# Application of an STFT-based filter in ultrasonic signals for strain monitoring

Lucas M. Martinho, Florencia Blasina, Nicolás Peréz, Alan C. Kubrusly

***Resumo*—Monitorar o nível de deformação é crucial em diversas aplicações. Sinais de ultrassom em meios reverberantes podem ser utilizados para esse fim através da observação do valor de pico do sinal obtido pela técnica de reversão temporal ou pela correlação cruzada. Neste artigo, apresentamos uma modificação dessa técnica em que um sinal de referência é alterado a partir de um processo de filtragem utilizando a transformada de Fourier de tempo curto, a fim de aumentar a sensibilidade do sinal à deformação. Essa técnica foi avaliada em sinais experimentais e foi capaz de fornecer um aumento de sensibilidade à deformação de até cerca de cinco vezes.**

***Palavras-Chave* — *Monitoramento de deformação, sinais de ultrassom, STFT***

*Abstract*— **Monitoring mechanical strain is relevant in several applications. Ultrasonic signals in reverberant media can be used to this purpose by observing the peak of the time reversal or cross-correlation signal. In this paper, we propose a modified technique in which the reference signal is altered using a short-time Fourier Transform based filter to increase the sensitivity to strain. This technique was evaluated in experimental signals and was able to produce up to about fivefold more strain-sensitive signals.**

***Keywords* — *Strain monitoring, ultrasound signals, STFT.***

## I. INTRODUCTION

Measuring and monitoring the mechanical strain of structures is relevant in several fields, such as, civil engineering [1] and aeronautic [2]. Ultrasonic waves can be used to this purpose by measuring the time-shift since the speed of propagation is proportional to the stress level of the propagating medium [3]. In plate-like structures, ultrasonic waves are usually dispersive and multimodal. Therefore, the detected signal can be composed of several waves which may overlap in time, rendering the identification of time-shifts complicated. In this case, the time-reversal signal processing or cross-correlation techniques produce a focused signal, similar to the matched filter approach, which can be used to monitor strain by the changes in the peak of the focused signal, as proposed previously [4].

In the analysis of dispersive multimodal wave signals, the received signal is usually composed of several waves distributed over time and in the frequency spectrum. Therefore, identification in either time or frequency domains is usually not possible. However, they can be better distinguished through time-frequency representations, such as the short-time Fourier transform (STFT) [5]. In this paper, we propose a technique to identify the components of the STFT spectrum less affected by strain and filter them out in order to increase the sensitivity of the strain monitoring process.

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## II. METHOD

### A. Original strain monitoring technique

In order to monitor the strain level, two ultrasonic transducers are positioned on a plate along the direction of propagation. An initial broadband pulse excites several waves in the plate under no strain which propagate until being received by the opposite transducer, this received signal is the impulse response of the plate. Fig. 1(a) shows the experimental received signal obtained with a piezoelectric transducer centered at 2 MHz, in a 3 mm-thick aluminum plate where transmitter and receiver were separated by 700 mm. This signal is used as reference for the time reversal or cross-correlation, producing a focused signal. See ref. [4] for details on this technique. Fig. 1(c) shows the experimental focused signal.

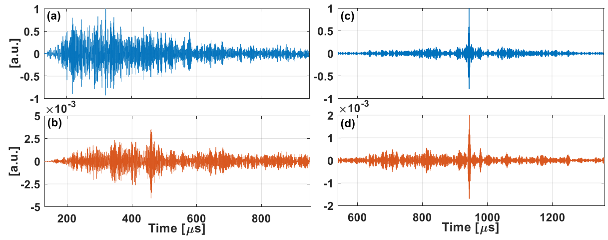


Fig. 1. Original reference signal (a), new reference signal with filtering technique at $\phi = 30^{o}$ (b), original time-reversal signal (c) and new time-reversal with filtering technique at $\phi = 30^{o}$ (d)

If a non-zero strain is imposed on the plate, the peak of the focused signal is shifted in time and decreases because the dependence on strain of the propagation speed of each wave is different [6]. Since many wave modes arrive distributed over time and at different frequencies, it is interesting to analyse how the many signal components are affected by strain in both time and frequency domains.

### B. Synthesis of high sensitive reference signal

The filtering technique is performed as follows. Initially, the STFT [7] for the impulse response signals under null strain, $Y_0(\tau,f)$, and under maximum strain, $Y_{\sigma_{max}}(\tau,f)$, are computed following Eq.1:

$$Y(\tau,f) = \int_{-\infty}^{\infty} y(t)w(t-\tau)e^{-j2\pi f t}dt \,, \qquad (1)$$

where $w(t)$ is a Blackman window function. Fig.2(a) shows the STFT spectrogram for the reference signal of Fig.1(a).

Next, these two spectra are cross correlated, which is calculated by multiplying them in the STFT domain:

$$S_{o\sigma}(\tau,f) = Y_0^{\,*}(\tau,f)\, Y_{\sigma_{max}}(\tau,f)\,. \qquad (2)$$

The phase of $S_{o\sigma}(\tau,f)$ represents the phase shift between the two signals, at each coefficient, here represented by the time-frequency pair $(\tau,f)$. Since the effect of strain in ultrasound

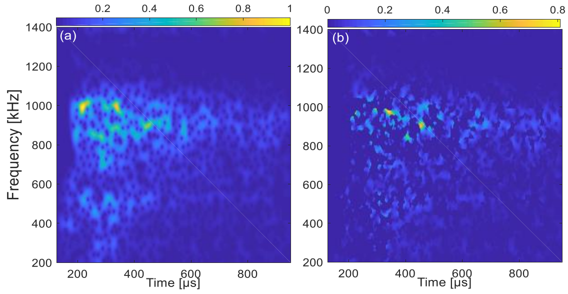


Fig. 2. Absolute value of the STFT of the original (a) and (b) filtered with at $\phi$ = 30º reference signals. The color bar indicates the coefficients' intensity.

signals is predominantly manifested in their phase [3], the phase of $S_{o\sigma}(\tau, f)$ should present high values for the components that are more affected by strain. Based on this principle, one can determine the sensitive coefficients. Sensitive coefficients present phase shift higher than a predefined threshold ($\phi$). The selection of the threshold depends on the specific application. Then, a zero-one function $M_{\phi,o\sigma}(\tau, f)$, is built, given by:

$$M_{\phi,o\sigma}(\tau, f) = \begin{cases} 0, & |\angle S_{o\sigma}(\tau, f)| \leq \phi \\ 1, & |\angle S_{o\sigma}(\tau, f)| > \phi \end{cases}, \quad (3)$$

where $\angle S_{o\sigma}(\tau, f)$ is the phase of $S_{o\sigma}(\tau, f)$. Filtering in the STFT domain is performed by multiplying $M_{\phi,o\sigma}(\tau, f)$, by the STFT of the original reference signal, under null strain:

$$Y_{filt}(\tau, f) = M_{\phi,o\varepsilon}(\tau, f)\, Y_0(\tau, f)\,, \quad (4)$$

This creates a new spectrum, $Y_{filt}(\tau, f)$, in which the spectral components that were deemed unfit, i.e. with low sensitivity, are eliminated. Fig.2(b) shows the STFT spectrogram for the new signal. As it can be seen, comparing it with the original signal, [Fig.2(a)] several components are absent.

Finally, $Y_{filt}(\tau, f)$ is transformed back to the time domain by the inverse STFT [7]. This new time domain signal is used as a reference for the original monitoring procedure, as explained in section II.A.

## III. Results

As an example, Fig. 1(b) shows the filtered signal for $\phi$ = 30º. Comparing it with the original reference signal [Fig.1(a)], one can see that its shape is altered due to filtering. The focused signal under null strain is shown in Fig.1(d). Note that it still preserves its focusing capability. However, the amplitude outside the main peak has increased, i.e. the energy concentration caused by the modified procedure is reduced since some content of the original signal has been removed.

The behavior of the peak amplitude and time, as a function of strain, is shown in Fig. 3 for the original and new procedure, with $\phi$ = 30º. The sensitivities for the amplitude reduction and time-shift are calculated by the angular coefficient of a linear fit (straight lines in Fig.3) of experimental peak value and time shift, respectively. As it can be seen, the proposed technique effectively increased both sensitivities.

Fig. 4 shows the amplitude reduction sensitivity and the energy concentration, which is the ratio of the energy inside the main peak to the energy of the remaining signal, as defined in ref. [4], as a function of $\phi$. Note that the sensitivity increases as $\phi$ increases until about 110º where it reached a maximum of fivefold the original procedure's value. Highly sensitive signals present, however, very low energy concentration of the focused signal. At about 30º a fair compromise between sensitivity gain and energy concentration decrease is met. A similar analysis could be carried for the time shift as a function of $\phi$, however, for the sake of brevity, only amplitude sensitivity is shown.

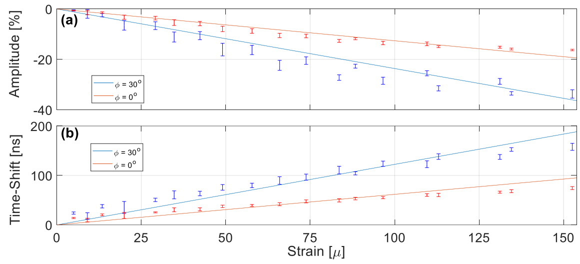


Fig. 3. Peak reduction (top) and time-shift (bottom) as a function of the strain. Symbols are experimental points, lines are linear fit. Blue bars and curves indicate reference signal obtained with $\phi$ = 30º and red bars and curves indicate measurements without filtering.

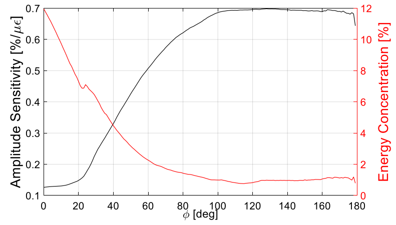


Fig. 4. Amplitude sensitivity and energy concentration as a function of $\phi$.

## IV. Conclusion

It was possible to identify the components in the reference signal that are most affected by strain through their phase shift in the STFT spectrum. Approaching the problem in the time-frequency domain is relevant because the detected signal is composed of several waves, which are affected by strain differently, arriving over the time range with different frequency content. This technique increased the peak amplitude and the time-shift sensitivities to strain, by the cost of decreasing the focusing capability. This may hinder monitoring through peak observation since it renders difficult to accurately locate the peak. One has to be aware of this trade-off.

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