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Strain sensitivity enhancement of ultrasonic waves in plates using phase filter

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***Abstract*—Ultrasonic guided waves can be used to measure mechanical strain in plates due to the stress-induced velocity change. Strain monitoring is usually performed by measuring the time-of-flight shift. However, interpretation of results can be difficult due to wave mixing, mainly when several dispersive modes propagate, or in the presence of reflections. In these cases, the time-reversal focusing technique can be used to monitor the strain level, by observing the peak of the focused time-reversal signal, which changes proportionally to the strain level. However, not all components of the spectrum contribute with the same sensitivity to strain changes. In this paper, we developed a signal filtering procedure based on the phase of the Fourier spectrum that increases the time-reversal strain sensitivity. The time-reversal process is modified by using a new signal as reference which is synthesized relying on prior knowledge of the impulse response at some non-null strain level. The technique was evaluated with different pairs of transducers in an aluminium plate, effectively producing more strain-sensitive signals. However, high strain-sensitive signal presents poor energy concentration which, in turn, can be difficult to detect. The technique can be adapted to provide strain-robust signals.**

***Index Terms*—Strain monitoring, ultrasonic guided waves signals, time-reversal, filtering.**

I. Introduction

Measuring and monitoring the mechanical strain of structures is relevant in several fields, such as civil engineering [1], oil and gas industry [2] and aeronautics [3]. Ultrasonic guided waves are widely used in the non-destructive evaluation and structural health monitoring of structures [4]. Ultrasonic waves can be used to monitoring strain by measuring the time-shift of received signals [5]–[7] since the propagation speed of an ultrasonic wave is proportional to the stress level of the medium, according to the acoustoelastic theory [8]. The acoustoelastic effect on ultrasonic guided waves is more complex than on bulk waves. Each guided wave mode presents different sensitivity to strain [9] which also depends on the frequency. That is, at each frequency, the time-shift that each mode may experience is different.

In plate-like structures, ultrasonic waves are generally dispersive and multimodal [10]. Therefore, due to a general excitation, the received signal can be composed of several waves which may overlap in time, rendering identification of time-shifts complicated. The time-reversal technique can be used to compensate for dispersion and multimodal behaviour of guided waves creating a focused signal even in the presence of reflections [11]. In a previous work, time-reversal signal processing was used in order to evaluate the variation of the longitudinal tensile stress in plates [12]. The principle relies on the mismatch of the system transfer function due to the presence of stress, which reduces the focusing capability of the time-reversal process, and in turn reduces the peak of the final focused signal, being therefore easily observable.

In this paper, we have modified the time-reversal procedure aiming for increasing its sensitivity to strain. It is modified by using a new signal as reference which is synthesized by means of filter based on the phase of the Fourier spectrum of the impulse response signal at some foreknown non-null strain level.

II. Theoretical Background

Consider a thin plate with two ultrasonic transducers spaced on the plate's surface, one used as transmitter and the other as receiver. When a broadband pulse is used to excite the transmitter, potentially several dispersive guided wave modes may be generated and consequently received at the receiver. Due to this dispersive and multimodal behaviour, it may be

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complicated to interpret the received signal. The signal is yet more complex when reflections from the plate's end are received. If the plate is subjected to stress each mode presents a different time-shift [9] and, due to the aforementioned nature of the received signal, identification of the stress effect in such a complex signal is impractical without resorting to some advanced signal analysis technique.

The time-reversal technique is a process that compensates for the multimodal and dispersive behaviour, allowing all the propagation modes to arrive synchronously at the reception point, producing a focused and recompressed signal [13]. This process can be summarized as follows. First, an impulse-like signal is sent from the transmitter. This produces a response signal in the receiver that can be considered as the impulse response of the system, say $h(t)$. The signal $h(t)$ obtained in this step is the reference signal for the remaining steps. Next, $h(t)$ is time-reversed, $h(-t)$, and retransmitted which produces a new signal received by the receiver, say $y(t)$. The latter is the time-reversal response which is maximum at its focusing instant, $t = 0$, where the time-reversal signal presents a high amplitude main peak. Assuming that the system is linear and remains unaltered, $y(t)$ can be computed numerically by convolving $h(-t)$ with $h(t)$. The numerical approach, however, does not enjoy the high physical energy obtained with the physical implementation.

In order to quantify the time-reversal focusing capability, the time-reversal energy efficiency, TREF, can be used, as proposed in [12]. It is defined as the ratio of the energy in the central peak of $y(t)$ to the whole signal's energy.

When strain is imposed into the plate, if the same reference signal is used as the time-reversed excitation, then the focusing capability decreases, which can be used as a way to monitor the strain changes in the medium. This can be understood by assuming that the transfer functions in the forward and reversed propagation steps are no longer the same. This happens due to the change in each mode's speed, according to the acoustoelastic theory [9]. Considering that the forward propagation step is performed under no stress and the time-reversed step is performed under longitudinal stress, then the strain dependence in the the time-reversal signal is given by:

$$y(\varepsilon, t) = \int_{-\infty}^{\infty} H^*(0, f) H(\varepsilon, f) e^{j2\pi f t} df \quad , \tag{1}$$

where $H(0, f)$ is the Fourier transform of $h(0, t)$, the reference signal under zero-strain, and $H(\varepsilon, f)$ is the system transfer function when the plate is subject to a strain ε, or the Fourier transform of $h(\varepsilon, t)$.

III. Phase Filtering Procedure

In this paper, the aforementioned time-reversal strain monitoring process is modified aiming to increase its sensitivity to strain. This is accomplished by using a new reference signal which is synthesized through a phase filter that relies on prior knowledge of the forward signal at some nonzero strain state. The filtering technique is performed as follows.

Initially, the Fourier Transform of the impulse response signals under null strain $h(0, t)$ and under some non-zero strain, say ε_1, $h(\varepsilon_1, t)$ are acquired. These two signals are cross-correlated, which is performed in the frequency domain by

$$S_{\varepsilon_1}(f) = H^*(0, f) H(\varepsilon_1, f) \quad . \tag{2}$$

As can be seen from (2), the phase of $S_{\varepsilon_1}(f)$ represents the phase shift between the two impulse responses, namely, $h(0, t)$ and $h(\varepsilon_1, t)$.

Assuming that the effect of strain in ultrasound signals is predominantly manifested in their phase [8], $S_{\varepsilon_1}(f)$ presents high phase values for the frequency components that are more affected by strain, i.e. the more sensitive components. Based on this principle, one can define the ϕ-sensitive frequencies as the ones whose phase of $S_{\varepsilon_1}(f)$ is greater than ϕ. Formally, a zero-one function, $M_{\phi,\varepsilon_1}(f)$, is built, given by:

$$M_{\phi,\varepsilon_1}(f) = \begin{cases} 0, & \left|\angle S_{\varepsilon_1}(f)\right| < \phi \\ 1, & \left|\angle S_{\varepsilon_1}(f)\right| \geq \phi \end{cases} \quad . \tag{3}$$

The actual filtering step consists of multiplying $M_{\phi,\varepsilon_1}(f)$ by the frequency spectrum of the original reference signal under null strain:

$$H_\phi(f) = M_{\phi,\varepsilon_1}(f) H(0, f) \quad . \tag{4}$$

This creates a new spectrum $H_\phi(f)$, in which the frequency components that were deemed unfit, i.e. with low sensitivity, are eliminated.

Finally, $H_\phi(f)$ is transformed back to the time domain by the Inverse Fourier Transform, given rise to $h_\phi(t)$. This new time-domain signal is used as reference for the original time-reversal monitoring procedure, as explained in section II. More precisely this signal should be used as the time-reversed excitation, instead of $h(-t)$. Therefore, the modified time-reversal signal becomes

$$y_\phi(\varepsilon, t) = \int_{-\infty}^{\infty} H_\phi^*(f) H(\varepsilon, f) e^{j2\pi f t} df \quad . \tag{5}$$

Observing (3) one can see that, when $\phi = 0$, the original signal remains the same, i.e., it is not filtered and, when $\phi = 180^0$, all of the original signal is filtered, thus $H_\phi^*(f)$ is nullified. That is, the higher the value of ϕ in $M_{\phi,\varepsilon_1}(f)$ in (6), the more sensitive to strain the filtered signal, $y_\phi(\varepsilon, t)$.

Conversely, if strain-robust signals are needed, this technique can be adapted, by reversing the phase criterion, to provide less strain-sensitive signals. In this case the zero-one function becomes:

$$N_{\phi,\varepsilon_1}(f) = \begin{cases} 0, & \left|\angle S_{\varepsilon_1}(f)\right| > \phi \\ 1, & \left|\angle S_{\varepsilon_1}(f)\right| \leq \phi \end{cases} \tag{6}$$

Note that, when $N_{\phi,\varepsilon_1}(f)$ is used for filtering out the unwanted components, because the threshold angle criterion is reversed compared to $M_{\phi,\varepsilon_1}(f)$, then for ϕ close to 180^0, the original signal remains unchanged whereas for low ϕ values, many components are removed. In other words, the lower the value of ϕ in $N_{\phi,\varepsilon_1}(f)$ the more robust the filtered signal, $y_\phi(\varepsilon, t)$, as opposed to $M_{\phi,\varepsilon_1}(f)$. The synthesis of strain-robust signals may be of interest when one intends to use $h_\phi(t)$ to monitoring for other disturbances, such as the occurrence of flaws, and the effect of strain in the signal should be mitigated.

IV. Results

Experimental signals were obtained with a pair of piezocomposite transducers centred at 0.5 MHz and another pair at 1 MHz in a 3-mm-thick, 800-mm-long aluminium plate. The setup follows [12]. One element of each pair was used as transmitter and the other one as receiver. Transducers were bonded on the plate's surface close to each of its longitudinal ends. The plate is mounted over a structure able to impose longitudinal tensile strain into the plate.

The reference signal acquired due to the first propagating step is shown in Fig.1(a) and (c) in both the time and frequency domains, respectively, for the 0.5 MHz transducer.

Throughout this paper, the proposed filtering is implemented by numerically convolving the reference signals. The focused signal is shown in Fig.2(a). As it can be seen this signal presents a high main peak, which concentrates part of the signal's energy; the level of energy concentration is measured by the TREF, in this case its value is 15.37%.

When a tensile stress is imposed into the plate, if the same reference signal [shown in Fig.1(a)] is used, then the focused signal is altered, according to (1). The peak amplitude decreases as strain increases. The red symbols in Fig.3 represent the main peak amplitude reduction related to the zero-strain value. The amplitude reduction sensitivity is calculated as the angular coefficient of a linear fit (red line of Fig.3) of experimental peak values. In this case, the sensitivity is $0.09\%/\mu\varepsilon$, where the unit of $\mu\varepsilon$ means here a strain of $\mu m/m$.

A. Strain-Sensitive Signal Filtering

The proposed filtering technique aiming to produce more sensitive signals is evaluated. Here, $S_{\varepsilon_1}(f)$ was calculated [see (2)] through the knowledge of the impulse response at the maximum strain used in experiments, i.e. ε_1 equals about 150 $\mu m/m$. Fig. 1(b) and (d) show the filtered reference signal, $h_\phi(t)$, for $\phi = 30^0$ in the time and frequency domains, respectively. Comparing it with the original reference signal [Fig.1(a)], it is clear that its shape in the time domain was heavily altered due to the filtering procedure. Observing the filtered reference signal in the frequency domain one can see that this is due to the removal of several of its frequency components. Those are the one recognized by $M_{\phi,\varepsilon_1}(f)$ as low-sensitive, i.e. with phase shift lower than $\phi = 30^0$.

The new reference signal is then used in (5). Fig. 2(b) shows the focused time-reversal signal under null strain. Note that it still preserves some focusing capability, even though the reference signal lost a great deal of its frequency content. This is assessed by the TREF, which has decreased to 5.96%. This reduction is caused by increase of amplitude outside the main peak.

Fig. 3 shows the behaviour of the peak amplitude, as a function of strain, for the modified technique in blue. As it can be seen, it has a higher angular coefficient, in absolute value, than the original technique (red curve). That is, it has a higher sensitivity to strain, equal to $0.35\%/\mu\varepsilon$. Thus, the sensitivity to strain was increased thanks to the proposed filtering technique by a factor of 3.9. A thorough assessment of the sensitivity as a function of the threshold angle was

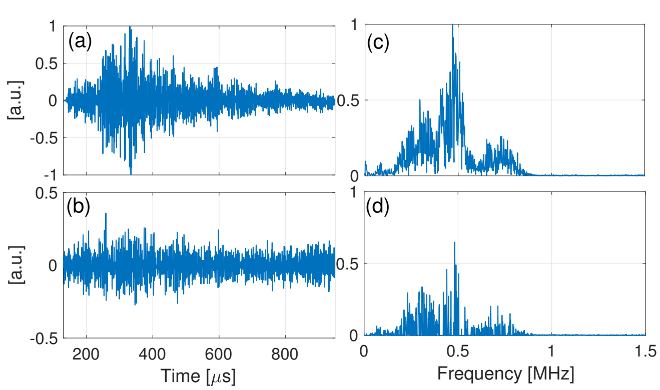

Fig. 1. Original, (a) and (c), and filtered, (b) and (d), reference signals obtained with the 0.5 MHz transducer pair at the time, (a) and (b), and frequency, (c) and (d), domains. Filtered signals were obtained using $M_{\phi,0\sigma}(f)$, at $\phi = 30^0$.

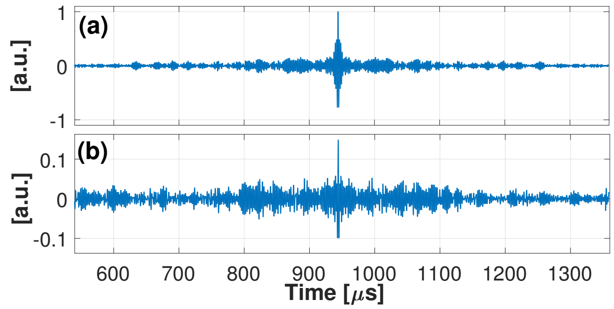

Fig. 2. Original (a) and filtered (b) time-reversal signal, obtained with a pair of piezocomposite transducers centered at 0.5 MHz, at $\phi = 30^0$.

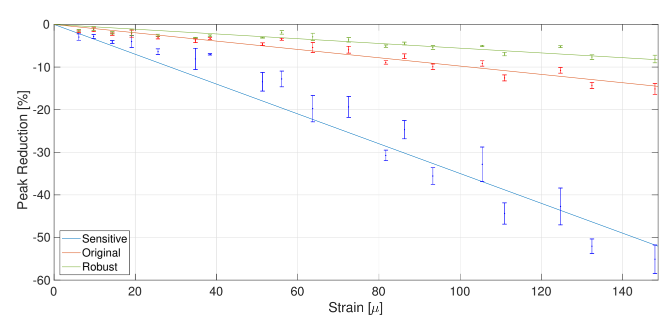

Fig. 3. Peak reduction as a function of strain, obtained with a pair of piezocomposite transducers centered at 0.5 MHz. Symbols are experimental points, lines are linear fit. Red symbols and line indicate measurements without filtering whereas blue symbols and line indicate reference signal at $\phi = 30^0$ using $M_{\phi,0\sigma}(f)$ and green symbols and line indicate the use of $N_{\phi,0\sigma}(f)$ at same ϕ.

performed by evaluating the whole procedure for ϕ from 0 to 180^o in 1^o step. Fig. 4.(a) and (b) shows the peak reduction sensitivity and TREF behaviour, respectively, as a function of ϕ. One can see that with a higher peak sensitivity was achieved as ϕ increases, up to about 80^0, reaching a maximum increase. The highest increase among all experiments was obtained with the 1 MHz transducer pair where sensitivity was increased to about eighteen-fold.

However, it is inherent to the process to reduce the focusing capability, TREF, as ϕ increases. This can be explained by the fact that the $H_\phi(f)$ has less frequency content than $H(0, f)$, i.e. its spectrum is poorer, resulting in a lower energy concentration [12]. Analysing, for instance, the response of the 1 MHz transducer pair to the filtering technique at 80^0, one can see that its focusing capability suffered a major reduction, reaching down to 0.27% thus severely compromising strain monitoring through peak observation.

B. Strain-Robust Signal Filtering

As stated in Section III, more strain-robust signals can be synthesized by using $N_{\phi,0\sigma}(f)$ instead of $M_{\phi,0\sigma}(f)$. The green line in Fig.3 shows the angular coefficient of the peak decrease trend line when using $N_{\phi,0\sigma}(f)$ with $\phi = 30^o$. As it can be seen, lower sensitivity was obtained, as it dropped from $0.09\%/\mu\epsilon$ to $0.06\%/\mu\epsilon$. The sensitivity as a function of ϕ is summarized in Fig. 5. Recall that, due to the inversion of the phase criterion, the results along the abscissa of Fig. 5 should be interpreted accordingly. For instance, for the 1 MHz transducer pair at about $\phi = 30^0$, the sensitivity decreased to $0.02\%/\mu\epsilon$, which corresponds to an increase in the robustness (the inverse of sensitivity) of almost two times. It can be concluded that, despite effective, the synthesis of more robust signals did not achieve the same level of enhancement as the strain-sensitive approach. On the other hand, Fig.5 shows that along most of ϕ axis, TREF does not suffer such a major reduction as in Fig.4.

V. Conclusion

It was possible to identify the frequency components in the reference signal that are most affected by strain through their phase shift compared to foreknown impulse response under non-zero strain. This technique was able to increase the peak amplitude to strain. However, an inherent trade-off exists, as increasing sensitivity come with a cost of decreasing the focusing capability, which may hinder monitoring through peak observation since it renders difficult to accurately locate the peak. By contrast, whenever strain-robust signals are needed, this technique can be adapted, by reversing the phase criterion, to provide less strain-sensitive signals. In this case, the increase of robustness was generally lower than the increase in sensitivity.

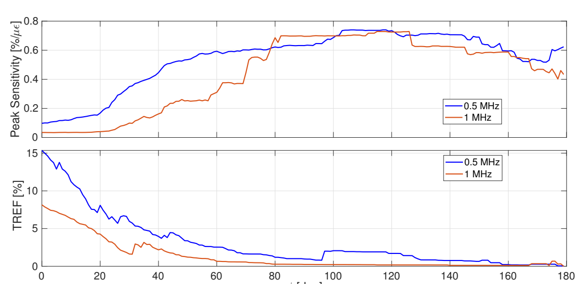

Fig. 4. Peak sensitivity and TREF as a function of ϕ using $M_{\phi,0\sigma}(f)$.

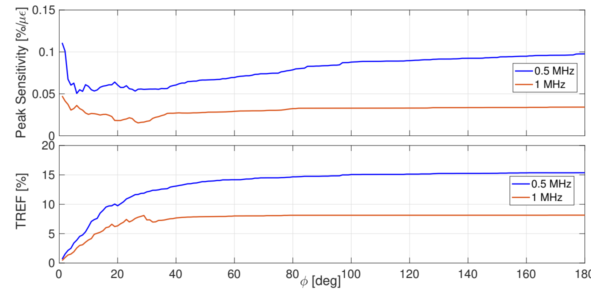

Fig. 5. Peak sensitivity and TREF as a function of ϕ using $N_{\phi,0\sigma}(f)$.

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