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Progress in Lamb Wave Testing and Research Based on PZT

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Abstract. Lamb Wave testing based on PZT has features that are sensitive to plate thickness direction, low cost and suitable for long distance. It has received more and more attention. In this thesis, the principle of Lamb Wave testing method is introduced, research status and image processing technology is summarized, and future work is outlook.

0. Introduction

The safety and reliability in national economy and people's livelihood important equipment or structure may occur debonding, cracking, aging, corrosion and loosing connection on typical structural damage, will cause structure performance decline, safety and reliability reduced, and even lead to significant disastrous accident. Researchers have been exploring for structural damage on-line detection methods. Due to two-dimensional in essence, Lamb Wave can be spread quite a long distance for slowly variation. Therefore, many researchers used it for long distance, especially for rough and rapid detection in large slab structure. Also, it is now widely used to study sheet structure detection because it is sensitive to material change of sheet thickness direction, which is helpful to test the integrity of structure. PZT (Piezo material lead zirconate titanate) can be widely used in material structure and combine with base body material well and it has positive and inverse piezoelectric effect. It can be used for sensing element and driving element in material structure, so it is widely used in Lamb Wave detection.

1. Lamb Wave detection principle based on PZT

1.1 Lamb Wave basic theory

1.1.1 Lamb Wave frequency equation

In infinite sheet, plate thickness of 2b, b is close to order of magnitude in ultrasonic wave phase. Hypothesis the next two interfaces are free, Lamb Wave frequency equation in spread of plate is as follows:

Symmetric mode：
$$\frac{\tan k_{os}b}{\tan k_{ol}b} = -\frac{4k_o^2 k_{ol} k_{os}}{(k_o^2 - k_{os}^2)^2} \quad (1)$$

Antisymmetric mode：
$$\frac{\tan k_{os}b}{\tan k_{ol}b} = -\frac{(k_o^2 - k_{os}^2)^2}{4k_o^2 k_{ol} k_{os}} \quad (2)$$

$$k_{ol}^2 = (\frac{\omega}{c_l})^2 - k_o^2 \quad k_{os}^2 = (\frac{\omega}{c_s})^2 - k_o^2$$

where k_0 is wave number in horizontal direction parallel to plate face， ω is angular frequency, $\omega = 2\pi f$ ， b is half thickness of plate, c_l is longitudinal velocity and c_s is transverse velocity. This is famous Rayleigh--Lamb frequency equation. This equation determines the relationship of Lamb Wave propagation velocity and specific frequency-thickness of plate.

1.1.2 The concept of phase velocity and group velocity

Direction Different vibration modal or vibration frequency of plate wave has different phase velocity in plate thickness, this phenomenon is called dispersion. Lamb Wave dispersion characteristics is depend on frequency equation, phase velocity and group velocity are two main parameters of studying Lamb Wave dispersion phenomenon, this elaborate the concept of phase velocity and group velocity. Lamb Wave is multi-model composite wave, phase velocity is refer to each wave propagation velocity and group velocity is refers to wave packet transmission speed, when Lamb Wave occurs dispersion in material, every wave spread as its own phase velocity, due to the different wave propagation frequency (different wave velocity), same phase of vibration stack up to a maximum amplitude, so same phase vibration velocity is group velocity.

Assume that the frequency of wave respectively ω_1 and ω_2, after superposition the equation is:

$$f(x,t) = A\cos(k_1 x - \omega_1 t) + A\cos(k_2 x - \omega_2 t) \tag{5}$$

k_1, k_2 respectively is wave number, A is amplitude. Use trigonometric identity for deformation:

$$f(x,t) = 2A\cos(\frac{k_1 - k_2}{2}x - \frac{\omega_1 - \omega_2}{2}t)\cos(\frac{k_1 + k_2}{2}x - \frac{\omega_1 + \omega_2}{2}t) \tag{6}$$

$$(k_1 + k_2)/2 = k_c \quad (\omega_1 + \omega_2)/2 = \omega_c$$

$$(k_1 - k_2)/2 = \Delta k \quad (\omega_1 - \omega_2)/2 = \Delta\omega$$

$$f(x,t) = 2A\cos(\Delta kx - \Delta\omega t)\cos(k_c x - \omega_c t) \tag{7}$$

From the formula, two different frequency harmonic superposition synthetic another wave, high frequency carrier spread at frequency ω_c and phase velocity $c_p = \omega_c / k_c$, low frequency modulation wave $\cos(\Delta kx - \Delta\omega t)$ spread at frequency $\Delta\omega$ and group velocity $c_g = \Delta\omega / \Delta k$ in plate. It is slow change amplitude for $2\cos(\Delta kx - \Delta\omega t)$ envelope $\cos(k_c x - \omega_c t)$ to fluctuation, so group velocity is the amplitude of wave velocity with slow change.

1.2 Sensor mechanism of PZT

1.2.1 PZT sensor mechanism based on variable of voltage monitoring

When piezoelectric ceramic is used as sensing element, the applied electric field is zero, then piezoelectric equation can be expressed as:

$$D_{ij} = d_{ij}\sigma_j \quad (i = 1\sim 3, j = 1\sim 6) \tag{8}$$

Piezoelectric ceramic charge output is response of its all directions of strain in polarization direction on the role,

$$Q = \sum d_{ij} E_{PZT} \varepsilon_j S \tag{9}$$

S ——piezoelectric ceramic sensing element of electrode covering area;

E_{PZT} ——piezoelectric ceramic modulus of elasticity;

ε_j ——strain ($j = 1\sim 3$).

Generally ,there is not have vertical external load Using piezoelectric sensors to structure surface monitoring, so the piezoelectric ceramic stress state of arrangement in structure on surface is two-dimensional, we put the piezoelectric ceramic strain response as weighted algebraic sum of lateral strain and axial strain, therefore, piezoelectric ceramic sensor output charge can be expressed as:

$$Q = (d_{31}\varepsilon_1 + d_{32}\varepsilon_2) E_{PZT} S \tag{10}$$

1.2.2 PZT sensor mechanism based on conductivity of conductivity monitoring variable

When using impedance method for structural damage monitoring, the output physical quantity of PZT is conductivity. Piezoelectric drive in impedance method is used as drive and sensing element. Because of direct and inverse piezoelectric effect, when applied electric field to make structure produce incentive, structure would make response to incentive and in turn change current in the piezoelectric drive, thus cause piezoelectric drive electrical impedance change. So change of the piezoelectric drive electrical impedance to reflect structure mechanical impedance.

Electrical conductivity of PZT is:

$$Y=\frac{i\omega S^a}{l^a}\left|(\varepsilon_{33}-d_{32}^2E^a)+\frac{d_{32}^2E^a\tan kl^a}{kl^a}\left|\frac{Z_r}{Z_r+Z_0}\right|\right| \tag{11}$$

d_{32}， E^a and ε_{33} respectively piezoelectric coefficient, elastic modulus and dielectric coefficient ,l^a is length of piezoelectric ceramic chip, S^a is area of piezoelectric ceramic, ω is applied voltage frequency, wave number k is $k^2=\frac{\rho^a\omega^a}{E^a}$, ρ^a is density of piezoelectric ceramic, Z_0 is piezoelectric ceramic chip own impedance, Z_r is structure of mechanical impedance.

From the type, when piezoelectric ceramic chip paste on the outside of main structure, the own impedance of piezoelectric ceramic chip is constant, while the change of external structure impedance Z_r is only factor to influence piezoelectric ceramic chip conductivity. So, the change of structure, such as existence of damage caused by structural impedance change will reflected through the changes of piezoelectric ceramic chip conductivity. In the meantime, when Z_r and Z_0 matched, the entire system will happened resonance and piezoelectric ceramic chip conductivity and displacement tends to be infinite. Therefore, from the conductivity peak of piezoelectric ceramic chip we can extract natural frequency of damage structure, due to existence of structural damage changed the structure modal characteristics, we can identify the location of damage through the change of measured natural frequencies. Impedance method has obvious superiority in near and early detection field.

1.3 Experiment

The experiment consists of two parts: hardware and software. The hardware includes matrix materials, piezoelectric patches, collecting system and various transmission lines; the software includes acquisition system of signal setting, data collection and settings, signal display and data processing parts. Through the collection damage before and after Lamb Wave sign, comparison through time-frequency analyzing, damage can be studied quantitatively and locationally. According to analyzing of all kinds of detected object, through changing piezoelectric element number and position, optimization of excitation sign, to optimize system through HHT analysis mode, damage can be detected better.

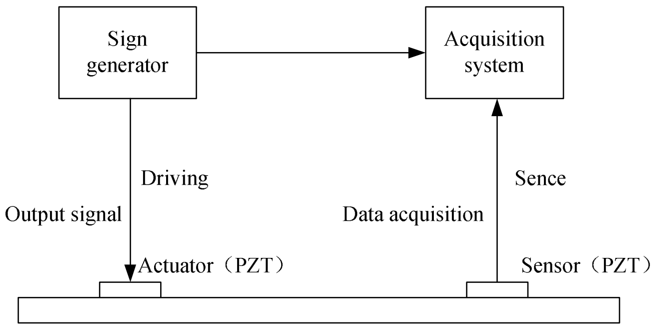

Fig 1. Flow chart of Lamb experiment

2. Research status

2.1 Domestic and foreign research status of Lamb Wave detection

In 1917, in the free state of plate boundary condition, British physicist H.Lamb get a special wave solution in wave equation[1], people called Lamb Wave. Along with development of technical, ultrasonic Lamb Wave detection technology began to apply in quality inspection of composite material in late 1980s. In 1995, United States National Aeronautics and Space Administration (NASA) engineers Saravanos made use of ultrasonic Lamb Wave to test experiments about hierarchical defects of composite material beam structure , for proving Lamb Waves in composite materials in application of theory and experimental[2,3]; American Oak Ridge National Laboratory Stephen w. Kercel, in 1990s, separated the mode Lamb Wave through signal processing methods[4].

Tongji university acoustics institute Haiyan Zhang and Zhenqing Liu studied the dispersion characteristics in sandwich plate structure of ultrasonic Lamb Wave[5]. Jiawei Li, the institute of aviation materials, also widely research the detection of Lamb Wave[6]. Jian Li and Songping Liu, by changing the sound wave incidence Angle, made a excitation of Lamb Wave in aluminum plate of different thickness and did the pattern recognition by using wave velocity method, two-dimensional Fourier transform method and smooth pseudo Wigner-Ville distribution method ,and also analysis testing[7].

2.2 Technology research status of Lamb Wave detection signal processing

At present, the Lamb Wave signal processing methods mainly can be divided into time domain, frequency domain and the time and frequency domain[8]. In 1996, NASA's Chinese American NordenE. Huang firstly put forward a Hilbert Huang transform (HHT), a new signal processing method[9]. It is called a major breakthrough in recent years about on the basis of linear and steady state spectrum analysis of Fourier transform.

HaiKun Wu proved STFT and HHT can effective recognize the Lamb Wave detection signal model, using the HHT method reflect the Lamb Wave signal model time and frequency distribution better[10]; ZhengMin Cao used HHT time-frequency analysis method in detection sign to make a very good reference for engineering application of Lamb Wave detection defect positioning and provides of quantitative analysis[11]; Zhihao Li respectively used short time Fourier transform (STFT) and a Hilbert Huang transform (HHT) methods to make the analysis and processing for experiment acquisition defect response sign and draw a conclusion that HHT is more suitable than STFT for Lamb Wave detection signal processing[12].

3. Outlook

(1)Along with the development of electronic technology and computer technology, Lamb Wave testing instrument and testing methods will develop quick, test method has developed form contact to non-contact, modern nondestructive testing technology will develop along the direction of intelligent automation, visualization, digitization, miniaturization, standardization, multi functionality and the information.

(2)With the development of information processing technology, the advanced method in the field of signal processing would be used more and more, to extract required characteristics fully and accurately, analysis the signal comprehensive and promote and develop Lamb Wave engineering testing technology.

(3)Optimizing and improving on incentive receiving sensor, choosing the most appropriate components and optimized sensor arrangement for Lamb Wave detection, through the method of combining theory with practice, by these the optimal scheme can be get for Lamb Wave detection.

(4)Try Lamb ware with combinations of other detection technologies such as modal analysis technology and EMI technology.

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