NDT&E International 80 (2016) 35–47

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Wave propagation in water-immersed adhesive structure with the substrates of finite thickness

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ARTICLE INFO

Article history:
Received 4 October 2015
Received in revised form
28 January 2016
Accepted 8 February 2016
Available online 19 February 2016

Keywords:
Water-immersed adhesive structure
Transfer matrix method
Finite thickness substrate
Perfect and sliding interfaces
Reflection and transmission coefficients

ABSTRACT

In previous theoretical studies on the adhesive structure, the substrate is mostly considered as a semi-infinite solid space and corresponding theoretical derivation is rarely related to the thickness of the substrate. In the paper, based on the transfer matrix method, we studied in the water-immersed trilaminar plate-like adhesive structure with the substrates of finite thickness and the perfect/sliding interfaces in the case of plane longitudinal wave incidence and deduced the expressions of reflection and transmission coefficients of longitudinal waves. In order to verify the accuracy and applicability of the deduced formula, this formula was firstly applied to the water-immersed steel–epoxy resin–steel adhesive structure with perfect interfaces and the calculated result was compared with the existing data. Taking the water-immersed aluminum–epoxy resin–aluminum adhesive structure with perfect/sliding interfaces as an example, the impacts of incident angle and frequency on the reflection and transmission characteristics of the longitudinal wave were then analyzed. Finally, the theoretical method was experimentally verified and the experimental results were well consistent with the numerical calculation results. The reflection and transmission coefficient curves of longitudinal wave showed the obvious resonance when the longitudinal wave was normally incident. Regardless of the substrate thickness, the frequency of acoustic waves or the incident angle, it can only confirm whether a sliding interface exists, but the interface to slide cannot be determined.

1. Introduction

Adhesive structures have been widely used in mechanical, electronic, aerospace and other fields [1]. In order to ensure the mechanical strength and stability of the adhesive structure in its service process, it is necessary to perform the nondestructive testing and evaluation for the performance of the adhesive interfaces [2,3]. Therefore, the studies on mechanical behaviors of adhesive interfaces and its characterization techniques are of great academic significance and application values [4,5].

The propagation characteristics of ultrasound in the adhesive structure and the nondestructive testing and evaluation of interfacial adhesive quality have drawn wide attention from the researchers [6]. In previous studies on the propagation characteristics of ultrasonic in adhesive structures, Michaloudaki et al. [7] assumed the substrate of the aluminum–epoxy resin–aluminum adhesive structure to be a semi-infinite solid space and explored the ultrasonic wave propagation characteristics of the interface in perfect connection or the debonding status by a reflection coefficient method. Pilarski et al. [8] studied the impact of the incident angle of ultrasonic wave on the reflection and transmission coefficients when the adhesive interfaces were perfectly connected based on the spring model method. Baik et al. [9] proposed a quasi-static model, studied the reflection and transmission characteristics of acoustic waves by means of normally incident body waves, and greatly improved the calculation accuracy of the reflection and transmission coefficients by introducing the inertial mass. Baljeet [10] studied the interaction of plane waves with the contact interface between two different monoclinic crystal semi-infinite solids, and obtained the ratio of the displacement potential amplitudes of the transmitted wave and reflected wave under different forms of interfaces. Thomson [11] presented a theoretical model of multilayer transfer and analyzed the characteristics of the adhesive layer with the reflection and transmission coefficients of the oblique incident acoustic waves. Based on the Thomson model, Rose [12] derived the reflection and transmission coefficient expressions of the ultrasonic body waves in multilayer adhesive structure with a perfectly connected interface and studied the propagation mechanism of the body waves in this structure.

In previous studies on ultrasonic nondestructive testing and evaluation of the quality of adhesive interfaces, Tattersall [13]

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http://dx.doi.org/10.1016/j.ndteint.2016.02.005

simplified the adhesive interface as a spring model to study the adhesive strength of the solid–solid contact interface by the pulse-echo technique, and presented and defined the stiffness coefficient of the adhesive interface for the first time. On the basis of the above results by Tattersall, Qiu et al. [14,15] and Wu et al. [16] studied the body wave propagation modes in weak adhesive structure with the methods of vertical and oblique incidences, distinguished the perfect, weak bonding, and debonding interfaces, and then carried out a numerical simulation with COMSOL. Wu et al. [17] studied the longitudinal wave transmission characteristics of the adhesive structure under the condition of water immersion and oblique incidence and successfully identified the perfect and debonding interfaces. Based on the transfer matrix method, Rokhlin et al. [18,19] took the adhesive interface as a viscoelastic thin layer to study the body waves propagation characteristics of multilayer adhesive structures when the adhesive layer with a finite thickness was between two semi-infinite solid media and analyzed the interaction of the ultrasonic body waves with perfect and debonding interfaces. Similarly, Wang [20] studied the reflection characteristics of layered solid medium with perfect and sliding interfaces by using the transfer matrix method, derived the simple expressions of the reflection and transmission coefficients under the longitudinal or transverse wave incidence, and provided a basis for the correct selection of the technical parameters to evaluate the quality of adhesive interface. However, Rokhlin and Wang did not study the case of the substrates with finite values. Murashov [21] discerned the debonding area of adhesive structure and made an experimental verification.

Different methods or interface simplified models had been adopted to study the adhesive structure. Nevertheless, in previous studies, most substrates of the adhesive structure are semi-infinite solid spaces and the thickness of the substrates was seldom studied. Generally speaking, if the substrate thickness of the adhesive structure is much greater than the wavelength of the ultrasonic waves, the substrate can be considered as a semi-infinite solid space. However, in the actual industrial production and applications, the thickness of many substrates is less than, equal to or slightly greater than the wavelength of the ultrasound. For example, the aircraft skin, thin-wall parts in dedicated vehicles and some special fireproof structures are aluminum-based, steel-based, magnesium-based or aluminum alloy-based adhesive structure with the substrate thickness of 2–5 mm. For this kind of adhesive structure, the thickness of the substrate should be taken into consideration and cannot be simply considered as a semi-infinite space in the ultrasonic testing. In addition, the reflection and transmission characteristics of acoustic waves in the water-immersed adhesive structure with sliding interfaces were seldom studied.

In this paper, taking the trilaminar plate-like adhesive structure commonly used in practical industrial productions as an example, based on the transfer matrix method, we firstly deduced the reflection and transmission coefficient expressions of longitudinal wave in the water-immersed adhesive structure with the substrates with finite thickness and perfect/sliding interfaces in the case of the plane longitudinal wave incidence. Secondly, we plotted the reflection and transmission coefficient curves of longitudinal wave through numerical simulation for the adhesive structure with perfect/sliding interfaces. Then, we studied the interaction between acoustic waves and different interfaces by analyzing the impacts of incident angle and frequency changes on the reflection or transmission characteristics of longitudinal wave. Finally, we experimentally verified the theoretical results.

2. Mathematics and formulation of the adhesive structure

In general, the contact interface between two solids has special and complex physical properties, which are different from and dependent on the characteristics of the two solids. Because the transmission mode will be changed when ultrasonic waves are passing through different contact forms of interfaces, the interface states can be analyzed via studying the reflection or transmission characteristics of the ultrasonic waves.

At present, the study methods of multilayer adhesive structure mainly include the spring model method, transfer matrix method, global matrix method, etc. However, the transfer matrix method is simple and widely used. The transfer matrix method adopted in this paper is expressed as follows. Firstly, we explored the relationship between the sound field in the upper/lower semi-infinite space and the particle vibration velocity (or displacement) and stress on corresponding interface. Secondly, we studied the relationship between the particle vibration velocity (or displacement) and stress on the upper and lower interfaces of each layer of the solid. Finally, appropriate boundary conditions were introduced into the model according to the interface situation between adjacent layers. In this way, the reflection and transmission sound fields of the entire multilayer system were gained. Since more boundaries need to be considered, it is more difficult to study the water-immersed adhesive structure with substrate thickness of limited value than the adhesive structure with the substrates of semi-infinite solid space. Especially, it is even more difficult to study the sliding interfaces.

Fig. 1 shows the geometric model of the adhesive structure. The bottom of the adhesive structure is set as the x axis of the Cartesian coordinate system and the plate thickness direction is set as the z direction. Medium 1 and medium 5 are semi-infinite fluid layers; medium 2 and medium 4 are respectively the upper and lower substrates of the adhesive structure; medium 3 is an adhesive layer. Substrates 2 and 4 and adhesive layer 3 are isotropic elastic solid media and their thicknesses are h_2, h_4, and h_3, respectively. The four interfaces among the 5 media are respectively interfaces 1, 2, 3, and 4. $\varphi_{i(n)}$ and $\varphi_{r(n)}$ $(n=1{,}5)$ are displacement potential amplitudes of incident and reflected longitudinal waves in fluids 1 or 5, respectively. ${\theta_i}^{(n)}$ and ${\theta_r}^{(n)}(n=1,5)$ are respectively the incident and reflected angles of longitudinal waves in fluids 1 or 5, ${\theta_i}^{(n)}={\theta_r}^{(n)}(n=1,5)$. If the harmonic plane waves with an angular frequency of ω enter the multilayer system from fluids 1 and 5 at the same time, these waves have the same wave vector component δ along the x direction. According to Snell's law, the wave vector component of the reflection waves in media 2, 3, and 4 along the x direction is also δ. If the nonlinear effect of wave propagation is neglected, the incident and reflected waves can be linearly superimposed in the same medium. In the paper, the viscous effect of fluid and the attenuation of acoustic wave propagation in the fluid and adhesive structure were not considered.

The particle vibration velocity in fluid can be expressed as $\vec{v}_{f(n)} = -i\omega\nabla\mathbf{\Phi}_{f(n)}(n=1,5)$ and the sound pressure can be expressed as $p_{f(n)}=\rho_{f(n)}\omega^2\mathbf{\Phi}_{f(n)}(n=1,5)$ [22], where ω is the angular frequency; ∇ is the Laplace operator; $\rho_{f(n)}(n=1{,}5)$ is the density of the nth fluid. It is assumed that $\mathbf{\Phi}_{f(n)}=\varphi_{i(n)}e^{ik^{(n)}\cos{\theta_i}^{(n)}z}+\varphi_{r(n)}e^{-ik^{(n)}\cos{\theta_r}^{(n)}z}(n=1,5)$ is the total displacement potential of the sound field in the nth semi-infinite fluid (the common phase factor $e^{i(\delta x-\omega t)}$ is ignored here). Since the angle of incidence is equal to the reflection angle in the same medium, the total displacement potential can also be written as $\mathbf{\Phi}_{f(n)}=\varphi_{i(n)}e^{ik^{(n)}\cos{\theta_i}^{(n)}z}+\varphi_{r(n)}e^{-ik^{(n)}\cos{\theta_i}^{(n)}z}(n=1,5)$, where $k^{(n)}$ $(n=1{,}5)$ is the wave number in the nth fluid.