Proposition and recommendations on a source localization method for popping noise in large window frames based on the analysis of lamb waves propagation

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ABSTRACT

Complaints concerning popping noises issued by thermal movement have increased due to the use of large window frames with energy-efficient glazing. This phenomenon can have multiple causes and is usually addressed by trial-and-error adjustments without knowledge of the problem location. We propose recommendations for accelerometers positioning and for a source location detection method based on the analysis of Lamb waves propagation signals measured on one in-situ aluminium frame. The method processes information carried by the S0 and A0 modes to estimate the problematic areas. Processing is done in temporal and temporal-frequency domain to decompose the signal into its S0 and A0 components. It shows that most of the energy is carried by the A0 wave while the S0 wave propagation time, due to non-dispersive characteristic at frequency * width of concern, can be used for source location detection based on wave front time of arrival detection.

1. INTRODUCTION

Complaints concerning popping noises issued by thermal movement have increased due to the use of large window frames with energy-efficient glazing. This phenomenon, which is induced by a mechanical stress under thermal constraints can have multiple origins amongst the variable parts of the frame and its fixations and is usually addressed by trial-and-error adjustments without knowledge of the problem location. This process is time consuming, costly and the success in solutioning the problem is uncertain and can lead to the whole frame replacement. To our knowledge, no publication exists on this subject. Thus, more information is needed on the subject and this paper will focus on localization of the problematic area on in-situ window frames.

This discussion is based on a real case where popping noise took place on an aluminium frame with a south exposition, Figure 1. The popping noise happened around noon (direct exposure to the sun light) and 17h, that is, when the temperature gradients on the frame were the highest. The contractor had reopened the frame to check if any fixation was blocked and was running out of solutions. To localize the most probable problematic area, 15 accelerometers were placed along the frame and popping noise events were registered at a 204800 Hz sampling frequency. Then, a simple technique based on the detection of the first accelerometer reached by the vibration was used to build an event map, see Figure 2. This simple technique has some limitations such as the need to have an accelerometer close to the source which can be difficult for large frames due to accessibility and due to the high number of accelerometers required to cover the entire frame. Those data are exploited a posteriori to analyse the vibrations and their propagation. Based on this analysis, preliminary findings can be exploited for recommendations on the accelerometer locations and signal processing techniques to help localize the vibration source.

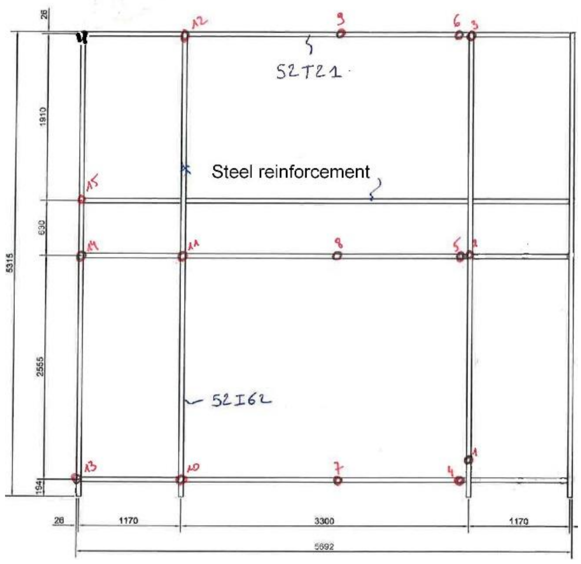


Figure 1 Dimensions of the aluminum window frame analyzed and position of the accelerometers.

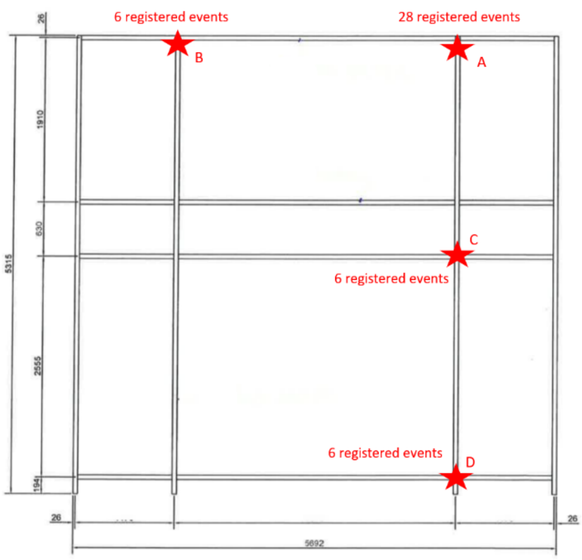


Figure 2 Map of the vibration-first-reached accelerometer.

According to acoustic emission testing (AE), a part of the non-destructive test (NDT) area which is used in structural health monitoring, emission sources can be evaluated through the study of their intensity and arrival time to collect information, such as their location. The waves propagating in thin plates, such as the aluminium foil used in window profile, (O. Xeridat [1]) “are of two types: Lamb waves, polarized in the sagittal plane, and shear waves polarized in the horizontal plane. Lamb waves induce two types of distortions: symmetric (S) and antisymmetric (A) modes. They have the advantage of propagating over long distances with little energy loss, justifying their intensive use in the field of non-destructive testing and evaluation. However, they involve several complications due to their vectorial nature, their dispersive nature and their multimodal propagation".

At first, localization based on time-of-flight (TOF) has been tested and has shown some uncertainties due to attenuation and dispersion. Secondly, a time-frequency analysis is conducted and information is used to isolate dispersive and non-dispersive wave propagation which provide information useful for localization.

2. SIGNAL ANALYSIS

The in-situ case study is based on an aluminum facade window frame. The frame dimensions are about 5.3 m x 5.6 m, and accelerometer positions are illustrated at Figure 1. Looking to find closest accelerometers from source event location by selecting the accelerometer first reached by the vibration, the most frequent first-reached accelerometer is the number 3, later referred to as Acc3, located on the same vertical profile as accelerometers Acc1, Acc2.

2.1. Temporal analysis

The classification on arrival time has been manually done based on a visual analysis of the temporal signals and also automatically based on the AIC picker [2]. First-reached accelerometers are adequately detected but as soon as attenuation and dispersion comes into play, the detection is more error-prone. An example of an event detected at Acc3 is shown at Figure *3* with signals from accelerometers 1, 2 and 3, located on the same profile. As the accelerometers are located around 2 meters from each other, the attenuation is clearly observable.

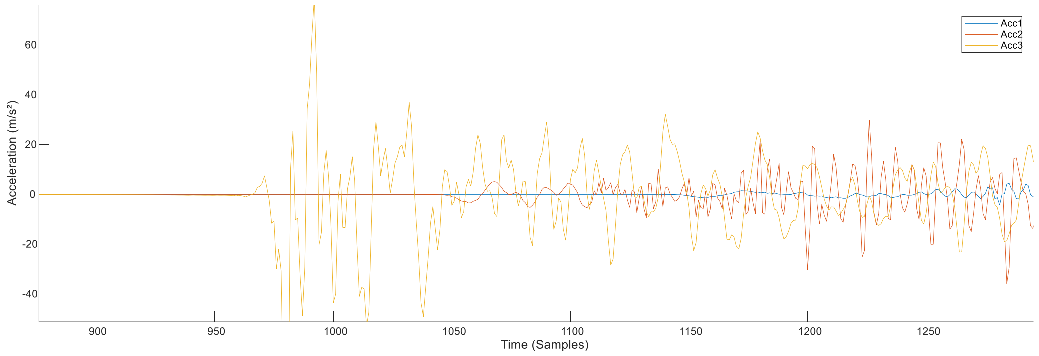


Figure 3 Temporal signal for accelerometers 1, 2 and 3.

For accelerometers 3 and 6, separated by a few centimeters but located on two different profiles, high attenuation is observed, see Figure 4. This is probably caused by the physical discontinuity between profiles.

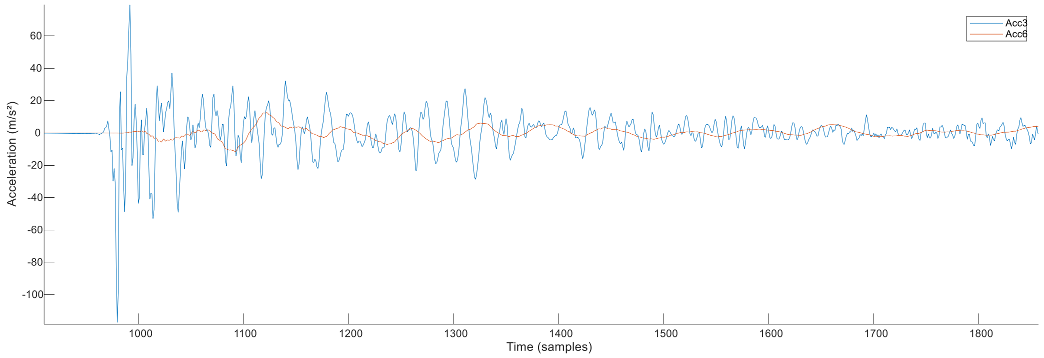


Figure 4 Temporal signals for accelerometers 3 and 6 on separate profiles.

The attenuation in both examples can be a problem for front wave detection as comparison can thus be applied to different parts of the signal. In an example given by Maji [3], it leads to a localization error up to 23 cm for 1m-separated accelerometers. But the attenuation linked to discontinuities also teach us that the source is tightly connected to the vertical profile and can be located with the three accelerometers 1, 2 and 3. Now, the relative position of the source on the profile still need to be found. As two accelerometers are on the outer boundaries of the profile, we could compute the source location based on the propagation delays and the propagation speed between Acc1, Acc2 and Acc3. To do so, we need to find the front wave with a sufficient precision which is not easy due to wave attenuation and dispersion as mentioned before.

2.2. Time-frequency comparison

Previous analysis is limited to the temporal domain but more information can be extracted from the signals by taking into account the spectral content evolution through time. In this work, switching from the temporal representation to the temporal-frequency domain is done with a chirplet transformation [4], [5] which has been preferred over Wigner-Ville, Short-Time Fourier Transform or the wavelet transform for its higher temporal resolution and its absence of cross-terms artefacts. Examples are given for Acc3, Acc2, Acc1 and Acc 6 in Figure 5.

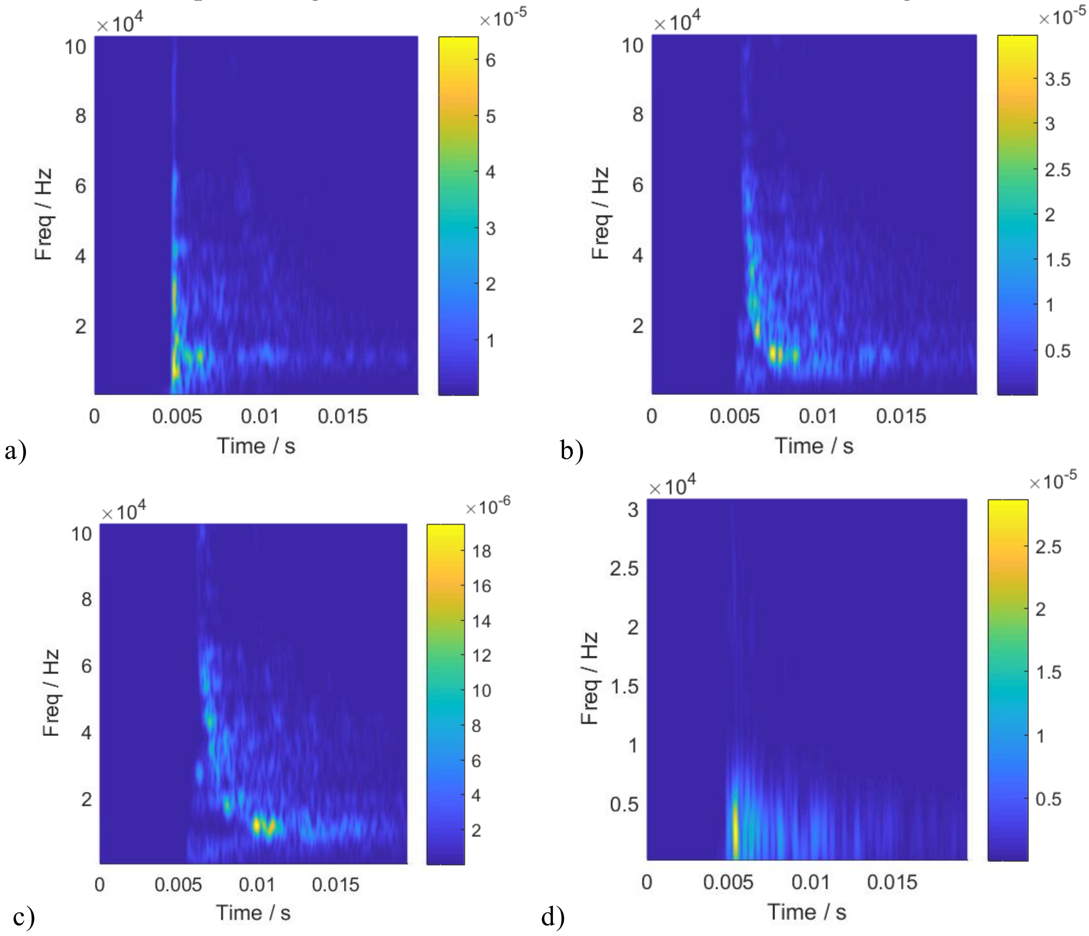


Figure 5 Time-frequency representation for accelerometers a) Acc3, b) Acc2, c) Acc1 and d) Acc6.

Acc6 signal is clearly lacking high frequency content (above 7-8 kHz) but more interestingly, we can see two propagation modes for waves traveling between Acc3, Acc2 and Acc1: dispersive and non-dispersive. These modes correspond to the first two Lamb wave modes A0 and S0 for aluminum whose velocity dispersion curves are given in Figure 6. Considering a standard aluminum frame foil thickness of 2 mm and a maximum signal frequency of 102.4 kHz, the region of interest on the dispersion curves graph is comprised in the green box. Then, the A0 wave is clearly dispersive while the S0 mode isn't. This is what we observe in Figure 5: a little bit of energy is transmitted by the S0 mode and travels at the same velocity for all frequencies while the most energetic part is transmitted on the A0 mode with lower velocity at lower frequencies.

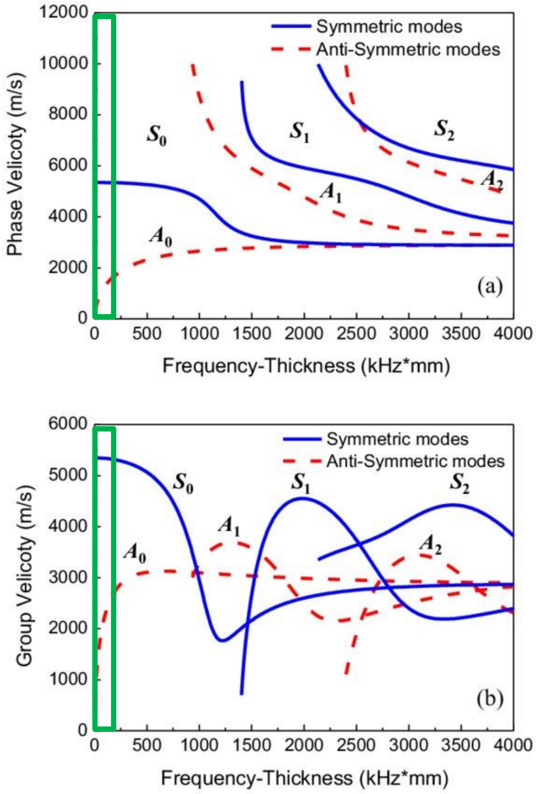


Figure 6 Dispersion curves of Lamb waves of a 2 mm aluminum plate: (a) phase velocity; (b) group velocity. From source **[6]**.

Interestingly, for Acc3, the energy is mostly localized around the same arrival time. It means that the vibration source is really close to Acc3 as dispersion of the impulse signal has not yet occurred or in a very limited way. This will lead to future work for developing a robust method based on dispersion backpropagation.

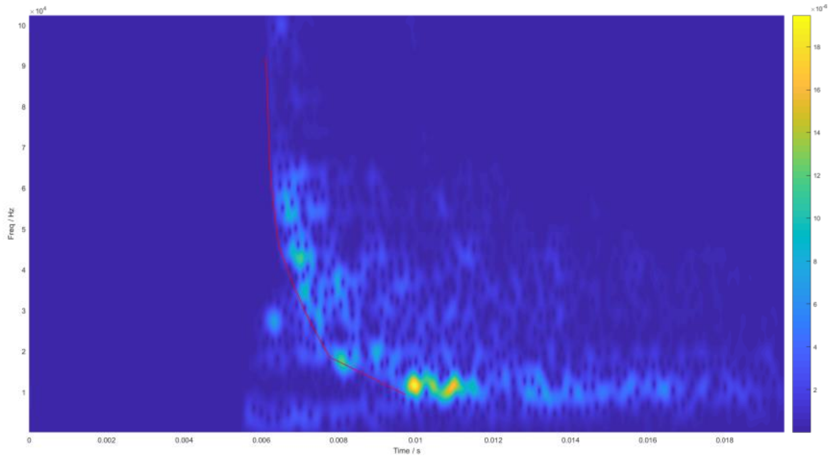
2.3. Future work: Localization based on A0 mode backpropagation

As illustrated in 2.1, localization based on the temporal front wave detection can be conducted. At accelerometers close to the source, it will detect A0 or/and S0 modes while at further positions, it will detect the S0 mode which only carries a small part of the energy and will be the mostly adversely affected by attenuation. Moreover, as the accelerometers are on a line, localization won't be effective for sources outside the area delimited by the outward receivers. Thus, accelerometers will have to be on the profile extremities.

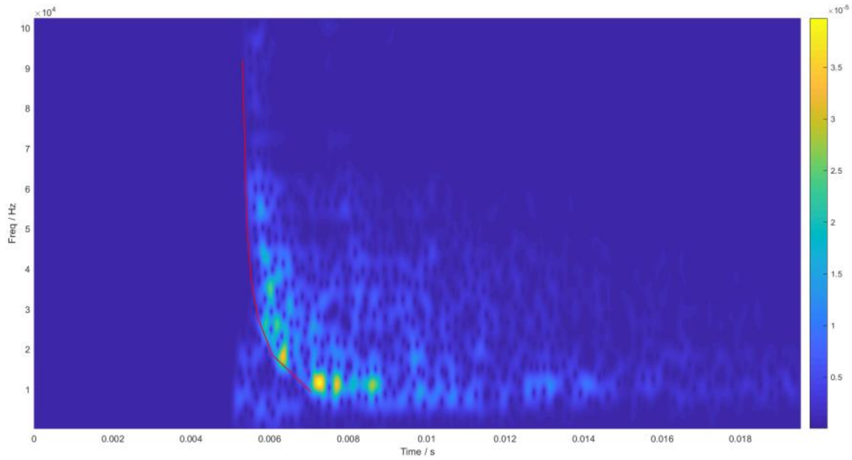
Another technique would take advantage of A0, the most energetic mode, which will be less adversely affected by attenuation and which has the ability to retrieve source location outside of the accelerometers area as explained below. With this technique, theoretically, only one accelerometer per profile could be sufficient as long as the dispersion curve of the A0 mode is known.

The idea behind localization based on dispersive propagation of impulsive signals is to backpropagate [3] the dispersed wave until reconstruction of an impulse, which corresponds to the vertical alignment of the wave energy on the time-frequency representation. The velocity profile could be obtained from simulations or measured in-situ from the TOF between two or more accelerometers separated by known distances. A precise and robust technique for TOF still needs to be evaluated, see Xu and Al. [7], [8] for multimodal and dispersive Lamb waves techniques, including cross-correlation, envelop moment, matching pursuit decomposition and dispersion compensation.

A basic example of backpropagation is illustrated in Figure 7. The A0 mode wave front velocity, Figure 8, has been crudely estimated based on manual and visual identification of the A0 wave front (red line) at Acc1 and Acc2. Then the wave front (red line) at Acc3 location has been estimated by backpropagation from Acc2. While the result is by no way perfect, the agreement with measurement is sufficiently good to pursue in this direction for future works.



a)



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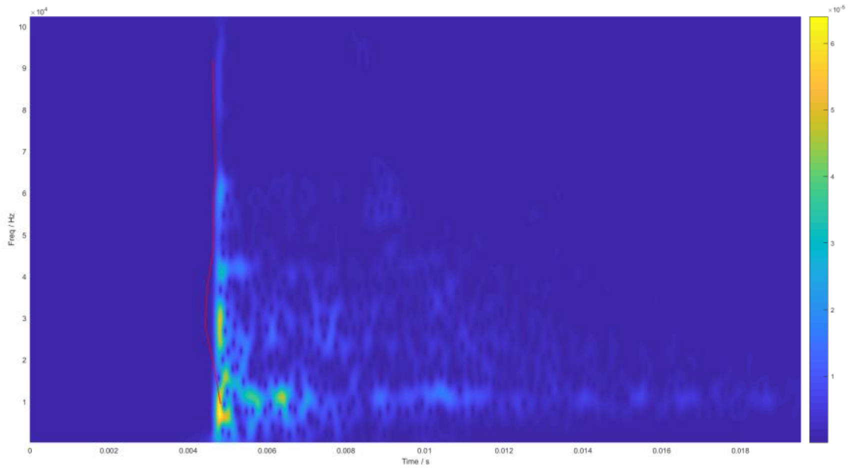

c)

Figure 7 Wave front a) manually selected for Acc1 b) manually selected for Acc2 c) reconstructed for Acc3.

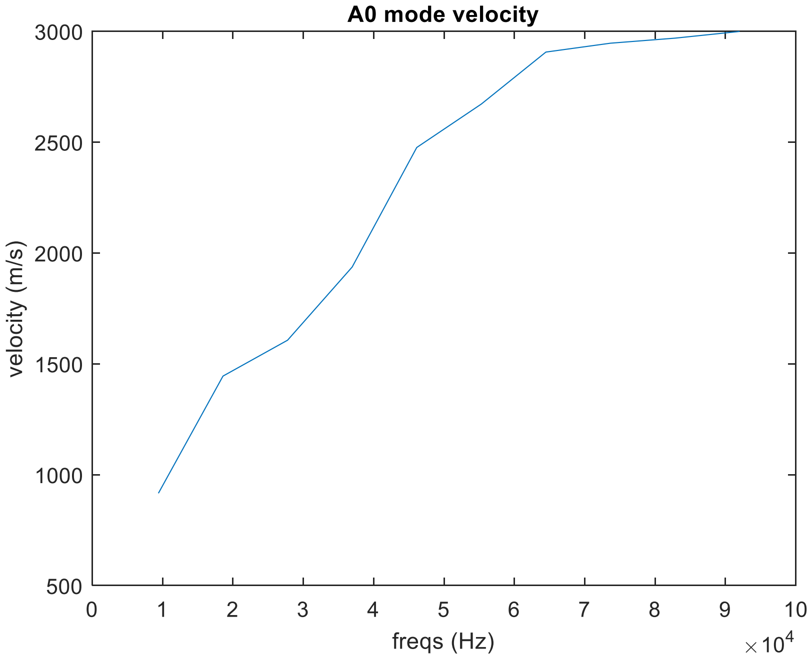

Figure 8 A0 mode estimated velocity curve from Acc1 and Acc2.

3. PROPOSITION

Here, we will propose a preliminary method for popping noise source localization. If the frame is easily accessible and not too big and while this hypothesis still needs to be tested on more cases, one accelerometer at both ends of each profile should allow to detect most of the events. First, detect the most energetic and first-reached accelerometer. Secondly, check on a time-frequency representation if dispersion is present. The more dispersion, the further the source is. If both accelerometers that are on both ends of the same profile exhibit dispersion, then the source is located in-between, at a relative distance proportional to their dispersion.

Covering the entire frame is not always possible because the number of accelerometers would be too high or because the in-situ accessibility is not easy. If the entire frame can be covered, than by using the time-frequency representation, it is easy to determine if the source is localized closely to an accelerometer. If not, then the dispersive wave A0 can be used to localize the source on a profile but the wave speed must be known for a number of frequencies. This property could be used to limit the number of accelerometers and only use easily accessible locations. If propagation is limited to one profile due to discontinuities, then it should be sufficient to use only one accelerometer by profile.

This technique based on the A0 mode dispersion could be used to avoid covering the entire frame with accelerometers. But, more investigations are needed to identify and develop a precise and robust backpropagation method, which is part of our future work.

5. CONCLUSIONS

Based on one in-situ measurement, temporal and temporal-frequency analysis, a first simple but crude method for popping noise localization has been tested. This method allows to easily detect events on the boundary of the frame and the temporal-frequency domain helps to detect how close the source is to the accelerometer. These results are part of a preliminary study and suggest that the dispersive propagation properties should be the next step toward a simpler and more robust detection method. More measurements, both in-situ and in-laboratory are mandatory for further development and validation of a localization method valid for various popping noise causes.

6. ACKNOWLEDGMENTS

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