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Structure Health Monitoring with Piezoelectric Sensors and Actuators

(Introduction of research at CIMSS and IWP measurement)

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The Center for Intelligent Material Systems and Structures (CIMSS) was established by Professor Craig A. Rogers as the Smart Materials and Structures Laboratory in 1987. August 1996, Dr. Rogers moved to Dean of the College of Engineering at the University of South Carolina in Columbia, and Dr. Harley Cudney, associate professor of Mechanical Engineering Department at Virginia Tech, was named Interim Director during the search for new director. I came to CIMSS as a visiting professor during the period of this important organizational change. In August 1997, CIMSS moved from the previous location located off-campus to the New Engineering Building on the campus of Virginia Tech. Dr. Daniel Inman, Professor of Engineering Science and Mechanics Department, was selected as the director of CIMSS and Dr. Cudney was appointed the associate director. Now the new CIMSS is continuing on and expanding the research of intelligent material systems and structures in various areas. In this article, I would like to introduce some representative research launched at CIMSS in the area of intelligent material systems and structures, and finally show my recent work to develop a new method of Impedance-Wave Propagation(IWP) measurement for the quantitative non-destructive evaluation of large structures.

1 Recent Research at CIMSS

Damage Detection and Structure Health Monitoring

CIMSS main attention has focused on the problem of damage detection and health monitoring of structures in an attempt to create self-diagnostic systems. These systems would provide structures that periodically perform a self-diagnosis through the use of embedded sensors, actuators and computing in order to provide warning of a structural change while in service.

There are three approaches currently under consideration. The first is the qualitative health monitoring (QHM) with an impedance-based technique. This technique utilizes the direct and the converse electromechanical properties of piezoelectric (PZT) materials, allowing for simultaneous actuation and sensing of the structure response. A small size PZT patch is boned to a structure and the variation in the electrical impedance of PZT is measured while driven over a high-frequency range at low power. Since the mechanical impedance of structures couples to the electrical impedance, the variation in the mechanical impedance caused by the structural damage brings a significant changes in the electromechanical coupling impedance. This technique is available for high-frequency range because the PZT is very sensitive at high-frequency range (typically > 50kHz). At such high-frequencies, the response is dominated by local modes and minor damage like small cracks, loose connections, and corrosion. Thus, it is possible to say with certainty that the change in signature is due to damage in the sensing area and not to a change in far-field boundary conditions, mass loading, etc. The technique has been successfully tested on critical sections of numerous complex structures which will be discussed in detail in the next section.

The second approach assumes absolutely no prior information about the model of the structure, but rather uses the beating phenomena obtained when tow signals of nearly the same frequency are combined. The idea of this approach is that using the beat phenomena magnifies small changes in frequency, thus producing a more sensitive algorithm. A pair of piezoceramics are embedded in a structure one as actuator and the other as sensor and the damage is then evaluated by the comparison of the signal of a healthy structure to that of the structure in its current state.

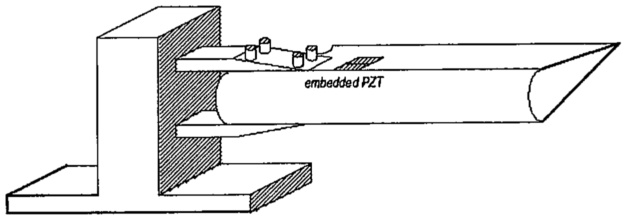

Fig.1 Picture of Monitoring damage in a helicopter.(J. Cattarius et al., 1996)

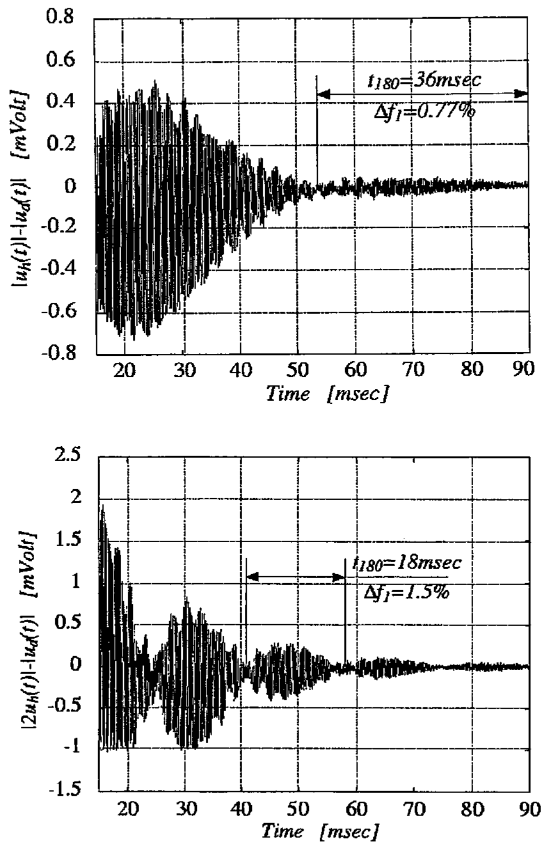

Fig.2. Blade response analysis. $\Delta f = \frac{1}{t_{180}} \frac{1}{2f_i}$, $i = mode$.(J. Cattarius et al., 1996)

As an example, this self-diagnostic method is applied to a helicopter blade section (Fig.1, J. Cattarius et al., 1996). Two piezoceramics were glued on the blade surface, one for excitation and the another for sensing. Further, a concentrated mass of about 0.1% of the total structure's, modeled as damage, was attached to the surface at different locations.

Initially, chirp signals were used to find the resonance frequencies of structure and then several narrowband Schroeder-phased signals were generated as excitation input around each resonant frequency. Figure 2 shows the examples of detected beating phenomena obtained at the two lowest resonance frequencies and demonstrates how both frequencies are affected by the local increase of mass. In the figures, the differences of the time response between the healthy blade (without mass) and the damaged blade (with mass) were plotted and the added mass causes a phase shift of 7.7% at the first lowest frequency, 1250 Hz, and 15% at 1800 Hz. It shows that this method can measure a small frequency change accurately.

The third approach is based on a linear non-conservative model of the structure or machine of interest and focuses on changes in damping. In a preliminary experimental study on how modal properties are effected by the torque of a bolted joint, the results show that the torque is proportional to the damping measured in the structures and indicates that it may be possible to construct a map between the tightness of a bolted joint and the measured damping in a structure. The diagnostic goal of this research is to continuously monitor the damping matrix and to map the damping matrix to the state of the torque of a bolted joint.

Active Damping Treatments

A traditional technique for reducing vibrations in structures is by layering a viscoelastic material onto a troublesome structure and covering it with a thin layer of material to enhance the shear in the viscoelastic material. Recently a piezoceramic layer has been used instead of a viscoelastic one to form a controllable or smart damping treatment, and has created major improvements in performance. However, the mechanics of such systems remains primitive and current models are not applicable in many practical applications. In the practical use, there is often a severe thickness constraint that requires the various treatment layers to be thin. A research project is launched in CIMSS to derive equations of motion for thin-layered systems so that it improves the performance of both active and passive damping treatments.

Particle Tagging for NDE of Composites

Development of active and passive particle tagging techniques for the nondestructive evaluation of nonconductive composites is another area being investigated in CIMSS. In passive tagging, conventional techniques, such as eddy currents, are used to inspect the presence and distribution of particles. In active tagging, the particles are excited by an external alternating magnetic field. The particle tagging techniques have been used in various applications: detection of defects, monitoring the state-of-cure of epoxy matrices, inspection of adhesive bonds, and inspection of damage during manufacturing or service.

Damage-Tolerant SMA Hybrid Composites

Combinations of ultra-tough shape memory alloy (SMA) elements with graphite and glass composite to increase the impact resistance is a continuous research topic in CIMSS. Preliminary results show that with the SMA fibers, impact resistance of the hybrid composite materials was increased and the composite-ply delamination was reduced as much as 25 percent. The goal of this research is a lightweight structural material system that also provides excellent impact resistance. This is accomplished by using a hybrid of the ultra-tough Nitinol and composite materials.

2 Impedance-Based Technique and Impedance-Wave Propagation Measurement

In this section, the basic concept of impedance-based technique is first presented, and then a new approach to the quantitative non-destructive evaluation based on the impedance wave propagation measurement is introduced. This work is currently being investigated by the author and Kabeya(NKK).

2.1 Impedance-Based Technique

Figure 3 shows the concept of the coupled electro-mechanical impedance between a PZT and a one degree of freedom system(Liang et al., 1994). The PZT is considered as a thin bar undergoing axial vibration in response to an applied alternating voltage. One end of the PZT is bonded to the external structure. The frequency-dependent electrical admittance (converse of impedance) can be obtained by solving the wave-equation for the PZT bar connected to the external mechanical point impedance of the structure (Sun et al., 1994):

$$Y = i\omega \frac{W_A l_A}{h_A} \left[\varepsilon_{33}^T (1 - i\delta) - \frac{Z_s(\omega)}{Z_s(\omega) + Z_a(\omega)} d_{3x}^2 Y_{xx}^E \right] \quad (1)$$

where $Z_a$and Z_s are the PZT actuator and the structure mechanical impedance, respectively, Y_{xx}^E is the complex Young's modulus of the PZT at zero electric field, d_{3x} is the piezoelectric coupling constant in the arbitrary x direction at zero stress, ε_{33}^T is the dielectric constant at zero stress, δ is the dielectric loss tangent of the PZT, and w_A, l_A and h_A are the width, length and thickness of the PZT actuator, respectively.

The first term in the above equation is the capacitive admittance of the free PZT giving the base-line gradual change in admittance with frequency. The second term includes the PZT own mechanical impedance as well as the external structure mechanical impedance. When a PZT is bonded to a structure, its own impedance Z_a is fixed, and the changes of the structural impedance Z_s determines the contribution of the second term to the overall impedance. Therefore, the structural impedance modifies the effective electrical impedance of the PZT transducer.

The coupled electromechanical impedance measurement in electrical terms is performed as follows: The impedance analyzer provides a constant alternating voltage signal (1 Vrms), at a selected frequency range typically higher than 50 kHz, to the PZT transducer. The magnitude and phase of the steady state current (after transient behavior has decayed) drawn by the PZT is recorded and converted into real and imaginary impedance. The damage in the structure can be detected by comparing the variation of the obtained electrical impedance of a healthy structure to that of the structure in its current state. The frequency range has to be high enough for the wavelength to be significantly smaller than the defect size.

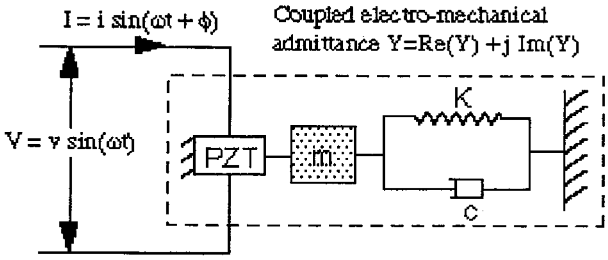

Fig.3 A 1-D model used to represent a PZT-driven dynamic structural system(Ayres et al., 1996).

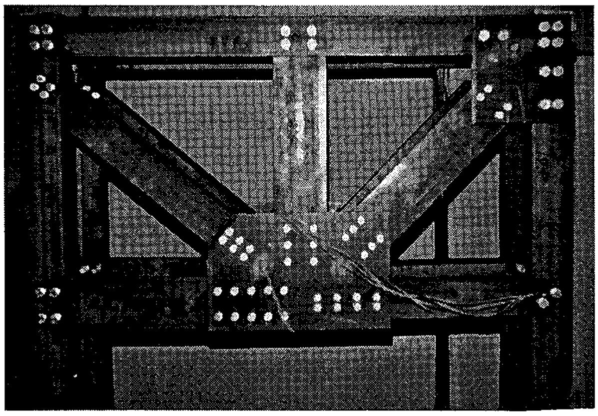

Fig.4 Experimental bridge joint (Ayres et al., 1996).

The impedance-based technique has been applied to a wide variety of structures for detection of cracks, loose connections, corrosion in metallic structures, and the detection of debonds and delaminations in composite structures in the laboratory. Here the detection of loose bolts in a structure is introduced to show how the impedance-based technique works. Figure 4 shows a massive quarter scale model of a steel deck truss bridge joint that experienced in-service failure (Ayres et al., 1996). The size of the model is 72 inches tall, 41 inches wide, and over 12 inches deep (Fig. 4). The entire structure weighs more than 500 pounds and is considered representative of a typical high-strength civil engineering steel structure. Three piezoceramic actuator/sensors were bonded at critical locations on the structure.

Figure 5 shows the experimental results of the real part of the impedance for the healthy structure and the damaged structure in which one local bolt was loosened, and Fig. 6 is the case when 14 local bolts were loosened.

A qualitative estimation of the structural health can be simply obtained by the damage index which is defined as the sum of squared differences of the real admittance changes at each frequency step.

$$M = \sum_{i=1}^{n} [Re(Y_{i1}) - Re(Y_{i0})]^2 \qquad (2)$$

This damage metric is normalized with respect to a reference damage to which all other damage will be compared against. The reference damage will thus have a 100% damage index. A damage index larger than 100% means more structural damage than the reference damage, and a damage index smaller than 100% means less structural damage than

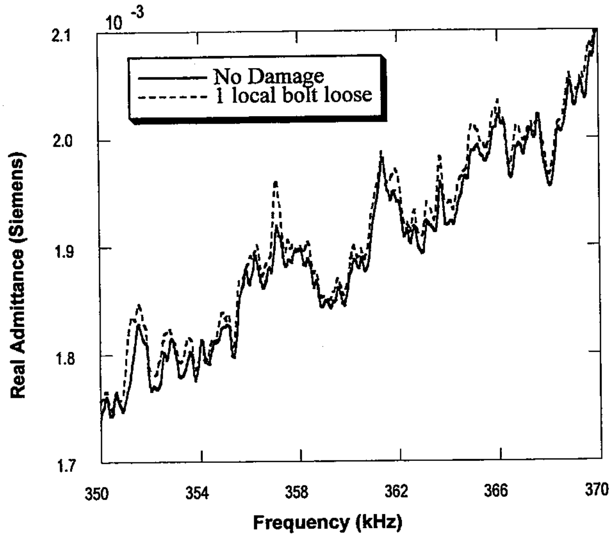

Fig.5 In the one-local-bolt damage tests, the variation in the real admittance shows that the impedance-based method is capable of detecting incipient damage(Ayres et al., 1996).

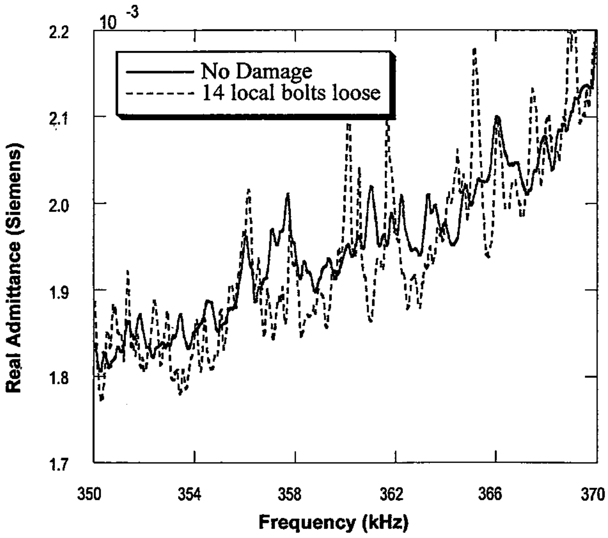

Fig.6 In the fourteen-local-bolt damage tests, the real admittance measurements before and after damage were completely different(Ayres et al., 1996).

the reference damage. Figure 7 shows the results of the damage index for one local loosened bolt, two, six and 14 bolts.

Comparing with the healthy structure response it is clear that the impedance measurement is very sensitive. Actually loosening one of the six bolts constituting the connection between the two structural members does not make a change in the global stiffness of the structure. That means the impedance measurement has the capacity of detecting an incipient-type damage. The results also indicated that the impedance measurement is insensitivity if a distant bolt is loosened.

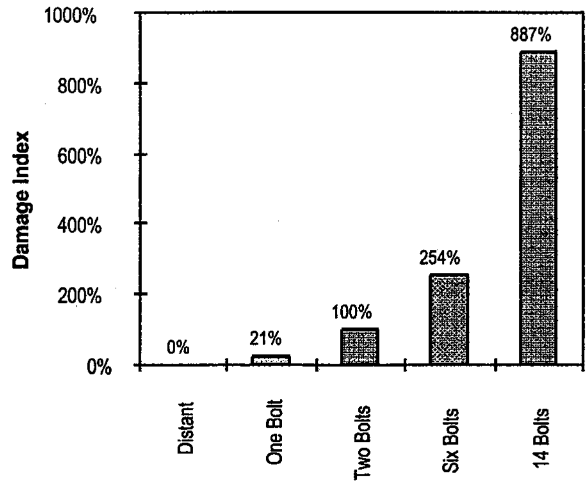

Fig.7 The different tests compared qualitatively against some known amount of damage(Ayres et al., 1996).

2.2 Impedance-Wave Propagation Measurement

As mentioned above, the impedance-based technique is sensitive and it is easy to detect even a small change in structures such as small crack, loose connection and so on, by measuring the change of the structural impedance in frequency domain. However, in the recent technique the damage index can show how much change the structural impedance has, but it is difficult to say where or how the damage occurred. Damage (for example, a loose bolt) may influence a lot of changes in structure properties, from which it is very hard to find out the most contributory factors influencing the damage. On the other hand, the model testing technique has been widely used for the damage detection of structures and it is efficient in low frequency damage detection if the sensing locations are selected suitably. However, it is not sensitive for detecting an incipient type damage such as small cracks and weak stress changes in structures which are considered to be explored in high frequency range.

Considering a certain length of beam without any damage driven longitudinally by an impulse force, a wave will propagate through the beam with the wave lengths related to the velocity and the length of beam. If the beam has a crack somewhere, the wave will be disturbed by the crack so that a reflected wave and the energy consumption will be occurred. It is reasonable to consider the damage is proportional to the energy loss. Further, since the wave velocity is a known quantity the wave frequencies just depend on the length of the beam. This means that it is possible to evaluate a damage quantitatively if the wave propagation can be easily measured . In this article, a new approach to the quantitative non-destructive evaluation based on the impedance wave propagation measurement is proposed and some experimental results are shown in proof of this concept.

Concept of Impedance Wave Propagation Measurement

Considering a one degree of freedom structure of mass m, damping c and stiffness k subjected to an external force $f(t)$, the equation of motion is

$$m\ddot{x} + c\dot{x} + kx = f(t) \tag{3}$$

let $v = \dot{x}$, and further assuming a case of a harmonic steady state excitation, then $x = \dot{x}/\omega i = v/\omega i$. So the above equation can be rewritten in form of

$$m\dot{v} + cv + kv/\omega i = f(t) \tag{4}$$

Applying Fourier Transform to Eq.(4), one has

$$Z(\omega) = \frac{F(\omega)}{V(\omega)} = i\frac{\omega - \omega_n^2}{\omega}m + c; \quad \text{where } \omega_n^2 = k/m \tag{5}$$

$$\mathrm{Re}[Z(\omega)] = c; \quad \mathrm{Im}[Z(\omega)] = \frac{\omega^2 - \omega_n^2}{\omega}m. \tag{6}$$

These equations indicate that the real part of impedance contributes to the structural damping or energy consumption and the imaginary part contributes to the resonance frequencies.

Next consider the one-dimensional wave equation

$$\frac{\partial^2 u}{\partial t^2} = \alpha^2 \frac{\partial^2 u}{\partial x^2} \tag{7}$$

where α is the phase velocity. The steady -state solution of this equation is

$$u = T\,e^{i(kx-\omega t)} + R\,e^{i(-kx+\omega t)} \tag{8}$$

where T is the complex amplitude of the forward propagation transmitted wave and R is the complex amplitude of the rearward propagation reflected wave. k is the wave number which is related to the wavelength λ by $k = 2\pi/\lambda$.

As an example, suppose that a beam of length L is subjected to the steady-state displacement boundary condition at the left boundary,

$$u(0, t) = Ue^{-i\omega t} \tag{9}$$

and the beam is free at the right boundary. Then the steady-state displacement results

$$u = \frac{U \cos[k(x - L)]}{\cos kL} e^{-i\omega t} \tag{10}$$

This solution predicts that the amplitude of the displacement is infinite when $\cos kL = 0$; that is, when $kL = (2n - 1)\pi/2$, where n is an integer. Then the resonance frequencies can be represented by

$$f_n = (2n-1)\alpha/4L; \ \Delta f = f_{n+1} - f_n = \alpha/2L \tag{11}$$

This means the frequencies just depend on the length between two boundaries for a certain material, and the interval of resonance frequencies Δf is constant. If damage occurs in the beam, the propagating wave will be transmitted or reflected at the location of damage with energy consumption. So using wave propagation measurement one can easily find out the location of the damage by seeking the frequencies, and the size or state of damage by calculating the energy consumption or damping effect from the impedance change.

Experimental Results

An aluminum beam was selected to test the impedance wave propagation measurement for damage detection. Figure 8 shows an aluminum test piece in size **450x38.5x3.15 mm**

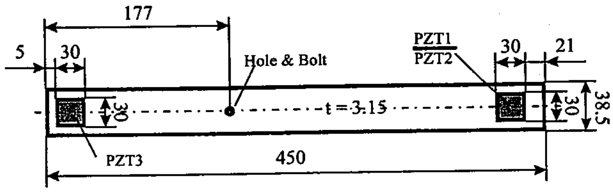

Fig.8 Experimental aluminum beam embedded with three PZTs.

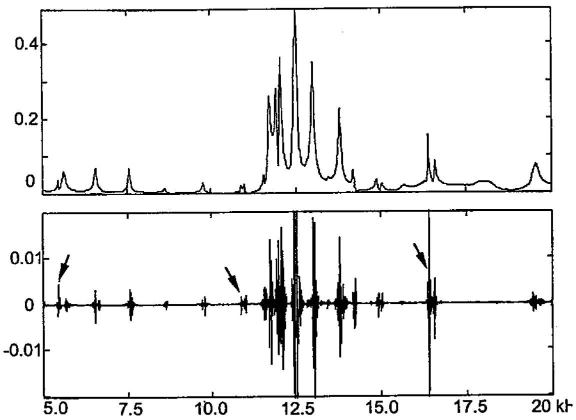

Fig. 9 Frequency response of transfer function for the beam with hole. Upper: gains of transfer function; lower: wavelet analyzed result.

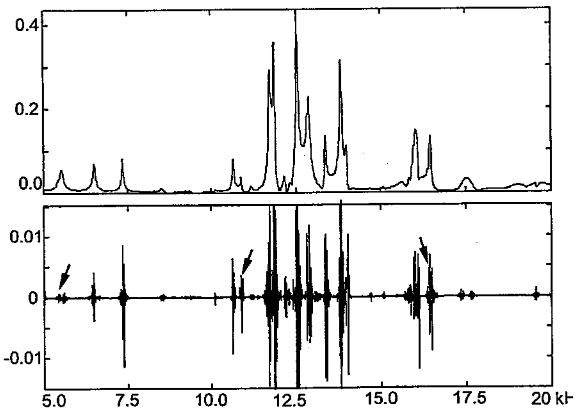

Fig. 10 Frequency response of transfer function for the beam with tightened bolt. Upper: gains of transfer function; lower: wavelet analyzed result.

with a hole and three PZTs. PZT1 and PZT2 are bonded on the opposite surface of beam and actuated by a constant alternating signal (2.5V) at frequency range 5-20 kHz. PZT3 is bonded to the another end of beam used as a sensor. In the experiment two cases have been tested and compared, a beam with a $\phi 5$ mm hole and with a tightened bolt.

Figures 9 and 10 show the transfer functions of input PZT1&2 to output PZT3. Figure 9 is for the beam with hole only and Fig.10 the case with a tightened bolt. Actuators PZT1 and PZT2 were driven in same phase in order to make a longitudinal compressional wave in the beam. Since the properties of PZT1 and PZT2 can not be exactly same and a real structure is also not symmetric, it is very difficult to make a longitudinal compressional wave without oscillating the other motion such as the bending motions. Usually the bending motions in an asymmetric structure is much more significant than the longitudinal wave motions. This means that it is difficult to find out the wave frequency from the bending frequency in practical use. Actually from Figs. 9 and 10 it is easy to know the bending modes and its corresponding frequencies. To seek the wave frequencies from the transfer function response, wavelet analysis is applied and the results are shown beneath each transfer function. The small arrows show the first three fundamental frequencies of wave propagation corresponding to the length of beam, which are 5.43, 10.86 and 16.30 kHz respectively. It is also found that these fundamental frequencies are independent to the damage in the beam, but the coupled motions of wave propagation and bending modes due to the damage show their difference between the beam with only the hole and the tightened bolt. This means the coupled motion frequencies are higher than the fundamental frequencies when the beam has a hole and are lower when a bolt is fixed tightly on the beam. From these frequency changes it is possible to give a rough quantitative estimate where the damage is and what kind of damage will be.

Figure 11 shows the frequency responses of the real part impedance between PZT1&2 and PZT3. Since the frequency limitation of

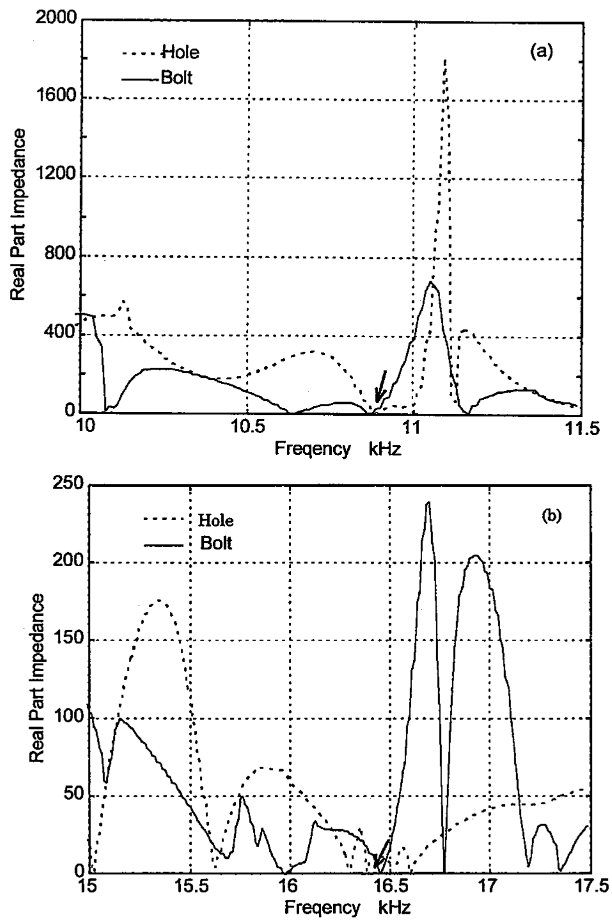

Fig.11 Real part impedance between PZT1&2 and PZT3 for the beam with a hole and a tightened bolt.

the measuring equipment is lower than 20 kHz, two frequency ranges centered at the second and the third fundamental wave frequencies were selected to measure the impedance of the beam with or without the bolt. As mentioned above, the real part impedance can be considered as structural damping or energy consumption. It also means that the higher the impedance is, the more the motion of beam is suspended. Although the signals lower than 20 kHz is not enough to explain the wave propagation properties quite well, it is evident that there are big differences between the beam without the bolt and with the bolt near the wave frequencies. This indicates again that the bending motions are coupled by the wave motions significantly near the wave frequency range, and it will be efficient to evaluate the damage quantitatively by calculating the impedance in the frequency range centered at a certain fundamental wave frequency.

3 Conclusions

Some of the research on structural health monitoring with PZT sensors and actuators was introduced. PZT material has been recently applied to a wide variety of structures and it is the key of the impedance wave propagation measurement for damage detection and structural health monitoring because it is easy in use, very sensitive, can be used both for sensing and actuation, and especially because the output of PZT is proportional to the velocity of strain or displacement. I believe the PZT will play an important role in the structural health monitoring in the near future.

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参考文献：

[1] J. Ayres, F. Lalande, Z. Chaudhry, and C.A. Rogers, 1996, "Qualitative Health Monitoring of a Steel Bridge Structure via Piezoelectric Actuator/Sensor Patches," *Proceedings, SPIE Nondestructive Evaluation Techniques for Aging Infracstructure & Manufacturing*, Scottsdale, AZ, 2-5 December, Vol. 2946, pp. 211-218.

[2] J.Cattarius and D.J.Inman, 1997, "Time Domain Analysis for Damage Detection in Smart Structures", *Mechanical System and Signal Processing*, 11(3), 409-423.

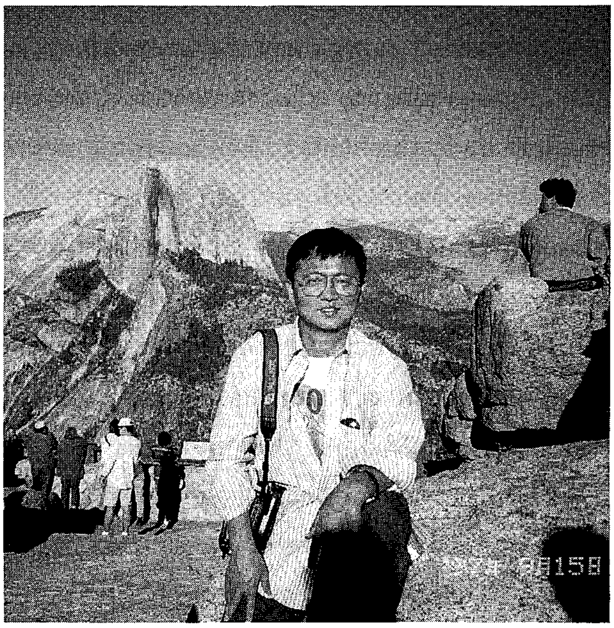
[3] C. Liang, F. P. Sun, and C. A. Rogers, 1993, "An Impedance Method for Dynamic Analysis of Active Material Systems," *Proceedings, AIAA/ASME/ASCE/AHS/ASC 34th Structures, Structural Dynamics, and Materials Conference*, LaJolla, CA, 19-21 April 1993, AIAA, Inc., Washington, DC, pp. 3587-3599.

[4] F.P. Sun, Z. Chaudhry, C. Liang, and C. A. Rogers, 1994, "Truss Structure Integrity Identification Using PZT Sensor-

Actuator," *Proceedings, Second International Conference on Intelligent Materials*, 5-8 June, 1994, Williamsburg, VA, Technomic Publishing Co., Inc., Lancaster, PA, pp. 1210-1222.

[5] V. Giurgiutiu, Z. Chen, F. Lalaneric and C.A.Rogers, 1996,"Passive and Active tagging of Glass-Fiber Polymeric Composites for In-Process and In-Field Non-Destructive Evaluation," *Journal of Intelligent Material Systems and Structures*, Vol.7 , 623-634.

[6] J.S.N.Paine and C.A.Rogers, 1994, "The Response of SMA Hybrid Composite Materials to Low Velocity Impact," *Journal of Intelligent Material Systems and Structures*, Vol.5 , 530-535.



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