Bridge Maintenance, Safety, Management, Health Monitoring and Informatics – Koh & Frangopol (eds)

Internal damage localization in a thick plate using moving sensing windows

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ABSTRACT: In this paper, damage such as internal crack is localized by using bulk waves through plate thickness. Finite element method (FEM) is employed to approximately solve a two dimensional elasto-dynamic problem in which both guided waves and bulk waves propagate for a prescribed traction and displacement boundary conditions of the thick plate. The most sensitive wave modes for internal cracks have been found to be diagonal bulk transversal wave modes. The sensing ranges of surface bonded active sensors are to be limited because bulk waves attenuate as they propagate through the medium. To overcome this limited sensing range of the active sensor, a new moving sensing window concept is developed for internal damage localization. Each sensing window encompasses of a pair of the surface bonded active sensors. The maximum size of sensing window is determined based on the signal-to-noise characteristics of bulk transversal waves. If there exists an internal crack on the effective diagonal wave path in a moving sensing window, the internal crack can be confirmed by measuring the attenuation of diagonal bulk transversal waves due to the internal crack. Considering all damage-confirmed wave paths of moving sensing windows, the location of the internal crack can be identified on a maximum likelihood basis. The validity of the proposed method is demonstrated by localizing an internal crack in 50mm thick plate. . It is shown that the proposed moving sensing window scheme improve the confidence of damage detecting for longitudinally long and thick plate

1 INTRODUCTION

As MEMS technique and IT technology rapidly develop, monitoring technique on infrastructures using high technologies has been adopted in civil engineering. Typical smart sensor, PZT made from ceramic material has a function of actuating and sensing simultaneously according to converting the electronic and mechanical energy mutually.

Researches on applying method of PZT sensor for structural damage detection has been reported. In previous researches, elastic wave excited from PZT sensor applied damage detection on the plate.

In particular, the delicate crack detection technique with Lamb wave assumed that wave propagation through thickness is ignored in a thin plate is proposed in aerospace engineering. But plates used in civil industry are as thick as ones in aerospace industry. Therefore propagation of bulk waves through thickness has to be considered. So conventional detection technique with Lamb wave cannot directly apply to civil. For the understanding of wave propagation characteristics for thick plate, semi-analytic method made a comparative study of analytic solutions from classical elastic wave theory and finite element method is achieved.

2 DAMAGE DETECTION USING BULK TRANSVERSAL WAVES

2.1 *Lamb wave theory*

The formulae for Rayleigh-Lamb frequency of Lamb wave on the 2D plate whose top and bottom are free surfaces derived from Navier Equation.

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2 pq}{(q^2 - k^2)^2} \tag{1}$$

where, $p = \sqrt{\omega^2 / c_L^2 - k^2}$, $q = \sqrt{\omega^2 / c_T^2 - k^2}$. In addition, angular frequency $\omega (= c_p \cdot k)$ is function with respect to unknown phase velocity c_p. H and k are plate thickness and wave number respectively. Eq. (1) has characteristic of transcendental function that various solutions are induced by a frequency. Hence the group velocity of Lamb wave c_g is given as follows.

$$c_g = \frac{d\omega}{dk} = c_p^2 \left[c_p - (fd) \frac{dc_p}{d(fd)} \right]^{-1} \tag{2}$$

The group velocity of Lamb wave is function with respect to the product of frequency and plate thickness(*fd*). Its graph is called as frequency-dispersion curve and is shown as follow.

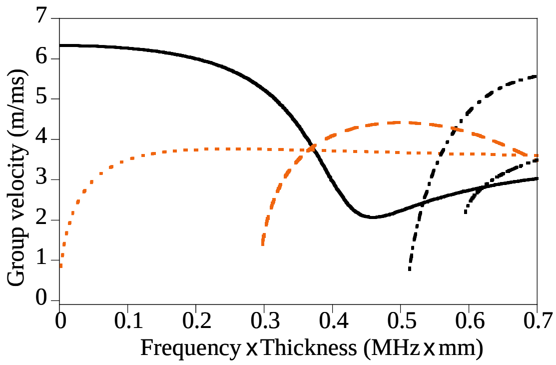

Figure 1. frequency-dispersion curve of Aluminum.

Curves of Figure 1. represent group velocities of symmetry (S) and anti-symmetry (A) modes. In addition, the bigger *fd* is, the more the 1st symmetry mode S_0 and the 1st anti-symmetry mode A_0 converge on velocity of Rayleigh surface waves on the surface of plate and bulk transversal waves. For the planar PZT is applicable to civil, if the effective frequency is 0.5MHz and thickness of typical thick plate is 40mm, group velocities of each modes is nearly converged on the Rayleigh surface waves and bulk transversal waves. Therefore, mode of Lamb wave cannot apply to internal crack detection of thick plate in civil and characteristic of bulk transversal waves in the plate.

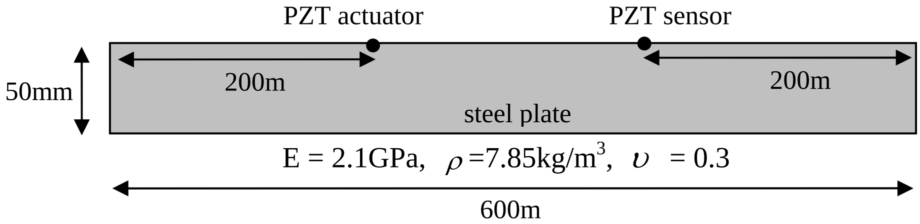

Figure 2. Geometry and material property of the section of steel plate.

For the characteristic recognition of Rayleigh surface waves and bulk transversal waves in the thick plate, FEM analysis is performed for the 50mm steel plate. The incident wave from PZT actuator is tone burst sine wave which has 400kHz frequency and it is excited during 1/2000sec.

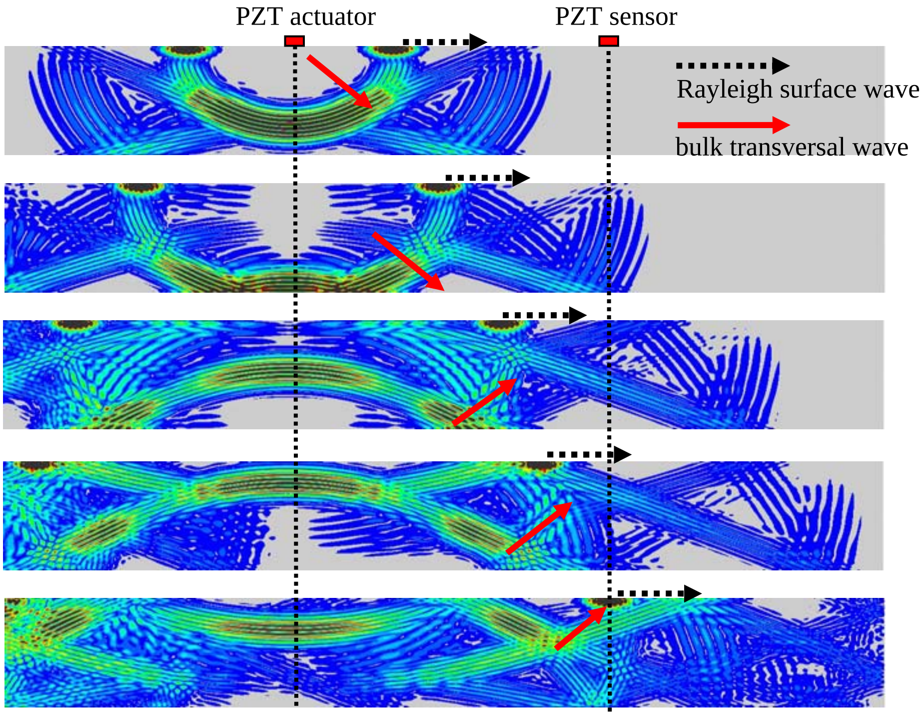

Figure 3. incremental wave path with time for Rayleigh and bulk transversal waves.

In the Figure 3., it is shown Von-Mises stress in the plate by the excitation of PZT actuator and Rayleigh wave and bulk transversal wave are apparent since their energy are large. These waves are distinguishable by using each wave velocities derived from their arrival time and displacement and are verified in comparison with analytic solutions. When the bulk waves are reflected from surface of plate, longitudinal wave and transversal wave cross each other by the mode conversion. Therefore, bulk waves which have various time differences are produced at every reflection. As a result, an increase in wave is a main factor to determine the space of PZT sensors with identification problem of waves and diffusion effect by attenuation in thick plate.

2.2 *Damage detection using bulk transversal wave*

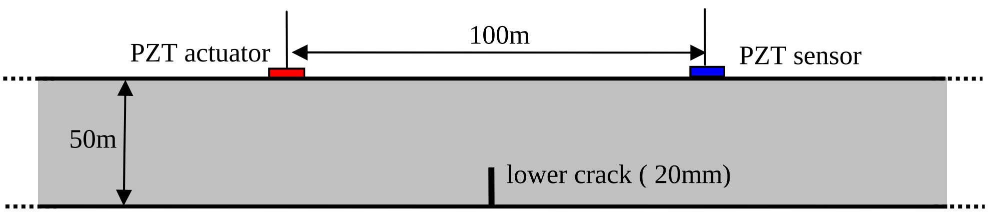

Figure 4. Geometry for damage detection in a thick plate.

This paper presents a damage detection for a thick plate by using a bulk traversal wave. There is a crack from the bottom to the inside of plate in lengths of 20mm. Analysis result is shown as follow.

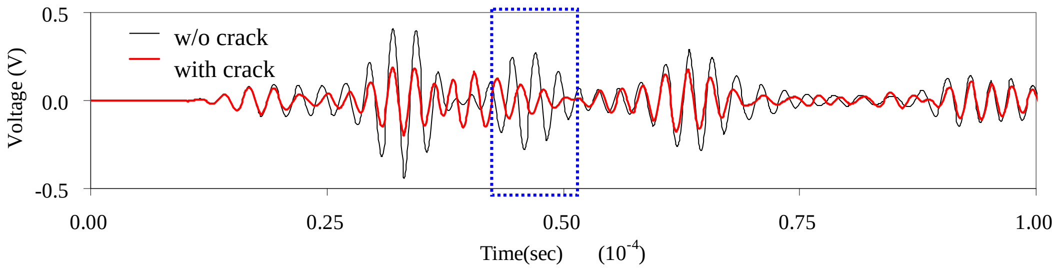

Figure 5. Received signals at PZT sensor with crack and without crack.

The window or box shown in dotted line of Figure 5. marks signal of bulk transversal wave and expresses existence or nonexistence of crack. To determine the extent of the crack, damage index is defined as follow by using the area of signal magnitude.

$$I = 1 - \frac{S_b}{S_a} = 0.63 \quad , \qquad [4.19\times10^{-5} < t < 5.27\times10^{-5}] \tag{3}$$

where, S_a and S_b are area of signal magnitude without crack and with crack, respectively. In other words, damage index I is closer to 1, the possibility of defect is bigger on account of the reduction of received signal magnitude due to reflection of bulk transversal wave on the crack surface. Von-Mises stress allows the observation of reflection effect of bulk transversal wave on the crack surface.

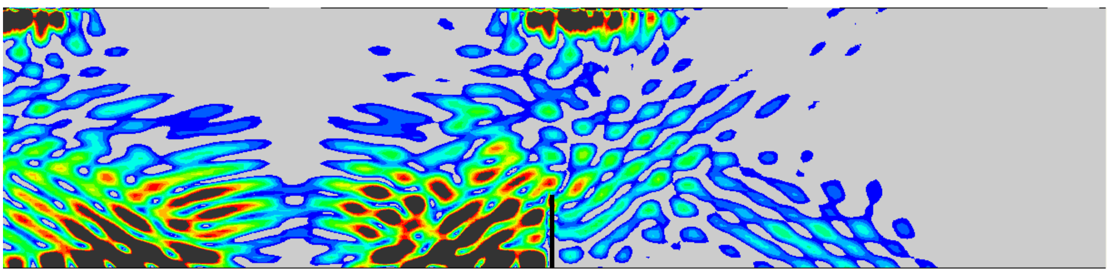

Figure 6. Reflected bulk transversal wave at crack.

3 MOVING SENSING WINDOW

Bulk transversal wave propagated through the inside of thick plate is characterized by attenuation that energy density per unit area diminishes during progress and diffraction on the free surface as crack. Therefore, it is expected that the further space of sensors are away from each other, the lower performance of damage detection would be. To prevent it, Moving Sensing Window which consists of a group of sensors and detects damage with step-by-step process in the longitudinal direction of plate is proposed.

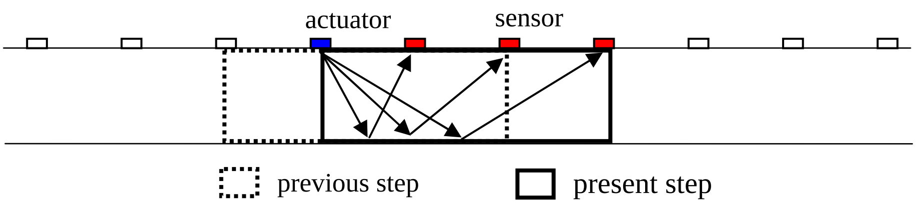

Figure 7. Concept drawing for moving sensing window.

Figure 7. is a conceptual scheme of moving sensing window which consists of 3 blocks, that is, 4 sensors. Bulk transversal wave propagated in diagonal direction from actuator to sensor is used for damage detection. To improve reliability, probabilistic evaluation methodology based on maximum likelihood estimation is introduced.

$$L(\theta) = \binom{n}{\theta} P^{\theta} (1-P)^{n-\theta} \tag{4}$$

where, P and θ are likelihood that crack would be in existence and the number evaluated that crack is in existence, respectively. Substitution 0.9 for P allows likelihood function to be monotone increasing function.

4 NUMERICAL TEST

Location of internal crack is the 12th sensing block from left side and crack detection scenario using moving sensing window is set up as Figure 8. Signals in the plate with and without crack at every moving step are extracted and damage indices are calculated from them.

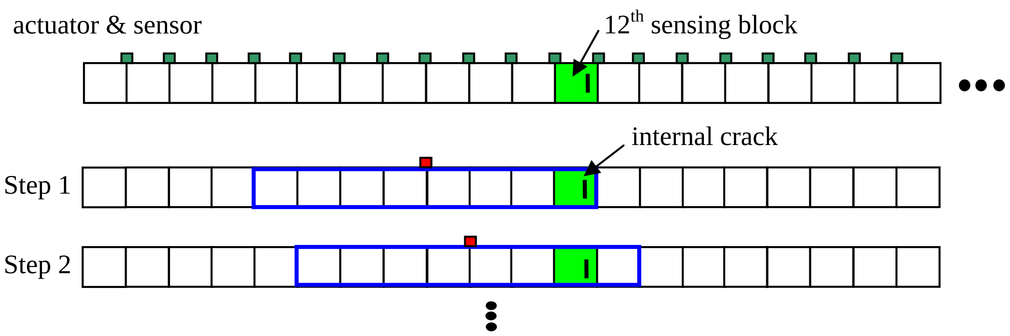

Figure 8. Crack detection scenario using moving sensing window.

Existence of crack is checked by using damage index for every step of moving sensing window. Relationship between sensor number and sensing block number is defined as Figure 9. at each step. In addition, existence of crack in sensing block is determined from this relationship.

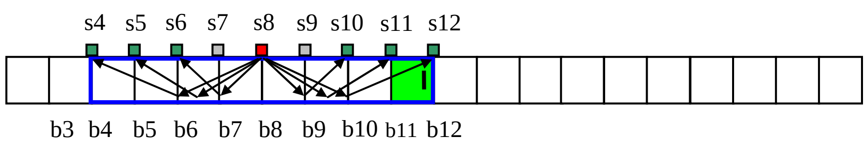

Figure 9. The configuration of moving sensing window at step 1.

In 6 available sensors, s12 sensor detects damage. And then because bulk transversal wave received from s12 sensor pass through b10, b11, and b12 sensing block, these blocks are assumed to be damaged. From these analyses and deductions, crack assessment between each sensor and sensing block leads to Table 1. As a result, it is determined that only b12 sensing block has a crack.

The number of crack assessment for each sensing block is counted as moving sensing window moves during 8 steps. If the number of crack assessment has maximum value, maximum likelihood is shown for maximum likelihood estimation. Therefore, b12 sensing block has maximum likelihood and it is expected to be damaged as following Figure 10.

Table 1. Crack assessment at sensing block.

Sensing block number ↓ / Sensor number →	b5	b6	b7	b8	b9	b10	b11	b12
s4	F	F	F					
s5		F	F					
s6			F					
s7								
s9								
s10						F		
s11						F	F	
s12						T	T	T
assessment	**F**	**F**	**F**			**F**	**F**	**T**

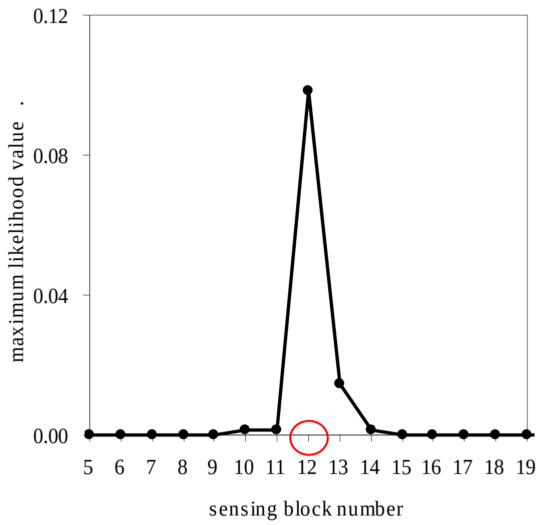

Figure 10. Localized crack location with maximum likelihood value.

5 CONCLUSION

This paper presents detection methodology for internal or bottom crack of thick plate by using bulk transversal wave. Moving sensing window technique that a group of a few sensors advances in the longitudinal direction and assesses damage with step-by-step process is proposed. From this technique, defection of arbitrary location in the plate can be detected by using wave map as movement of sensing block with a few sensors considering superposition and attenuation. In addition, probabilistic evaluation methodology based on maximum likelihood estimation is introduced for reliability. Crack assessment is evaluated at each moving step. Finally, damaged location is estimated by using maximum likelihood value applied to probability mass function with respect to the number of crack assessment for all sensing blocks.

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