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A signal processing approach to exploit chirp excitation in Lamb wave defect detection and localization procedures

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ABSTRACT

A non-linear Lamb wave signal processing strategy aimed at extending the capability of active–passive networks of PZT transducers for defect detection is proposed. In particular, the proposed signal processing allows to use chirp shaped pulses in actuation, instead of classically applied spiky pulses, requiring thus lower input voltages. To such aim, the acquired Lamb waves are processed by means of a two-step procedure: a warped frequency transform (WFT) to compensate for the dispersion due to the traveled distance, followed by a compression procedure to remove from the signals the induced chirp frequency modulation. Next, the resulting signals are exploited to feed an imaging algorithm aimed at providing the position of the defect on the plate. The potential of the procedure is demonstrated and validated by analyzing experimental Lamb waves propagating in an aluminum plate where defects were emulated by posing an added mass on the plate. The proposed automatic procedure is suitable to locate defect-induced reflections and can be easily implemented in real applications for structural health monitoring.

1. Introduction

In recent years, ultrasonic guided waves (GWs) received a great deal of attention among non-destructive tests community due mainly to the ability to travel long distances without substantial attenuation as well as to the versatile multimode/frequency examination for defects classification and sizing. Among the various applications based on GWs, numerous approaches have been proposed to detect defects in plates-like structures by means of Lamb waves [1–4]. Generally, active–passive networks of transducers are considered, where one or more actuators are used to generate GWs and the sensors work as wave detectors. The time-waveforms acquired by the receivers, triggered on the actuator, are subsequently analyzed to locate and characterize the defect.

Unfortunately, several dispersive modes appear simultaneously in the received signals, thus limiting the potential of such approaches. The modes, in fact, overlap in both time and frequency domains and simple Fourier analysis techniques are not able to separate them. Recent works in the area of time–frequency representations (TFRs) [5–8] show great promise for applications in non-destructive evaluation and material characterization, as a mean to interpret ultrasonic propagation in various structures. In fact, since the propagation characteristics are directly related to both the intimate

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structure and mechanical properties of the medium, the dispersive properties of GWs can reveal important information for structural health monitoring purposes.

Nevertheless, fast identification and separation of Lamb modes are challenging steps in the process of damage detection, even in the time–frequency domain. Such task is complicated by the fact that high energy pulses have to be excited in order to get readable echoes from weak reflectors. To excite such high energy pulses, two alternatives can be considered: (i) short spiky pulses or (ii) chirped pulses.

Short pulses, usually few cycles sinusoids with Gaussian envelopes [9–11], are commonly adopted and somehow simpler to be interpreted, as many of the recently proposed dispersion compensation algorithms [12,13] or time–frequency tools [14] are perfectly suited to process them. However, the pulser circuit must handle very high voltages (up to 1 kV) and requires mains power supply. This can be unpractical in many situations, especially when the available power supply is limited, and whenever a portable device relying on battery power has to be built [15]. In such cases, actuation by means of chirped pulses is the most effective solution.

Chirped pulse transmissions found its first wide-spread applications in radar systems. Essentially, such technique consists in transmitting long linear or non-linear frequency modulated signals, so that the pulse energy is stretched in time, but the resolution is not compromised thanks to the broad frequency spectrum of the signal itself. Broadband chirped techniques have been previously applied to ultrasonic non-destructive testing [16,17], but are unusual in GWs-based applications because of their dispersive detrimental effect (see for instance [18]).

In this work, we discuss a novel methodology to tackle signal dispersion in case of chirped excitations. The proposed procedure is based on a two-step pulse compression strategy. In the first step, the warped frequency transform (WFT) is exploited to compensate for the group delay of the acquired signals from the dependency on the distance traveled by the waves [19]. The second step is aimed at the compressing the chirped frequency modulation. The compensated and compressed signals reveal immediately the distance traveled by the waves, and are next used to feed an imaging algorithm that show the position of the defect on the plate.

The main benefit of the proposed strategy for active–passive networks of sensors is the possibility of using lower input power with respect to procedures based on spiky pulses. In addition, being the signal processing fast as a standard discrete Fourier transform, the procedure is well suited for real-time SHM applications of plate-like structures.

The work is organized as follows: the proposed group delay compensation procedure will be presented in Section 2 together with some results on numerically simulated waveforms; an experimental validation is presented in Section 3. The conclusions in Section 4 end the paper.

2. Group delay compensation

2.1. Design the frequency warping operator

The WFT is a unitary time–frequency transformation that produces a flexible sampling of the time–frequency domain. Given a generic signal $s(t)$ whose frequency representation is $S(f) = \mathbf{F}\{s(t)\}$, $\mathbf{F}$ being the Fourier transform operator, the frequency warping operator $\mathbf{W}_w$ reshapes the periodic frequency axis by means of a proper function $w(f)$, that we will call from now on *warping map*, such as [19]

$$s_w(t) = \mathbf{W}_w\{s(t)\}$$

$$\mathbf{F}\{s_w(t)\} = \sqrt{\dot{w}(f)} \cdot S(w(f)) \quad (1)$$

where $s_w(t)$ is the so-called warped signal, and $\dot{w}(f)$ represents the first derivative of $w(f)$. The discrete WFT can be efficiently computed with fast Fourier transform algorithms and interpolations [19].

As shown in [20], the WFT can be exploited to compensate for dispersion induced by a traveling Lamb wave. To this aim, the warping map $w(f)$ can be defined, through its functional inverse [19,21], such as

$$K \frac{dw^{-1}(f)}{df} = \frac{1}{c_g^M(f)} \quad (2)$$

where $1/c_g^M(f)$ is the nominal dispersive slowness relation of the M-th Lamb wave whose dispersive effect has to be compensated. K is a normalization parameter selected so that $w^{-1}(0.5) = w(0.5) = 0.5$.

As an example, a 3 mm thick aluminum plate with Young modulus E=69 GPa, Poisson's coefficient $\nu = 0.33$ and density $\rho = 2700\ \text{kg/m}^3$ is considered. The group velocity curve of the A_0 mode depicted in Fig. 1(a) has been used to compute the warping map depicted in Fig. 1(b), along with its functional inverse, by means of the following steps:

1. Compute the group velocity curve $c_g^M(f)$ of the M-th wave to be compensated within the signal (the A_0 mode in this case) and define its inverse $1/c_g^M(f)$.
2. Perform the numerical integration $\int_0^f 1/c_g^M(f)\, df$ to compute the left hand term of Eq. (2): $L_H(f) = Kw^{-1}(f)$.
3. Compute $K = 2 \times L_H(0.5)$ and $w^{-1}(f) = L_H(f)/K$.
4. Compute $w(f)$ from its functional inverse $w^{-1}(f)$.