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Detection of damages in underwater metal plate using acoustic inverse scattering and image processing methods

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ABSTRACT

Non-destructive testing and structural health monitoring are essential for safety and reliability of marine kinetic energy related fields. In this work we address the problem of damage detection of underwater finite length plates using acoustic inverse scattering and image processing methods. Time series signals and the 2D images obtained from these signals have been studied to improve detection accuracy. Optimal parameters are selected for near-end edge echoes elimination and binarization is used to reduce computational complexity. A robust and simple method was proposed to detect and localize a possible damage in 2D images based on image processing and analysis. Experimental results show that the detection rate for crack damage reaches 100% and localization accuracy reaches 96% on average.

1. Introduction

Underwater structural health monitoring (SHM) has been an important research topic prompted by the maritime industries such as marine kinetic energy and offshore drilling. It is mainly used to maintain and preserve the structural integrity from damages which are defined as changes to the material and/or geometric properties of a structure. The underwater structure damages which may affect the system's performance are mainly caused by degradation over time from seawater–corrosion, storms, vibration and other environmental factors. In the last few decades there has been tremendous interest in developing methods for underwater SHM and nondestructive testing (NDT) techniques. However, it remains a challenging field because many conventional NDT techniques like magnetic particle inspection [1], radiography [2,3], thermal inspection [4] or eddy current [5] cannot be performed in underwater environment.

For the last decade, tremendous advances have been made in SHM using various technologies many of which are currently becoming increasingly common. Conventional ultrasonic techniques, such as the normal incidence pulse echo etc, have difficulty in resolving echoes from near-surface damages where the reflections from the damages often lie within the length of the transmitted ultrasonic pulse. Guided waves on the other hand have been receiving considerable attention because of their advantages: propagation over long distances due to low attenuation; inspection of relatively large areas without the necessity of moving the transducers; inspection of the whole cross section of the structure; possibility of testing structures with coating or insulation with no significant loss of sensitivity; possibility of using several propagation modes, with different sensitivity to each type of defect [6]. Among different guided waves, Lamb waves are the most widely used types in damage detection in terms of SHM which can offer a reliable method of estimating the information about damage in a structure in terms of location, severity and type of damage [7,8].

Much work has been done on damage detection based on Lamb waves propagation in plate structures. This is because the approach is suitable for structures with low geometrical complexity, especially for methods based on reflection analysis. Research works based on lamb waves have extensively been used in damages detection in plates and pipes [9,10]. A damage localization method in an aluminum plate using a propagating wave is proposed in [11]. Vander et al. [12] introduced an image compounding technique that uses the information obtained from different propagation modes of Lamb waves for non-destructive testing of plate-like structures. A literature survey of recent significant works for damage detection in composite structures

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using guided wave over the last few decades is presented by Su et al. [13]. The methods introduced above are damage detection applications based on changes of propagating waves in metal or composite plate structures.

Ultrasonic imaging helps the operator in decision making in a variety of applications in which image processing techniques were applied to improve inspection accuracy. Karimi et al. studied ultrasonic image processing for defect detection using the stability of the image gradients and the transient temporal nature of the defect echo [14]. Domingueza and Gibiat proposed an ultrasonic imaging based non-destructive testing method in which testing image is constructed from the computation of forward field and adjoint field in the time domain [15]. Position and sizes of the holes in aluminum parts can be obtained accurately. Mitri et al. studied non-destructive imaging of flaws using comparison of continuous-wave and tone-burst excitation modes in vibro-acoustography [16]. Dickinsona proposed an acoustic inspection system for aircraft composite panel damage detection which provides visual information on damage nature and size [17]. In Ref. [18], a high-resolution imaging based inspection method was proposed using linear arrays and Lamb waves for isotropic plate-like structures. A 1-mm-thick aluminum plate with artificial defects was tested with linear arrays and Lamb waves to obtain a compounded image with narrower main lobe. Polarity images are combined by a logical AND operation with threshold level of 70% to improve detection accuracy.

Although the Lamb waves are widely used for damage detection in plate structures, there present difficulties in detecting damages in underwater applications. Tremendous work has being done in the mechanics of wave propagation and researches on damage detection using acoustic scattering from simple objects immersed in water, such as plates, cylinders, cylindrical shells, spheres or spheroids, are studied and proposed [19–24]. In Ref. [25,26], the influences of underwater environment for the symmetric or anti-symmetric Lamb waves and the mechanism of scattering of plates immersed in water are studied. Further investigations on underwater Lamb waves reflection analysis for SHM applications are necessary.

In our previous study [27], we addressed the problem of straight groove damage detection in a metal plate immersed in water using acoustic scattering method. The proposed approach in this paper is different from the methods mentioned above in which features such as image gradients stability, the computation of forward field and adjoint field were used for detection. In this work, we focus on the problem of underwater damage detection in plate structures using Lamb wave reflection analysis and image processing methods. Time series signals and 2D images are studied. Regions that are propitious to damage detection and localization are segmented for further analysis. Optimal parameters are selected for near-end edge echo elimination and binarization to reduce computational complexity. Finally, two different damage localization methods are proposed and compared. The main contributions of this work are as follows:

- A simple and robust underwater SHM method for plate structures is proposed based on image processing methods.
- Optimal parameters are selected automatically to reduce computational complexity and improve accuracy of damage detection and localization.
- Two efficient and accurate damage localization methods are proposed for underwater finite plate structures using Lamb waves reflection analysis.

In the following sections, we first introduce characterization and instrumentation for experiments of this work. The characteristics of acoustic time signals and resulting 2D images are studied. Based on these characteristics the damage detection and localization method is proposed in Section 3. Optimal parameters selection methods are introduced and discussed. Experimental results are given in Section 4. Finally, we discuss the experimental results of the proposed scheme and conclude the paper.

2. Characterizations and instrumentation

The main focus of this work is the monitoring of hydrokinetic energy system structures. The access of underwater hydrokinetic energy systems is difficult. Health monitoring technologies are therefore important and critical due to the difficult environment for inspection.

Simplified experimental equipment was designed to test the proposed method and main characteristics of each device were summarized in the experimental setup. The top view representation of the device (Fig. 1(a)) and a sample of tested plate are respectively given by Fig. 1(b) and (c). This experimental context is a simplification of the real conditions. As is shown in Fig. 1(a), the plate is vertically hung by two nylon threads in a water-filled cylindrical tank (diameter = 300 mm and depth = 200 mm). In Fig. 2(b), E_1 represents the near-end edge of the plate with respect to the transducer and the second edge is E_2. Some damages may present on the plate at different positions. Plates with and without damage are tested, the length is equal to 300 mm, width is $L = 194$ mm and the thickness is $e = 1.5$ mm. These plates are made of stainless steel: the longitudinal wave velocity is $c_L = 5790$ m/s, the shear wave velocity is $c_T = 3100$ m/s and the density is $\rho_{ss} = 7900$ kg/m^3. The damage position is pointed by F and the quantity $\delta * L$ represents the distance between E_1 and F. The density of the water is $\rho_w = 1000$ kg/m and the speed of sound is $s_w = 1470$ m/s.

In this research, the acoustic scattering from a plate immersed in water is studied. Two modes of Lamb waves are generated: the symmetric S_i mode (Eq. (1)) and anti-symmetric mode A_i (Eq. (2)). The phase velocities V_{Lamb} of these waves are obtained from the complex roots k of Eqs. (1) and (2):

$$\left(k^2+s^2\right)^2 ch(qd)\cdot sh(sd) - 4k^2qs\cdot ch(sd)\cdot sh(qd) + \frac{\rho_w c_w^2 q}{\rho_{ss} c_T^2 r}(k^2-s^2)(k^2-r^2)\cdot sh(qd)\cdot sh(sd) = 0 \quad (1)$$

$$\left(k^2+s^2\right)^2 sh(qd)\cdot ch(sd) - 4k^2qs\cdot sh(sd)\cdot ch(qd) + \frac{\rho_w c_w^2 q}{\rho_{ss} c_T^2 r}(k^2-s^2)(k^2-r^2)\cdot ch(qd)\cdot ch(sd) = 0 \quad (2)$$

where ω is the pulsation, e is the plate thickness, $d = e/2$, $k = \omega/V_{Lamb}$, $k_L = \omega/c_L$ with c_L the velocity of the longitudinal wave in the plate, $k_T = \omega/c_T$, with c_T the velocity of the transversal wave in the plate, $k_W = \omega/s_W$ with s_W the speed of sound in water, $q^2 = k^2 - k_L^2, s^2 = k^2 - k_T^2$ and $r^2 = k^2 - k_w^2$. ρ_w, ρ_{ss} are the density of the water and of the steel respectively, and $sh()$ and $ch()$ are hyperbolic functions. The detailed derivation of (1) and (2) is given in Appendix. Fig. 2 presents the dispersion curves of group and phase velocities for symmetric and anti-symmetric Lamb waves in an infinite plate immersed in water at low frequency. For Lamb waves S_0 (Fig. 2(a)), the velocity is almost constant in the explored frequency domain; it can be generated at the critical angle defined by the Snell–Descartes Laws. For anti-symmetric Lamb waves the velocity has two trajectories. A first trajectory with a phase velocity always smaller than the sound velocity in water; this wave is called A_0^- wave (Fig. 2(c)). It is not possible to generate it from the Snell–Descartes laws; however, a number of resonances are established from this wave. Therefore, in order to explain it, it is assumed that