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Review

Self-focusing Lamb waves based on the decomposition of the time-reversal operator using time–frequency representation

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ABSTRACT

Active ultrasonic arrays are very useful for structural health monitoring (SHM) of large plate-like structures. Large areas of a plate can be monitored from a fixed position but it normally requires precise information on material properties. Self-focusing methods can perform well without the exact knowledge of a medium and array parameters. In this paper a method for selective focusing of Lamb waves will be presented. The algorithm is an extension of the DORT method (French acronym for decomposition of time-reversal operator) where the continuous wavelet transform (CWT) is used for the time–frequency representation (TFR) of nonstationary signals instead of the discrete Fourier transform. The performance of the methods is compared and verified in the paper using both simulated and experimental data. It is shown that the extension of the DORT method with the use of TFR considerably improved its resolving ability. To experimentally evaluate the performance of the proposed method, a linear array of small piezoelectric transducers attached to an aluminum plate was used to obtain interelement responses, required for beam self-focusing on targets present in the plate. The array was used for the transmission of signals calculated with the DORT-CWT algorithm. To verify the self-focusing effect the backpropagated field generated in the experiment was sensed using laser scanning vibrometer.

Contents

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1. Introduction

Flat or slightly curved plates can be found in numerous engineered structures where high safety standards are required. Guided waves (GWs) offer considerable advantages in monitoring (SHM) applications, where large plate-like areas of the involved structure have to be assessed. GWs that propagate in thin plates, known as Lamb waves, are multimodal and dispersive. Their nature becomes even more complex when the inspected plate is inhomogeneous, for instance, in the case of carbon fiber reinforced panels (CFRPs). Structural discontinuity (e.g. a damage) present in the structure scatters the incident GWs in all directions and additional modes can be produced due to the mode conversion phenomena. Therefore, damage detection and localization is a complex task and advanced signal processing has to be applied to characterize the damage [1].

Serious difficulties encountered in nondestructive testing (NDT) and SHM applications with the use of GWs could be overcome using time-reversal concept. For instance, time-reversal mirrors (TRMs), a powerful tool introduced for ultrasonic waves [2,3], enabled improvement of signal to noise ratio [4] and reduction of the effect of dispersion [5,6]. More recently, the concept of the time-reversal was used to develop a technique in which a defect can be detected without a historical baseline data captured for the untouched structure [7,8]. A reconstruction property of the time reversed Lamb waves has been employed in the baseline-free technique. A wave transmitted from the source to another point, captured there, time reversed and reemitted is expected to be identical with the excited input signal. However, if a damage is present in the structure the reconstruction property breaks. Therefore a comparison of the snapshots of the emitted and reconstructed wave yields information about the damage. This approach has been applied to a composite [7,8] and aluminum plates [9].

The baseline-free methods based on the wave reconstruction property are beyond the scope of this work. This paper is concerned with monitoring of plate-like structures using self-focusing arrays. The methods presented in the successive sections rely on the originally developed TRM approach, so a closer look will be given at its operation principle. In the TRM method an array of transducers, working in a pulse-echo mode, is used to focus the wave on a target existing in the medium. The algorithm is performed in three steps: in the first step one of the array elements is used as a transmitter that excites ultrasonic waves in a structure. If a scatterer exists in the investigated medium it produces an echo that is captured by the array elements in the second step. In the last step, the acquired signals are time reversed and reemitted by the array to the medium, so the generated wave is focused on the target [2]. The TRM was used in [4] to self-focus Rayleigh waves and to detect surface and subsurface holes of sub-wavelength dimensions. The signal to noise ratio achieved with the TRM was better than that obtained with classic surface transducers. Not only the selective focusing, but also the dispersion compensation could be observed when the TRM has been applied to Lamb waves [5,6]. The authors reported positive results obtained for the signals excited with a laser impact and acquired by an array of transducers. Those signals were distorted due to the dispersion phenomenon, e.g. a large duration of the S_0 mode. The signals were time-reversed and generated in the structure and an investigation of the impacted area showed that a temporal and spatial recompression was achieved.

When more than one scatterer exists in the structure it is possible to obtain a selective focusing on the strongest reflector with the use of the iterative TRM [10]. In this approach, the reception and reemission steps are repeated. However, in the SHM applications focusing on targets with lower reflexivity is also desired. In order to detect and focus the wave on the multiple scatterers' case DORT method has been introduced [11]. DORT is a signal processing technique that is capable of estimating the time delays required to selective focus waves on a target, based on the received data. The method has been successfully applied in a NDT application [12] as well as to the Lamb wave characterization [13].

In this paper experiments showing that DORT method enables selective focusing of the wavefield on scatterers will be presented. It appears, however, that in some cases resolving multiple scatterers with this method may fail. To deal with this problem a new method employing TFR of the signal has been proposed. Lamb waves propagating in a thin plate generate normally nonstationary responses due to the dispersive phenomenon; therefore the CWT, widely applied to the analysis of Lamb waves responses [8,14], was used to calculate the TFR of the signals. The scatterers that could not be resolved correctly in the frequency domain could be resolved in the time domain. In this way it was possible to considerably improve resolution of the DORT method.

This paper is organized as follows: Section 2 outlines a theoretical background of DORT and the DORT-CWT algorithms. The theoretical presentation is followed by simulation and experimental results where the proposed method is compared to the classical DORT approach.

2. Theoretical background

To place the proposed approach into context, this section gives a brief review of the DORT technique followed by a description of the proposed extension of this method.