Mechanical Systems and Signal Processing 91 (2017) 111–121

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

A pulse coding and decoding strategy to perform Lamb wave inspections using simultaneously multiple actuators

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ARTICLE INFO

Article history:
Received 14 February 2016
Received in revised form 25 September 2016
Accepted 11 December 2016
Available online 10 January 2017

Keywords:
Lamb wave inspections
Spread spectrum pulse coding
Warped frequency transform
Wavenumber filtering
Laser vibrometry

ABSTRACT

The performance of Lamb wave based monitoring systems, both in terms of diagnosis time and data complexity, can be enhanced by increasing the number of transducers used to actuate simultaneously the guided waves in the inspected medium. However, in case of multiple simultaneously-operated actuators the interference among the excited wave modes within the acquired signals has to be considered for the further processing. To this aim, in this work a code division strategy based on the Warped Frequency Transform is presented. At first, the proposed procedure encodes actuation pulses using Gold sequences. Next, for each considered actuator the acquired signals are compensated from dispersion by cross correlating the warped version of the actuated and received signals. Compensated signals form the base for a final wavenumber imaging meant at emphasizing defects and or anomalies by removing incident wavefield and edge reflections. The proposed strategy is tested numerically, and validated through an experiment in which guided waves are actuated in a plate by four piezoelectric transducers operating simultaneously.

1. Introduction

In recent years, ultrasonic Guided Waves (GW) received a considerable attention from the nondestructive evaluation (NDE) and structural health monitoring (SHM) community because of the GW ability to travel long distances without substantial attenuation as well as to their versatile multimode/frequency nature that allows for defect classification and sizing [1]. Among the main applications, the detection and localization of defects and impact in plate-like components has gathered the attention of several research fields including aeronautics. In this context, GW are usually excited and sensed through multiple piezo-electric transducers arranged in different array configurations. The receivers can be triggered on the actuator and the acquired time-waveforms are subsequently analyzed to locate and characterize defects and/or impacts. Similarly, piezo-actuators can be combined with non-contact receivers, such as Scanning Laser Doppler Vibrometers (SLDV) [2], or air coupled probes [3].

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http://dx.doi.org/10.1016/j.ymssp.2016.12.014
0888-3270/

In order to enhance the inspection abilities of such monitoring systems, it can be convenient to increase the number of transducers (probes) used for the monitoring task. Multiprobe systems can be implemented in several different configurations and can be distinguished on the basis of the level of coordination among the probes [4]. One common configuration in GW inspections is based on the use of a ''single TX - multiple RX'', that is the use of a single transmitting transducer (TX) and multiple receiving transducers (RXs), i.e. one actuator and multiple sensors. This solution has a clear advantage with respect to ''single TX - single RX'' systems because it allows for an N_R-fold reduction of the acquisition time, being N_R the number of receivers from which the signal is gathered. However, there are still some limitations in operating ''single TX - multiple RX''. Firstly, devices such as SLDVs or air coupled probes acquire single-point measurements sequentially. This means that to acquire multiple scan-points simultaneously the acquisition devices should be replicated. This is very unpractical given the high costs of such equipments and unfeasible if the number of desired RX grows. Secondly, the usage of a single transmitting transducer might bring some risk, in the sense that if the defect cross-section is small and it is located perpendicularly to the wavefront, most likely the defect will not be detected.

As such, multiple transmitting transducers procedures, i.e. ''multiple TX'', are generally adopted to reduce such risks. Conventional multiple TX systems for guided wave based structural health monitoring usually relies on a time-division multiplexing scheme, where each piezoelectric transducer acts in turn as the transmitter. In this context, either tone-burst signals [5] or chirp signals [6] are widely used. This solution is very effective but, if N_T is the number of TXs, the total inspection time is a linear function of the product $N_T \times N_R$.

An alternative solution is to operate simultaneously multiple TXs. The presence of multiple simultaneously operated TXs makes the system radically different from the other considered cases, introducing the possibility of interference among the multiple excitations injected in the system within the received signals.

To treat such interference, one may use *frequency division* [7]. However, frequency division limits the successful usage of pulse-compression because it hampers the excitation of large bandwidth pulses which are required to achieve high resolution defect imaging. In addition, frequency division suffers the dispersive and multi-modal nature of guided waves due to which, for the same distance of propagation, the same wave attenuates differently at different frequencies.

Another possible alternative is given by the use of *code division* [8]. Such alternative has a clear advantage in terms of transducer bandwidth exploitation, but it requires some special processing when applied to systems based on GWs. In fact it is mandatory to counteract the detrimental effect of dispersion and multi-modal propagation to achieve the desired pulse-compression performances. To this aim, a pulse coding and decoding strategy based on the Warped Frequency transform (WFT) [9] is proposed in this work. The WFT has two beneficial effects: (1) it compensates the acquired signals for dispersion, (2) it preserves the pseudo-orthogonality of the excited waveforms, because it is computed with a unitary operator, thus allowing, at the same time, efficient pulse compression and interference cancellation. A subsequent post-processing procedure based on wavenumber filtering [10] is applied to the pulse compressed signals for the final damage imaging.

The paper is organized as follows: in Section 2 pulse encoding via Gold codes will be reviewed and its limitation for distance estimation purposes in guided waves based approaches is highlighted. In Section 3 the proposed dispersion compensation and pulse compression procedures will be presented and applied to some numerically simulated waveforms. The advantages of the proposed strategy are shown through an experimental validation aimed at detecting a notch in an aluminum plate in Section 4. The conclusions end the paper.

2. Spread spectrum pulse coding

In the bulk ultrasound research field, several schemes that allows to operate ''multiple-TX'' systems by using encoded pulses have been successfully presented [11]. In this paper, the employed encoding is based on Gold-codes which provide excellent cross-correlation properties with minimum mutual interference [12]. This methodology removes the requirement of a switching network, because demodulation can be achieved in post-processing by means of a matched filter (cross-correlation function), and this is the reason for their large usage in wireless CDMA-communication systems since they can provide multi-user access.

In Fig. 1(a) and (b) two sample Tx_i signals are depicted. The two signals are obtained considering two different Gold sequences of length $L = 2^5 - 1$ applied to a sinusoid of frequency of 200 kHz. The autocorrelation of Tx_1 and the cross-correlation between Tx_1 and Tx_2 are plotted in Fig. 1(c). From Fig. 1(c) it can be seen that the autocorrelation is very peaky and that the cross-correlation between different coded pulses is very low. Such properties imply that such kind of pulses are very well suited for time-of-flight estimation problems when the acquired signals are corrupted by jamming interferences produced by multiple simultaneously actuated pulses as in ''multiple-TX'' systems. Other coding strategies have been successfully applied to ultrasound inspections [13], however the benefit brought by coded waveforms are almost completely lost when adopted for GW inspections, in case of highly dispersive propagation.

In Fig. 2 it can be seen how the decoding works when applied to a numerically simulated guided waves signal $s(t, D)$ represented in Fig. 2(b). In particular, the signal has been computed by simulating the propagation of Lamb waves in a 3 mm thick aluminum plate using Fourier domain techniques [14]. A propagation distance of $D = 200$ mm between the transmitter (TX) and the receiver (RX) has been used. As actuation pulse $s(t, 0)$ the Gold modulated sinusoid of Fig. 2(a) centered at