Experimental study of passive defect detection and localization in thin plates from noise correlation

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Abstract

This paper reports experimental results on a passive imaging technique for structural health monitoring to detect the occurrence of defects in plate-like structures. This technique is based on the fact that the active transient response between two sensors can be passively retrieved by cross-correlating the ambient noise-field recorded on these two sensors. A correlation matrix is estimated from friction noise recorded on a transducer array. It is observed that the accuracy of the estimated transient responses strongly depends on the spatial distribution of noise sources. The best convergence is obtained when the noise is uniformly distributed over the whole plate area. Defects are localized by applying a dispersive beamforming algorithm to the difference between the correlation matrices obtained with and without (w/o) defect. It is shown that the quality of the active transient response reconstruction is not a strong requirement for the defect localization. Indeed, the defect is successfully localized even if the noise source distribution is not uniform, provided that it remains spatially stationary between the states w/o defect. A simple theoretical framework is proposed to interpret these results.

Keywords: Passive defect localization, Ambient noise correlation, Flexural waves, Beamforming

1. Introduction

The idea of Structural Health Monitoring (SHM) is to provide real-time integrity control of structures to reduce maintenance costs. SHM principles include active (Pitch-catch, Pulse-echo) and passive sensing technologies (V. Giurgiutiu (2008), J. L. Rose et al., (1994)). Commonly, in active sensing mode, an excitation signal is sent to one transducer and other sensors pickup the medium responses. Passive sensing is differentiated from active one in that no energy is purposely assigned into the structure and sensors are deployed in a pure listening mode for collecting signals mined for defect detection. Here, we propose an original passive method based on noise correlation approach. The idea here is the passive estimation of the Green’s functions (GF) of the medium by using ambient noise (for instance, aerodynamic noise for aeronautical application). The main application of the GF extraction from noise correlation function (NCF) is in seismology (B. Artman., (2002), N. M Shapiro., (2004)). Passive GF estimation also offers promising applications in other domains ranging from ultrasound to medical imaging, but only a few works are...
devoted to SHM. In this field, a pioneer work consisted to use the traffic excitation to recover resonant frequencies and modal damping of a bridge from NCF (C. R Farrar., (1997)). Later, this approach has been applied to extract the Rayleigh-Lamb Green’s transient responses on plates (E. Larose et al., (2007)). To detect a defect, an original method has been proposed (E. Moulin., (2009)) that is particularly efficient when noise sources distribution is not uniform. Recently, based on numerical simulation results, the beamforming of the NC matrix estimated by a sparse array, can be efficiently used to localize a defect (L. Chehami et al., (2014)). Here, we first experimentally study the quality of the GF reconstruction from frictional noise in an aluminum plate, then, the obtained responses are used to detect and localize defects. Finally, the effect of noise distribution and stationarity, on the defect imaging ability is quantified.

2. Passive GF reconstruction and principle of defect localization

The results presented here are valid for a thin solid plate. The matrix of correlations of signals received on a sensor network when the plate is subject to acoustic noise produced by sources distributed on the plate, can be written as (L. Chehami et al., (2014))

\[ C(t) = [G(t) - G(-t)] \otimes f(t) + n(t), \]

where \( f(t) \) is an equivalent source term and \( G(t) \) is the Green’s function matrix. This equation can be interpreted as the deterministic GF retrieval by noise correlation. The quantity \( n(t) \) corresponds to the spurious contributions which degrade the quality of this Green’s function reconstruction. It should be noted indeed that if the noise sources are uniformly distributed (here, friction noise), \( n(t) \) decays toward zero. In such a case, we find the classical result that, the time derivative of the cross-correlation yields the difference between the causal and anti-causal Green’s function (L. Chehami et al., (2014)).

When talking about passive imaging, two processes are distinguished: i) GF reconstruction , ii) Resolution of an inverse problem to estimate the defect (or sources) location. Here, as commonly done in many imaging methods, the retrieved impulse responses are used to localize the defect (H. Gao et al., (2005)). The defect feature is discriminated by computing the differenced noise correlation matrix \( \Delta C(t) \) between matrices \( C^{ref} \) and \( C^{def} \) built-up from the states without and with defect, respectively. The geometrical estimation of the defect location is then performed by beam-forming \( \Delta C(t) \), taking into account the A0 Lamb wave dispersion (for more details about the localization technique see (L. Chehami et al., (2014))). Some experimental results are shown in the next section.

3. Experimental results

Measurements are made using an array of eight transducers bonded to an aluminum plate of dimensions 1.5 m² and 3 mm thickness. A broadband noise is generated by rubbing continuously and manually the whole plate surface with a soft scrubbing pad. Waveforms are digitized at a sampling rate of 96 kHz during 60 s. First, the correlation matrix \( C^{ref} \) is built-up from the waveforms acquired in the healthy plate. A typical result of the cross-correlation between two channels is plotted on Fig. 1-(a). The transient response directly recorded when one of the two transducers acts as a source is plotted on the same figure (magenta dashed line). The good agreement in both amplitude and phase confirms the ability to passively estimate the transient response in a very efficient way using this particular type of
noise. Then a small defect simulated by a glued-on mass (9 mm in diameter, 10 mm long) was attached to plate surface, and correlation matrix $C_{def}$ is estimated. The differenced matrix $\Delta C(t)$ is then used to localize the defect. The ability of this technique is confirmed by the successful localization result shown on Fig. 1-(b). The friction area is indicated by a black dashed rectangle and the defect by a small square. The transducers positions are indicated by "×".

In the previous example, the correlation matrices are estimated from the case where the noise is generated on the whole plate area. However, in real application conditions (aeronautical field, for example), sources might be distributed in a non-uniform way over the structure surface. Therefore, it is interesting to study the influence of the spatial noise distribution on the GF reconstruction accuracy and on the defect localization.

Here, we propose to study this aspect first on the GF reconstruction. To this end, a sequence of frictional noise is generated over a small area of roughly $37 \times 33$ cm$^2$ size indicated by a black dashed rectangle. Here again the same pair correlation is plotted and compared to the active response (see Fig. 2-(a)). Contrary to Fig. 1-(a), the cross-correlation displayed on Fig. 2-(a) shows an inaccurate reconstruction of the active response. But, even if the retrieved GF is not perfect, the imaging process is sufficiently efficient so that the spurious speckles caused by the reconstruction errors $n(t)$ remain below the level of the main lobe. This is confirmed on the beamforming result shown on Fig. 2-(b). As can be seen, the defect is still successfully localized.

Among the factors that can influence the defect imaging, there is the aspect of the non stationarity of the noise. Indeed, in real conditions, the noise generation areas might be different between the reference and the damaged states. To simulate this effect, the matrices $C_{ref}$ and $C_{def}$ are again estimated but from different noise areas. This effect is illustrated on Fig. 3-(a). As can be seen, when the generation areas are close, $\Delta C(t)$ beamforming cancels sufficiently the spurious contributions and makes the localization acceptable. Contrary to this case, on Fig. 3-(b) where the noise areas are more distant, the defect detection is impossible. For this last case, $\Delta C(t)$ beamforming increases strongly the spurious lobes which are dominant compared to the main lobe.
4. Discussion

We have shown previously, that the defect can be localized even with small noise areas, but the spatial stationarity is necessary especially when the noise areas are widely spaced. A simple way to interpret these results consists to express the differenced correlation matrix $\Delta C$ from Eq. (1):

$$\Delta C = [\Delta G(t) - \Delta G(-t)] \otimes f(t) + n_B(t) - n_A(t) + \delta n_B(t),$$

where $A$ (resp. $B$) is the noise generation area used for the acquisition of the correlation matrix without (resp. with) defect. $\Delta G$ is the part of the Green’s function due to the defect. The terms $n_A$ and $n_B$ are the spurious contributions, without the defect, obtained for generation areas $A$ and $B$, respectively. Finally $\delta n_B$ is the difference of the spurious terms obtained with and without defect when the noise is generated in area $A$. When the generation areas are identical ($A = B$) (case of Fig. 2-(b) for example), even if $n_A(t)$ is quite strong because area $A$ is small compared to the whole plate area, the difference between the correlation matrix cancels this contribution and only the small spurious contribution $\delta n_B(t)$ remains (L. Chehami et al., (2015b)). This last enhances a little the spurious lobes on the images, compared to the main lobe on the defect due to $\Delta G(t) - \Delta G(-t)$. On the contrary for different areas, $n_B(t) - n_A(t)$ might be the strongest contribution, possibly making the defect non-localizable such as observed in Fig. 3-(b).

5. Conclusion

Passive defect imaging in plate structures can be performed despite the imperfect Green’s function reconstruction. Nevertheless, because of the differential acquisition of the correlation technique, we have shown that the defect localization capability is more sensitive to spatial non-stationarity of the noise than to the quality of the Green’s function estimation. Hence, we have experimentally shown and by using low software and hardware constraints, that the method is suitable and robust to detect defects. These preliminary experiments are very promising for Structural Health Monitoring applications using ambient noise and are expected to be of considerable value in the future. Further work will focus on a full theoretical development to be able to provide some basic characteristic parameters of the defect.

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References


