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Simultaneous excitation system for efficient guided wave structural health monitoring

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ABSTRACT

Many structural health monitoring systems utilize guided wave transducer arrays for defect detection and localization. Signals are usually acquired using the "pitch-catch" method whereby each transducer is excited in turn and the response is received by the remaining transducers. When extensive signal averaging is performed, the data acquisition process can be quite time-consuming, especially for metallic components that require a low repetition rate to allow signals to die out. Such a long data acquisition time is particularly problematic if environmental and operational conditions are changing while data are being acquired. To reduce the total data acquisition time, proposed here is a methodology whereby multiple transmitters are simultaneously triggered, and each transmitter is driven with a unique excitation. The simultaneously transmitted waves are captured by one or more receivers, and their responses are processed by dispersion-compensated filtering to extract the response from each individual transmitter. The excitation sequences are constructed by concatenating a series of chirps whose start and stop frequencies are randomly selected from a specified range. The process is optimized using a Monte-Carlo approach to select sequences with impulse-like autocorrelations and relatively flat cross-correlations. The efficacy of the proposed methodology is evaluated by several metrics and is experimentally demonstrated with sparse array imaging of simulated damage.

1. Introduction

Lamb waves offer potential for structural health monitoring (SHM) because of their capability of propagation over a relatively long distance with low attenuation while maintaining sensitivity to changes in structural characteristics [1,2]. A common strategy for Lamb wave SHM is to use arrays of transducers together with the "pitch-catch" data acquisition method; i.e., exciting each transducer sequentially and recording responses by the remaining ones either simultaneously or separately [3–5]. However, in both cases the data acquisition process can be time consuming since multiple transmission-reception cycles are needed to loop through all of the transmitters. Additional switching time may also be required depending upon the specific hardware implementation. A further increase in data acquisition time occurs when extensive signal averaging is used to achieve a high signal-to-noise ratio (SNR). For example, the data acquisition time of an eight-element sparse transducer array can be several minutes for a pulse repetition time of 100 ms and 50 averages for each reception. Such a long data recording time can severely limit the efficiency of the Lamb wave SHM system and cause problems for field applications.

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A major adverse effect of a long data acquisition time on Lamb wave SHM is signal mismatch if environmental and operational changes occur during the acquisition process. Even in the laboratory small temperature changes are possible in the span of a few minutes, and it is well-known that these small changes have a significant effect on Lamb wave signals [6,7]. Load changes are also possible, such as in the case of aircraft maneuvers during normal operations, and these changes also affect Lamb wave signals [5,8]. Various methods have been proposed to compensate for such changes, but it has been shown that improved performance is obtained when all signals are acquired under the same environmental conditions, particularly applied load [9].

A straightforward approach that can minimize the data recording time is to excite all transmitters simultaneously, which has been applied to ultrasonic ranging systems [10,11]. The major issue arising from the simultaneous excitations is ultrasonic crosstalk; i.e., signals from different transmitters overlap with each other at reception. The most promising methods to minimize crosstalk are those assigning a unique excitation for each transmitter and applying matched filtering at reception [10–13]. Therefore, the key is to select a series of excitation signals that have good correlation performance; i.e., a sharp autocorrelation and a flat cross-correlation. Signals that have been commonly used include linear and non-linear chirp sequences and pseudo-random binary sequences such as Barker codes, Golay codes, Gold codes, and chaotic sequences [12,13].

In this paper, we apply the simultaneous, coded excitation method to a spatially distributed array of transducers that generate and detect Lamb waves. This problem is similar to the ultrasonic ranging problem in that transducers are bandlimited, but it is significantly different in that the crosstalk is much more severe and dispersion prohibits direct application of matched filtering. Since the Lamb wave sensors are omnidirectional and operate in pitch-catch mode, all transmissions are present in all received signals in approximately equal strengths. Thus, what is considered "signal" versus "crosstalk" depends upon which transmitter is being considered during analysis. In contrast, ultrasonic ranging system transducers are directional (albeit with significant beam spread) and each channel of interest uses a transmitter and receiver that are essentially co-located (comparable to pulse-echo mode), resulting in an inherently larger signal of interest compared to the crosstalk coming from the other transmitters.

Another issue when applying simultaneous excitations to a guided wave transducer array is that from a practical standpoint there must be dedicated transmitters and receivers. For reception to occur on a transmitting transducer, a T-R (transmit-receive) switch must be used to protect the receive amplifier during the transmission, which effectively limits the length of the excitation to the time prior to the first signal arrival. For typical systems this time could be as short as tens of microseconds, which would essentially prohibit coded excitations of useful lengths (i.e., hundreds of microseconds). Thus, for a system with N transducers, rather than being able to acquire $N(N-1)/2$ unique signals as is customary with separate excitations, the N transducers must be split into N_T transmitters and $(N-N_T)$ receivers, yielding a reduced total of $N_T(N-N_T)$ possible signals.

Proposed here is a method of constructing multiple excitation signals by concatenating a number of linear chirps. Each chirp has its start and stop frequencies randomly selected within a certain frequency range, which ensures that the excitation lies within the desired bandwidth. The selection of those start and stop frequencies of chirps is optimized using a Monte-Carlo approach with an objective function defined to maximize the main lobe of the autocorrelations while minimizing the side lobe level of the auto-correlation and the peak values of the cross-correlations. On reception, a dispersion-compensated filtering approach as described in our previous work [14,15] is adopted here as a consequence of the dispersive nature of Lamb waves. Performance is evaluated by comparing signals to those obtained via separate excitations as well as by comparing delay-and-sum images constructed by residual signals before and after introduction of simulated damage. This paper is an extension of results previously reported by the authors [16]. A similar approach was described by De Marchi et al. [17] for guided wavefield imaging using a laser vibrometer but with different excitations and processing methods.

The rest of this paper is organized as follows. Section 2 introduces the theoretical background of the Lamb wave multi-transducer simultaneous excitation system, including a review of dispersion-compensated filtering and details of the excitation sequence construction. Section 3 quantifies the parameter choice during excitation construction by simulations. Section 4 describes two experiments using an 8-element transducer array on an aluminum plate. Section 5 demonstrates and discusses the performance of the proposed method, and Section 6 contains concluding remarks.

2. Theory

2.1. Dispersion-compensated matched filtering

Conventional matched filtering refers to the cross-correlation between the measured signal, $w(t)$, and the excitation signal (a.k.a. the template), $s(t)$,

$$\begin{aligned} R_{sw}(t) &= \int_{-\infty}^{+\infty} s(\tau)w(t+\tau)d\tau \\ &= \int_{-\infty}^{+\infty} s(\tau-t)w(\tau)d\tau. \end{aligned} \tag{1}$$

This process is also referred to as pulse compression in non-dispersive wave propagation scenarios used in radar, sonar, and bulk wave ultrasonics, where the measured signal $w(t)$ can be thought of as the sum of scaled and shifted versions of the