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Nonlinear secondary noise sources for passive defect detection using ultrasound sensors

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A B S T R A C T

This paper introduces the concept of secondary noise sources for passive defect detection and localization in structures. The proposed solution allows for the exploitation of the principle of Green's function reconstruction from noise correlation, even in the absence of an adequate ambient noise. The main principle is to convert a part of low-frequency modal vibrations into high-frequency noise by exploiting the frictional contact nonlinearities. The device consists of a mass-spring resonator coupled to a flexible beam by a rough frictional interface. The extremity of the beam, attached to the surface of a plate, excites efficiently flexural waves in the plate up to 30 kHz when the primary resonator vibrates around its natural frequency, i.e. a few dozens Hz. A set of such devices is placed at random positions on the plate surface, and low-frequency excitation is provided by a shaker. The generated high-frequency noise is recorded by an array of eight piezoelectric transducers attached to the plate. A differential correlation matrix is constructed by subtracting correlation functions computed from noise signals at each sensor pairs, before and after the introduction of a local heterogeneity mimicking a defect. A simple array processing then allows for the detection and estimation of the defect location from this differential correlation matrix. Beyond the successful proof of concept, influence of experimental parameters, such as the number of secondary sources or the variability of the position of the shaker application point, is also investigated.

1. Introduction

Theoretical and experimental studies have shown that, under the assumption of diffuse noise, the cross-correlation of the recorded fields in two points A and B of a medium gives access to the impulse response between these points as if one receiver acted as an active source [1–7]. The mathematical expression associated to this property is

$$\frac{\mathrm{d}}{\mathrm{d}t}C(A, B, t) \propto \left[G(A, B, t) - G(A, B, -t)\right], \tag{1}$$

where C is the cross-correlation, and G is the medium Green's function.

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In ultrasound applications, and particularly in structural health monitoring field, power consumption and complexity of the electronics might represent key issues for the standard methods used in active configurations (pitch-catch). An alternative way could then consist in taking benefit of ambient noise to reveal defects (cracks, holes, …) by passively estimating the Green's functions using the physical principle illustrated by Eq. (1).

The possibility of detecting and localizing defects using ambient noise (friction noise, acoustic noise…) more or less uniformly generated on surface plates has been demonstrated numerically and experimentally in recent works [8,9]. Suitable noise sources for this application should be uncorrelated, with fixed locations and with wideband frequency contents in the ultrasound range. Such source characteristics might not be often available in a natural way. On the other hand, low frequency vibrations sources are common in a number of applications, including transportation, machinery, etc. These sources preferentially excite the first structural modes. Since they are very low frequency, strongly correlated from a point to another and possibly non-stationary, such vibrations cannot be used for the passive defect localization application. To overcome this problem, a prototype of an artificial secondary "passive" acoustic source is proposed. Its role is to transfer part of the energy from the ambient low frequency (LF) vibrations to a secondary high frequency (HF) field by exploiting the frictional contact nonlinearities.

Generally, friction resulting from the sliding contact between two solids, gives rise to diverse forms of waves within solids and frequently leads to undesirable sounds (brake noise, rail-wheel noise…) in the surrounding medium [10–13]. Dry friction-induced vibrations have been the subject of a huge amount of research works, particularly in acoustics [14,15,11,16–21], where the usual objective is to minimize unwanted acoustic emissions. However, recent works [22] have investigated the possibility of using friction nonlinearities as a tool for transferring energy from an acoustic field to another one at different frequencies. In this context, the development of an artificial acoustic secondary source, needed for passive SHM applications, is based on a system constituted by a primary resonator that is connected to a secondary one by a rough sliding interface. The vibration of the main resonator, induced by the ambient low-frequency noise, allows the frictional sliding at the contact interface with the secondary resonator. The dry frictional contact provides then a wideband excitation, generated by nonlinear friction-related effects (roughness, stick-slip, …), which excites the secondary resonator and generates a secondary acoustic field with wide frequency spectrum. The generated secondary field is shown to efficiently excite the flexural waves (A_0 Lamb mode) on an elastic plate in the ultrasound range.

The paper is structured as follows: In Section 2, the passive defect localization method based on the correlation technique, developed in previous works [8,9], is introduced and serves as the reference technique. Then, Section 3 reports the design of the secondary acoustic source and the principle of the energy transferring by dry friction. In Section 4, the HF secondary noise generated by the proposed device is used to detect defects in plate-like structures. In Section 5, the analysis of the effect of a variable position of the LF excitation point on the defect localization images is presented. Finally, some conclusions are presented in Section 6.

2. Passive defect localization

A reverberating plate with a set of transducers fixed on its surface and subject to ambient acoustic noise is considered. It has been shown in a recent work [8] that the differential correlation matrix, that is obtained from the subtraction of the correlation matrices with and without defect, can be expressed as

$$\Delta\mathbf{C}(t) = [\Delta\mathbf{G}(t) - \Delta\mathbf{G}(-t)] \otimes f(t) + \Delta\mathbf{n}(t), \tag{2}$$

where $\Delta\mathbf{G}$ is the part of the Green's function due to the defect and $\Delta\mathbf{n}$ is called the correlation residue (or reconstruction error). This second term corresponds to the part of the differential correlation that is not included in the first term $[\Delta\mathbf{G}(t) - \Delta\mathbf{G}(-t)] \otimes f(t)$. Since this first term can be interpreted as a passive retrieval of information contained in the Green's function, $\Delta\mathbf{n}$ corresponds to a spurious residual that will not contribute to the detection. It strongly depends on the number and the distribution of noise sources (more details about the correlation residue are given in previous works [8,9]). Function $f(t)$ can be considered as a virtual excitation waveform and is given by

$$f(t) = \frac{N_S \tau_a}{2\mathcal{S}\rho h} \int_{-\infty}^{t} R_n(\tau) d\tau, \tag{3}$$

with h the plate thickness, ρ the volume density, $\mathcal{S}$ the plate area, $R_n(\tau)$ the autocorrelation of the noise source and τ_a the characteristic attenuation time constant of the plate.

As shown in previous works [8,9], this differential correlation matrix can be used as the input of a defect localization algorithm, as though it was an actively acquired signal matrix. However, two conditions are necessary for efficient detection: first the noise should have non-negligible components in the useful frequency band (where wavelengths are of the same order of magnitude as the defect size) and second, the correlation residue should be small compared to $\Delta\mathbf{G}(t) \otimes f(t)$.

The second condition means that the noise sources should be both uncorrelated and well distributed over the plate surface or at least, as will be explained later, with unchanged spatial distribution between the acquisitions with and without defect. This can be illustrated through the following considerations. Notations A and B refer to two given spatial distribution configurations of the noise sources used for the acquisition of the correlation matrix without and with defect, respectively. The expression of the reconstruction error can then be written as