocal of electrical impedance).

The change of the electrical impedance tested by the piezoelectric material includes the information of the structural state. By comparison of the impedance spectra before and after damage, i.e. via comparing the impedance curve measured at any time with the baseline one, the development of internal initial damage and occurrence of new damage can be determined, so it is efficient to conduct health monitoring and damage diagnosis of the shell structure.

Impedance/Admittance is an intrinsic property of a structure. When the state is constant, its value is constant and closely related to damage. Therefore, the admittance of the structure is usually detected to recognize the occurrence of damage. The piezoelectric constitutive equation of the piezoelectric wafer (Equation (1) in Reference [5]) is extended to two dimensions, and meantime the current density along the thickness direction of piezoelectric sensor is obtained. Then the current is obtained by integral of current density in the PZT surface, and correspondingly the electric admittance calculation expression (Equation (1) in Reference [6]) is obtained by using the current-voltage relationship.

3. Experiment

3.1. System design

The schematic diagram of the experimental principle is shown in Figure 1. The piezoelectric wafer is attached onto the outside surface of the shell by super glue and connected to the Agilent impedance analyzer to sense the structural state change by insulated cable. The Agilent 4294A is used to measure the structural admittance curves respectively before and after damage within the test frequency range (40 Hz ~ 110 MHz) covered by it, and the data is transmitted to the computer through the general purpose interface bus (GPIB) or network cable. The precise impedance analyzer Agilent 4294A is a comprehensive test instrument for high-efficiency impedance measurement and analysis of components and circuits. With automatic balanced bridge technology, the basic impedance accuracy is ±0.08%. It has excellent accuracy of high quality factor (Q) / low loss factor (D) for analysis of low loss components, and a wide range of signal levels allows accurate evaluation of the device under real operating conditions.

![Figure 1. The principle of structure.](image)

The measurement conditions were controlled in a laboratory environment of 18 degrees Celsius and a humidity of 35%, and the vibration around the measurement was eliminated. The piezoelectric piece used is of the PZT-5A type, both as a driver and as a receiver. The experimental specimens were
selected from four shells with radius \( a=300 \text{mm} \), height \( b=500 \text{mm} \), thickness \( c=5 \text{mm} \) and radian \( \alpha=\pi/4, \pi/3, 5\pi/12, \pi/2 \) respectively. The schematic and physical diagram are shown in Figure 2(a) and 2(b), in which all the curved plates are of the same model, same batch, and processed by the same processing technology. The specifications of the piezoelectric wafers are PZT-5A with dimensions of 20 mm \( \times \) 12 mm \( \times \) 1 mm. The specific performance parameters of the test piece, the piezoelectric wafer and the adhesive layer are shown in Tables 1 ~ 3 of Reference [5].

3.2. Admittance analysis of test pieces before and after damage

The Agilent 4294A’s measurement range is set at 10 kHz \( \sim \) 700 kHz with 200 same intervals, i.e. the step frequency is 3.45 kHz. During the experiment, each operating condition is measured at least twice, and the measured curves are averaged to eliminate the accidental factor before plotting. Previous studies have shown that the real part of the admittance of the piezoelectric wafer can reflect the structural damage well, and its imaginary part is not sensitive to the damage, so the abscissa is the measurement frequency domain and the ordinate is conductance, the real part of the admittance, which unit is Siemen. The corresponding results are shown below:

![Figure 3. Real part of admittance spectrum of 45° and 60° shell.](image)

![Figure 4. Real part of admittance spectrum of 45° and 75° shell.](image)
Figure 5. Real part of admittance spectrum of $45^\circ$ and $90^\circ$ shell.

As can be seen from the above figure, the shape of the admittance spectrum is roughly the same for the curved plate, only slightly deviated at the peak, and can be completely distinguished by the frequency corresponding to the maximum conductance peak in the range of $110\text{kHz} \sim 180\text{kHz}$. The later the peak position is, the bigger radian there is for the curved plate. Meantime, the differences also reflect that a little PZT can be sensitive to the area with sizes $471\text{mm} \times 500\text{mm}$.

Figure 6. Layout of PZT and hole.

Damage is artificially manufactured in each shell structure with a small through hole of 3 mm in diameter, and then PZTs are arranged at the center and a corner of the outer surface of the shells to analyze the influence of different radians on the damage. The arrangement position and arrangement form are the same, as well as the damage position of the piezoelectric piece. The hole position is shown in Figure 6. Then select 800 measurement frequency points, that is, the maximum number of points to achieve the highest accuracy in the same frequency domain.

As seen in the above figures, in addition to the clearly visible resonance points, there are many small peaks, which are caused by the rough boundary resulted from processing. Many minor vibrations occurred due to the extremely uneven surface, but the roughness of the shell surface differs by an order of magnitude with respect to the degree of damage, therefore it does not affect the damage detection of the structure to a large extent. In addition, some slightly higher peaks are mainly due to the possible asymmetry of PZT during bonding, and these peaks are called asymmetric harmonic responses. The central and marginal PZTs were used to measure the change of the admittance spectrum before and after the damage as follows:
Figure 7. Real part of admittance spectrum tested by central PZT.

Figure 8. Real part of admittance spectrum tested by PZT on the corner.

As can be seen from Figure 7 and Figure 8 above, there are three distinct peak groups in the range of 10 kHz ~ 700 kHz all the time. By comparing the conductance curves before and after damage, it can be seen that the admittance spectra in each figure are roughly similar, and only small differences appeared in peak position, indicating the consistence and effectiveness. For the four kinds of arc plates, each plate uses two piezoelectric wafers to measure the admittance spectrum before and after the damage. When measured with the central PZT, the changes before and after the damage at the first two peak groups are obvious and when the corner PZT is used, it changes only at the first peak group. At the same time, it can be seen that the highest peak in Figure 7 is slightly higher than the highest peak of Figure 8, which is because that the farther the PZT is from the location of the damage, the more energy is consumed. When the shell radian is 90°, the central piezoelectric piece is only about 350 mm away from the hole, which is much smaller than the distance of 500 mm from the hole on the corner.

Statistical analysis is performed on all points of the admittance spectrum based on RMSD [7]. It can be seen from Figure 9 that the statistical measurement standard of RMSD is very effective in the damage detection of the shell structure, in which all the DI values observed more than 0.2 indicate that the structural state has changed greatly. After all the points are analysed in the frequency domain, the effect is obvious, and it can be used as a criterion for damage of the shell structure, especially in a sensitive frequency domain. At the same time, it can be seen that DI is larger when measured by the central piezoelectric sheet, mainly because the distance between the central PZT and the damage is closer, although the sensitivity range of the piezoelectric wafer can reach two meters.
4. Conclusions

The damage detection method based on the EMI method is effective for detecting the small hole damage appearing in the shell structure, and can clearly distinguish the damage existence by the electric admittance spectra at normal and damaged states. At the same time, by carefully comparing the above figures, the following conclusions can be drawn:

(1) When non-destructive, the increase of the radian of the shell structure will cause some harmonic frequency points to move towards the right, with the amplitude change not large;
(2) The trend of the admittance curves before and after the damage is about the same, only the difference occurs at the peak group;
(3) The real part of the admittance changes correspondingly after damage, which is mainly due to that the transmission of vibration energy is influenced;
(4) The measurement results of the PZTs at different positions are different, but the general law of admittance curves from all the PZTs is similar for the curved plates with different arcs, and the position do not affect the detection result of damage at all;
(5) The statistical RMSD of the admittance spectrum can be used as the damage criterion.

For the further research, crack damage close to hole belonging to the structure itself will be studied based on the sensitivity on the minor changes of structural state using high-frequency EMI method, which is incapable for other traditional detection methods.

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