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Impact of resynchronization errors on the localization quality of defects in reverberant plates

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Abstract. In the context of Structural Health Monitoring (SHM), recent research works have been carried out to take advantage of the correlation of ambient noise to locate and characterize defects in reverberant plates. The back-propagation-based imaging algorithms developed in this way require that the signals recorded by the sensors of the control network be perfectly synchronized. This implies that these sensors must be linked to a common clock to ensure their synchronization, which generates significant complexity of the monitoring system in the case of embedded applications. Post-processing resynchronization is a promising solution to deal with this problem. However, in less favorable cases and especially in the presence of additive noise, this resynchronization could be made with some errors. In this work, we are interested in quantifying statistically the degradation of the contrast of localization images as a function of the statistical parameters of resynchronization errors. The obtained results are promising and can be of great interest for embedded applications.

1. Introduction

The need to monitor the structural state of infrastructures using systems with low energetic and hardware resources has given rise to so-called "passive" imaging techniques that take advantage of ambient noise to locate defects in reverberant mediums. These techniques, which require no controlled emissions, guarantee significant energy savings throughout the monitoring process. The works presented in [1, 2] have shown that it is possible to reconstruct the Green's function of a given medium using the cross-correlations between a set of sensors recording the ambient noise to which the medium is subjected.

Recently, the field of Structural Health Monitoring (SHM) has undergone a significant evolution with the growing adoption of autonomous sensor networks integrated directly into the structures themselves [3, 4]. This innovation aims to transform the way we monitor the integrity of infrastructures by enabling continuous and real-time monitoring. The use of these embedded sensors reduces the complexity of traditional



monitoring systems and increases their efficiency, as they provide accurate and immediate data on the condition of structures. This enables engineers and maintenance managers to make rapid and informed decisions, minimising the risk of structural failure and extending the life of installations.

Although independent sensor networks dedicated to SHM have demonstrated a significant reduction in cost and complexity, resynchronization remains a major challenge for this technology [5, 6]. In fact, since each receiver operates with its own independent internal clock, significant drifts occur between the recorded signals. To remedy this, a lot of synchronization methods have been proposed in the literature [7, 8, 9]. However, it should be noted that the most precise ones require the use of additional hardware or communication protocols so that the sensor network is well synchronized. Nevertheless, this contradicts the idea of developing autonomous monitoring networks with low material and energy resources.

The Peak Correlation Technique (PCT) [10, 11, 12] is recognized as promising method for detecting time shifts between signals. Basically, it involves correlating the positive and negative time lags of the cross-correlation between signals recorded by a pair of sensors. A peak in this correlation corresponds to the time shift between these signals, facilitating sensor resynchronization in post-processing without the need for additional electronic hardware complexity. However, the presence of noise in the measurement process can lead to imperfect resynchronization and subsequently poor defect localization.

This work is outlined as follows : we initially focus on theoretically quantifying the impact of resynchronization errors on the quality of defect detection in elastic reverberating plates. Subsequently, we conduct some numerical simulations to validate the theoretical findings.

2. Theoretical developments

We consider a configuration of N independent acoustic sensors placed on a plate exposed to some ambient noise (see Fig. 1). The methodology for detecting and localizing potential defects involves cross-correlating the noise recorded by each sensor, coupled with the implementation of a back-propagation and dispersion-compensation algorithm developed in [13, 14]. Indeed, by computing the positive time lag in differential noise cross-correlation between two cases—with and without a defect—it is possible to isolate the defect signature. Subsequently, a pixel-by-pixel back-propagation technique is employed to construct an image that accurately localizes the defect.

We assume that each receiver operates with its own independent internal clock, which can result in potential time drifts between recorded signals. Consequently, resyn-

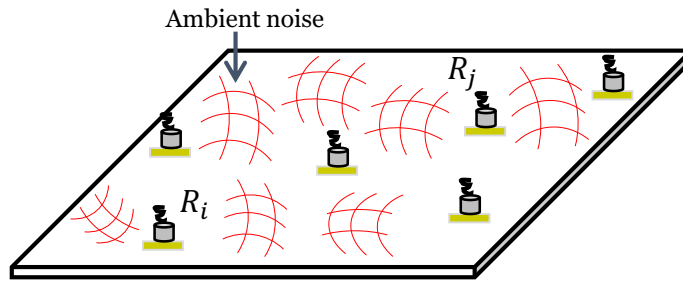


Figure 1: Schematic representation of the studied configuration.

chronization of the signals is essential before applying the previously explained localization algorithm.

Here we are interested in quantifying the degradation of the defect detection as a function of resynchronization errors. For this, we define a contrast ratio denoted C_r between the case with resynchronization error and a reference case without resynchronization error as

$$C_r = \frac{\langle I_{res} \rangle}{I}, \quad (1)$$

where I_{res} and I are the defect pixel intensities in the cases of imperfectly and perfectly resynchronized signals respectively and $\langle \cdot \rangle$ denotes the mathematical expectation on a set of realizations on synchronization errors.

In a previous work [15], we have shown that in the case of small values of the standard deviation of resynchronization errors, the contrast ratio can be written as

$$C_r \approx 2\pi |p(\omega_0)|^2, \quad (2)$$

where $p(\omega_0)$ is the probability density function of resynchronization errors at ω_0 the central frequency of the bandwidth.

This formulation demonstrates the relationship between localization performance and the standard deviation of the resynchronization errors. This relationship will be applied and validated through a numerical example in the next section.

3. Numerical validation

In order to validate the previously obtained theoretical results, a numerical simulation is carried out in this section using a finite element code ELMER. This code simulates acoustic wave propagation in a finite plate using the Reissner-Mindlin plate model.

The configuration tested (see Fig 2) consists of an aluminum plate of dimensions $1 \times 0.5 \text{ m}^2$ and thickness 3 mm, its physical properties are noted in table 1.

Table 1: Aluminum’s physical properties: density ρ , Young’s modulus E and Poisson’s ratio ν .

Material	ρ ($kg.m^{-3}$)	E (GPa)	ν
Aluminum	2700	70	0,35

On the surface of this plate, we place an array of 8 sensors at known positions and a distribution of 600 sources uniformly distributed around the sensors. A defect is modeled by a point contact normal to the surface of the plate at position (53, 26) cm.

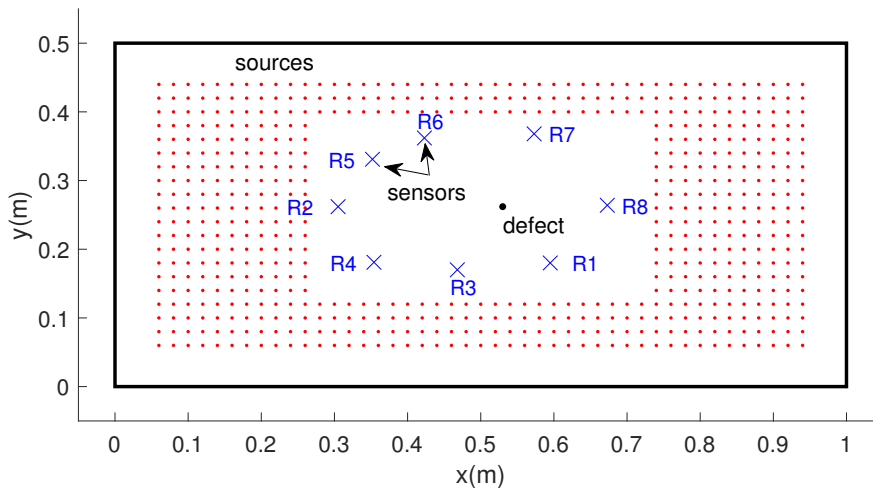


Figure 2: Simulated configuration: aluminum plate 1×0.5 m² and 3 mm thick. 8 sensors (blue crosses). 600 sources uniformly distributed around the sensors (red dots). A point defect at position (53, 26) cm.

The emission signal is a Gaussian-windowed sine of frequency $f_0 = 20$ kHz. The sampling frequency is 2.5 MS/s. For each pair of receivers, the summed cross-correlation over all sources is computed.

The back-propagation-based imaging algorithm previously recalled is then applied on the positive time lag of computed differential cross-correlations. The obtained localization image is shown in Fig. 3. Pixel intensities are normalized with respect to the maximum intensity. As expected, the defect location is correctly localized.

Now we are interested in highlighting the effect of synchronization errors on the defect localization image quality. These errors are modeled by random shifts following a Gaussian distribution $\mathcal{N}(0, \sigma)$ introduced on the computed cross-correlations. For each value of σ , the contrast ratio between the cases with and without synchronization errors

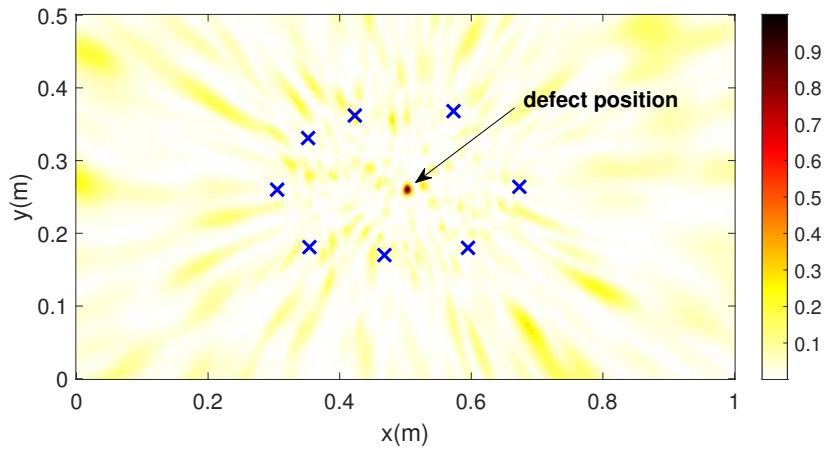


Figure 3: Defect localization image.

is computed and averaged over 500 realizations. This averaged numerical contrast ratio can then be compared to the theoretical expression established in Sec. 2.

In the case of a Gaussian distribution, the Fourier transform of the probability density function is

$$p(\omega) = \frac{1}{\sqrt{2\pi}} e^{-\frac{\sigma^2 \omega^2}{2}}. \quad (3)$$

Consequently, Eq. 2 in Sec. 2 becomes

$$\mathcal{C}_r = e^{-\sigma^2 \omega_0^2}. \quad (4)$$

The corresponding curves as a function of σ are represented in Fig. 4, along with the averaged numerical contrast ratio computed from the simulation.

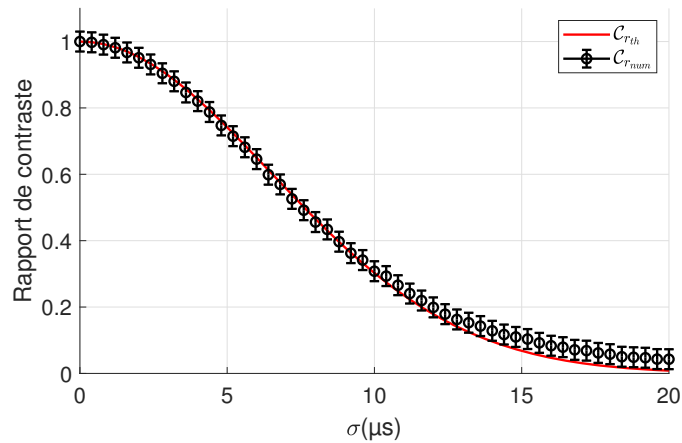


Figure 4: Comparison between numerical (error bars curve) and theoretical (solid line) contrast ratios.

Referring to Fig. 4, the numerical contrast ratio matches the theoretical prediction for small values of σ , ($\sigma \leq 12 \mu s$). Above $12 \mu s$, we notice a discrepancy of the numerical curve compared to the theoretical one. This is due to the assumption of low sigma values considered in the theoretical developments. The error bars are estimated from the fluctuations of the contrast ratio with respect to the realizations on the synchronization errors. The small error bars indicate that the contrast ratio does not fluctuate significantly across realizations and can be favorably compared with the developed theoretical formula [Eq. 4].

4. Conclusion

This paper addresses the issue of potentially imperfect signal resynchronization in passive imaging using the PCT in plate-like structures, particularly when employing acoustic sensors with independent time-bases. First, we have developed a theoretical formula to quantify how the contrast ratio in defect localization images deteriorates as a function of the statistical properties of resynchronization errors in correlation functions. Then, a finite element simulation was conducted in order to validate the relationship between the contrast ratio and the standard deviation of resynchronization errors.

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