inter.noise 2014
MELBOURNE AUSTRALIA
16-19 NOVEMBER

Application of the virtual time-reversal technique to transient sources localization in complex immersed structures

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ABSTRACT

Transient sonar detection systems have been developed over the last decades, and hence transient noise emissions from ship have become a matter of concern for acoustic discretion. One step towards the mitigation of transient noise emissions from ships consists in the accurate localization and identification of the noise sources. We use in this paper the virtual time-reversal method to localize vibratory transient noise sources. The localization system is implemented and tested in a representative naval structure. The test structure considered here is a semi-cylindrical ribbed shell partially immersed in water, equipped with some machinery items (pumps, engines, etc.). Due to the size of the structure and its complexity, the virtual model is constructed using point to point transfer function measurements. This transfer function database is then used to reemit reversed signal and to identify the transient source location. Various experiments are performed to demonstrate and analyze the performances of the localization system with both vibratory and acoustic excitations. The robustness of the method towards various parameters such as the measurement points meshing and the frequency band considered is detailed.

Keywords: localization, transient underwater noise I-INCE Classification of Subjects Number(s): 41.3, 74.9

1. INTRODUCTION

Underwater noise emitted by ships, machines or offshore platforms are two natures: stationary and transient. If the first ones have been deeply studied, in particular within the framework of the optimization of the discretion and the stealth of naval ships, the second haven't received the same attention. New types of sonar based on the detection of transient noises have appeared recently. The emission of impulsive noise thus becomes a new risk, which must be taken into account in design process of the ship or naval system. In the field of civilian applications, this topic can also be of interest, as impulsive noises of strong intensity generated by offshore platforms can be very harmful for the environment (bio-acoustic impact on the marine wildlife).

One way of mitigating transient underwater noise emissions is to lower the source levels. However, it is obviously necessary to identify and localize the mechanical and/or acoustical source responsible for the transient noise emission. The first step towards the control of transient noise emissions thus consists in the accurate localization of the source. These shocks appearing in a unexpected way and because of the complexity of the structure, the localization of the source is sometimes not straightforward.

This paper aims at presenting a method for the accurate localization of transient noise sources in a complex naval structure, by using the virtual time-reversal method. Section 2 gives an overview of the virtual time-reversal method applied to the localization of transient noise sources. Section 3 describes the naval structure used for the experiments and section 4 presents the experimental results. Conclusions and perspectives are given in section 5.

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2. VIRTUAL TIME-REVERSAL METHOD

The problem thus concerns the propagation of elastic waves in large-scale complex structures, for which the virtual time-reversal method is particularly interesting since it takes advantage of the complexity of the structure for the localization of sources. In particular, we shall be interested in the propagation in the audible frequency range, in order to benefit from large propagation distances, allowing improving the accuracy of the localization.

The time-reversal method was proposed in the 80s by Pr. Mathias Fink (1, 2). The method is used in various domains, such as in imaging where it allows increasing the visibility of a defect as explained in (3). The time-reversal method has also been used for tactile applications on control surfaces (4). The domain of the communication is also concerned, in particular underwater communication thanks to the use of waveguides properties (5). The detection of defects also benefited from the time-reversal method (6). Finally, note that in (7), Derode et al. studied an important aspect of the time-reversal method: the number of sensor to be used to re-emit the signals. If the increase of the number of sensors improves the focusing it seems that this improvement saturates rather quickly.

In order to determine the location of a transient noise source, we use the basic principle of the time-reversal technique. It is indeed possible to determine the position of the source of the transient noise by recording the signals on a set of sensors distributed on the hull, by reversing these signals and propagating them back in the structure. The signals naturally focus towards the location of the source of noise.

However, this “standard” method presents three major drawbacks which make its use difficult in an industrial context:

- the determination of the focal point implies measuring the structure response in numerous points;
- the method consists in the emission of inverted transient signals through the structure. Due to the stationary self-noise of the ship, these re-emitted transient signals have to be of sufficient intensity, which is incompatible with the objective of ship acoustic discretion;
- the complete instrumentation of the structure needed for the measurement and emission of transient signals is dufficult to implement for technical and cost reasons.

To overcome these limitations we use the method of virtual time-reversal. The localization of transient sources by the virtual time-reversal method exactly corresponds to the standard time-reversal technique, to the exception that the recorded signals are re-emitted in a numerical model instead of the real structure. Obviously the numerical model must be sufficiently representative of the real structure under consideration. Several types of virtual structures can be used: finite-element models, analytical models, or transfer function measurements. In the case of a complex structure such as a ship, a finite element model would be inappropriate for obvious reasons of calculation times. On the contrary, an analytical model could not faithfully reproduce the complexity involved in such structures. It was hence decided to use a point to point model of vibratory transfers between the points of potential source locations and the points where the signals are measured. This method has the advantage of reproducing the behavior of the structure almost perfectly and is, once the transfer functions measured, fast to be implemented. The virtual model built in this way allows then localizing the transient noise sources by the only knowledge of vibratory signals measured on the hull.

3. NAVAL STRUCTURE UNDER CONSIDERATION AND DESCRIPTION OF PERFORMED EXPERIMENTS

3.1 Test naval structure

The naval structure under consideration is a semi-cylindrical immersed ribbed shell fully equipped with machinery. Its total mass is 210 tons, its length x width is 18.77 x 4.96 m and the draft is 2.5 m. An external view of the test structure is shown in Figure 1. The semi-cylindrical shell is divided into three compartments, which are separated by two bulkheads. A schematic view of the compartments is shown in Figure 2.

As the test structure was originally part of an existing submarine it is still equipped with machinery. One can see in Figure 3 a picture of compartment 2, illustrating the internal equipment and the complexity of the test structure. The considered naval structure used for the experiments is hence representative of a large-scale complex structure such as a submarine.

3.2 Description of performed experiments

Measurements were performed with several accelerometers (sensitivity of 100 mV/g) placed on the hull; the excitations consisted of a shock produced by an impact hammer. Several tests were performed to analyze the performances of the virtual time-reversal method for the localization of transient sources.

The first series of measurements, named test series A in the following, consists in verifying that source localization can be performed when the source and receivers are placed within the same compartment. The

Figure 1 – External view of the test structure.

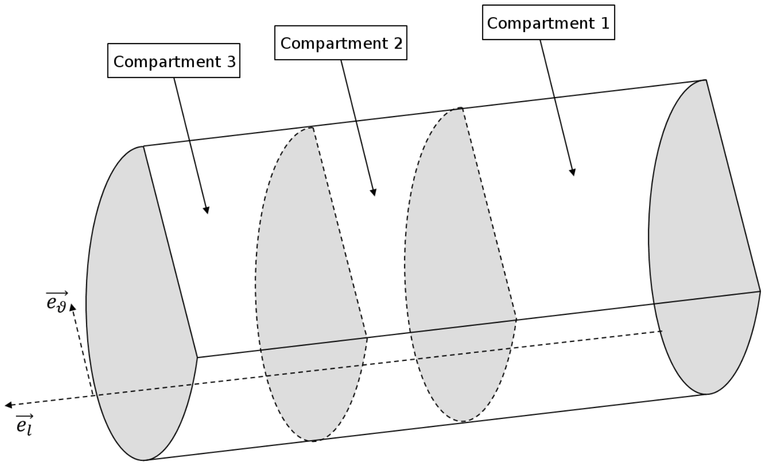

Figure 2 – Schematic view of the test structure.

Figure 3 – Internal view of compartment 2.

distance between excitation points and accelerometer measurements is varied both in the longitudinal (test series A1) and circumferential axis (test series A2).

The second series of measurements, named test series B in the following, consisted in verifying the accuracy of the source localization when the excitation and control points are in different compartments. The difficulty here resides in the presence of a high impedance mismatch due to the bulkheads between compartments.

In both test series A and B, the transient excitation to be localized is reproduced at the same exact location that was used for the construction of the numerical model of the structure (transfer function measurements). In the third series of measurements, test series C, we seek to evaluate the performances of the method when the transient excitation is not exactly localized on the transfer function measurement excitation location. In test series D, the excitation is not localized in the positions used for reference measurements. Furthermore, the frequency band taken into account in the post-processing is varied to evaluate the influence of the measurement bandwidth on the accuracy of the localization.

4. RESULTS

4.1 Test series A

Two accelerometers (noted R1 and R2 in Figure 4) are separated by about 2 m and are placed on the hull in compartment 1. Five control points (noted S1 to S5 in figure 4) are defined in the same compartment. Two consecutive control points are separated by 1.5 m and the closest control point is 2 m from the sources.

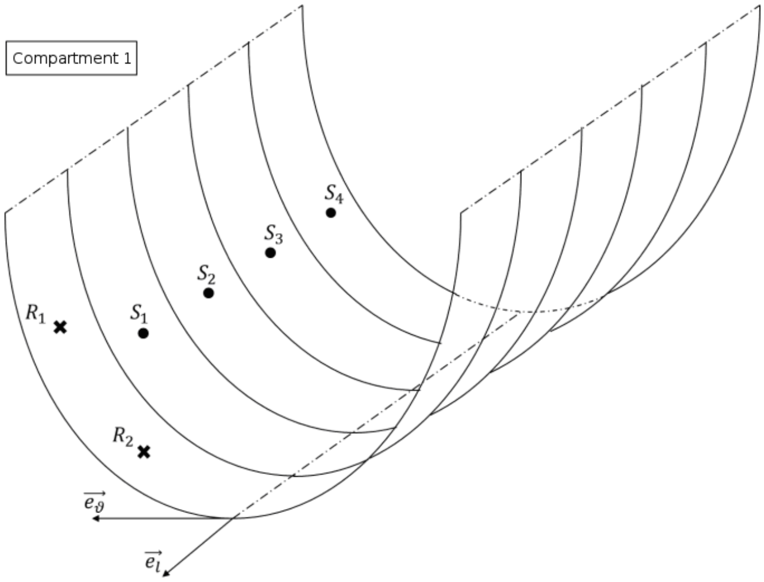

Figure 4 – Schematic view of the excitation and measurement points for test series A1.

The first step in applying the virtual time-reversal method is to construct the numerical model of the naval structure. As explained in section 2, the numerical model used here consists in point to point transfer function measurements between sources and receivers locations. The virtual model of the naval structure is hence constructed by measuring the transfer functions between source localization and control points, resulting in 8 measured transfer functions.

Once the learning phase is performed, one can next perform localization tests. Excitations were applied on control points S1 to S5 and post-processing of recorded signals on accelerometers R1 and R2 gives as an output a “localization coefficient” for each control point. The higher this coefficient is for a given control point, the closest the transient source is from this control point.

Figure 5 below shows the calculated localization coefficients when control point S3 is excited. As one can see, the virtual time-reversal method implemented here successfully identifies the source location. The same test was repeated with the excitation location on S1 to S4; source localization was successful in every case. Note that in this test series, the excitation is reproduced exactly at the same location than the one used for transfer function measurements (construction of the structure numerical model).

The same kind of localization tests were performed with control points located between two ribs on both sides of the structure (see Figure 6). Localization coefficients are given for the excitation located on control point 5 (opposite side from the measurement points, see Figure 7). As one can see, the transient source localization method successfully identifies the source location.

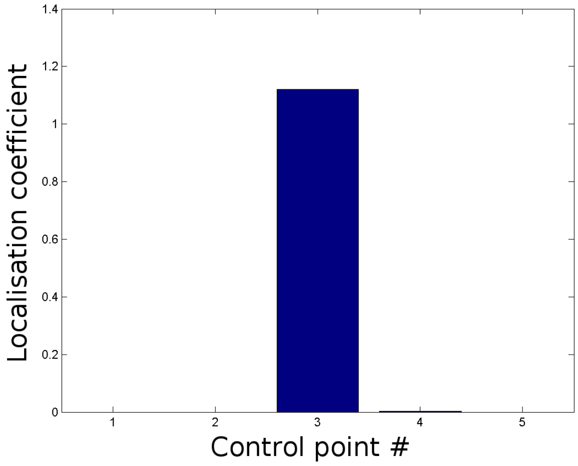

Figure 5 – Localization coefficients for test series A1; control point #3 is excited.

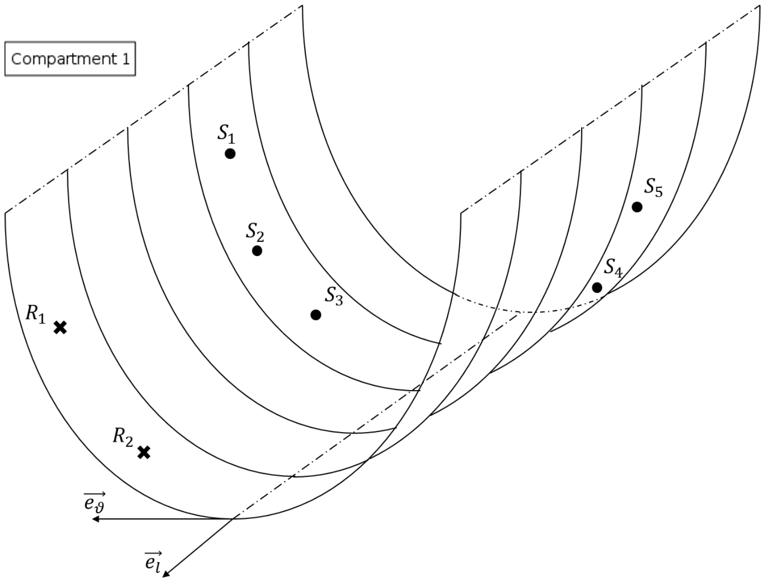

Figure 6 – Schematic view of the excitation and measurement points for test series A2.

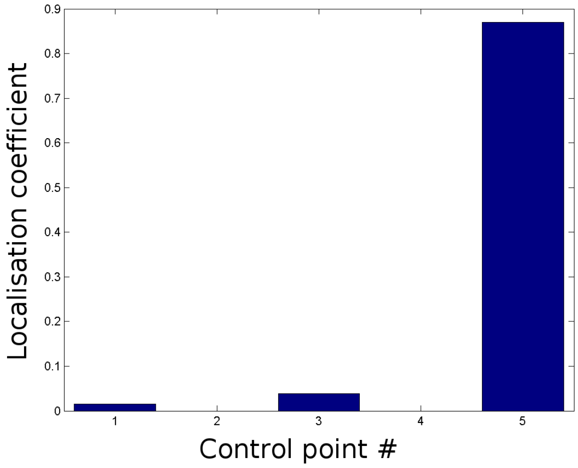

Figure 7 – Localization coefficients for test series A2; control point #5 is excited.

4.2 Test series B

The second series of tests is similar to the first one, except that control points and accelerometers are located in different compartments. The test case is presented in Figure 8. Control points are located in compartment 3 while control points are placed in compartment 1. A transient excitation is applied successively on control points S1 to S5. As an example, one can see on Figure 9 the localization coefficients obtained when control point 1 is excited.

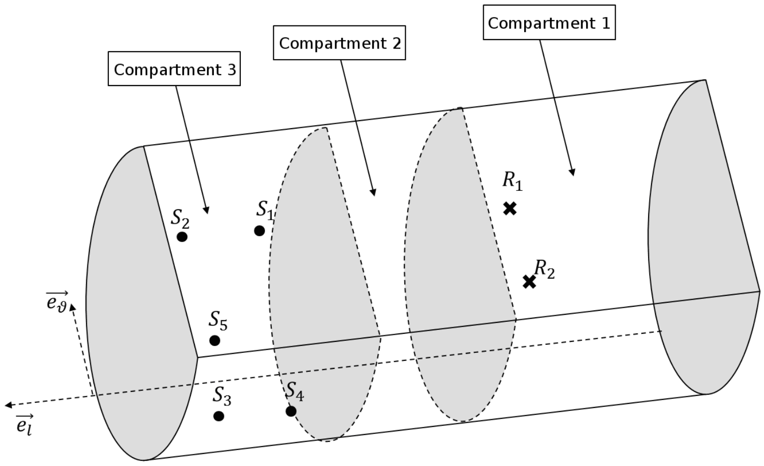

Figure 8 – Schematic view of the excitation and measurement points for test series B.

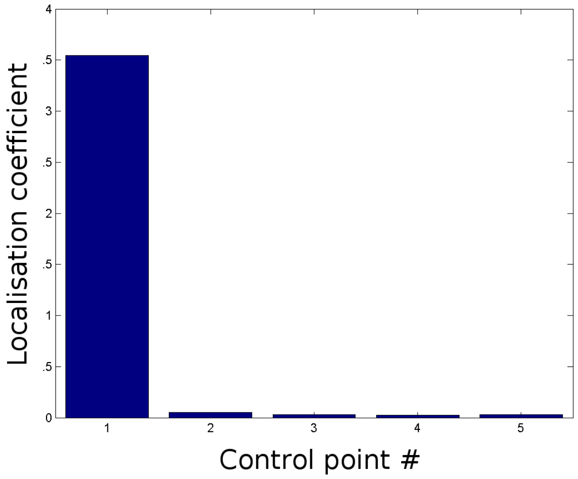

Figure 9 – Localization coefficients for test series B; control point #1 is excited.

4.3 Test series C

In both test series A and B, the transient excitations to be localized are reproduced at the same exact location that was used for the construction of the numerical model of the structure (transfer function measurements). In this third test series, the transient excitation to be localized is not in the same position.

We use as a test case a seawater valve rigidly mounted on the hull. The excitation point used for transfer function measurement is located at the fixation point on the hull, while the excitation point used for transient source localization is on the valve itself. Figure 10 illustrates the two different excitation points used. The seawater valve is located in compartment 1 while measurement points are located in compartment 3.

Figure 11 below shows the localization coefficient obtained. It can be seen that even if the excitation is not located in the same position as the reference measurement, the virtual time-reversal method successfully identifies the location of the transient excitation (control point S1). However, note that the amplitude of the localization coefficient of control points S2 to S5 is not null: the modification of the transfer path decreases the localization contrast.

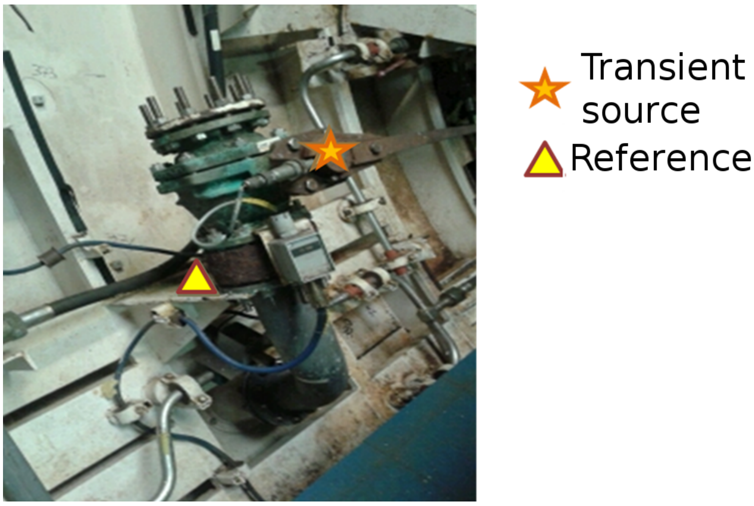

Figure 10 – Location of excitation points used for the construction of the numerical model (reference point) and the transient excitation to be localized.

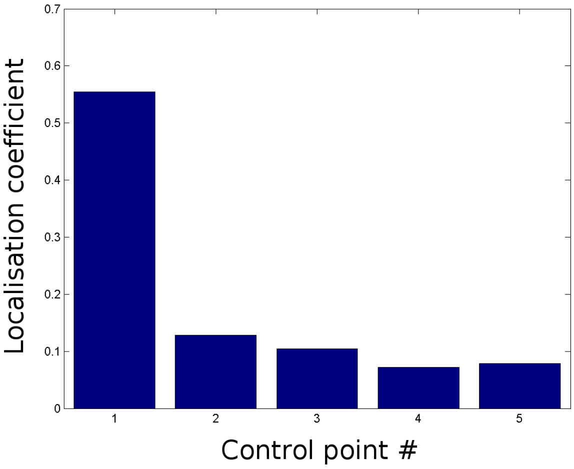

Figure 11 – Localization coefficients for test series C; control point #1 is excited.

4.4 Test series D

Control points in test series D are organized on a 3x3 rectangular grid. Accelerometers are 40 cm apart from each other and the excitation to be localized is in between control points #8 and #9, 10 cm away from control point #9. See Figure 12 for a schematic view of the test configuration. Different bandwidths used for post-processing are considered: 2 - 3 kHz (frequency band 1), 500 Hz - 1.5 kHz (frequency band 2) and 1-250 Hz (frequency band 3).

Localization coefficients for these three cases can be seen on Figure 12 below. It can be seen that as the frequencies considered are lowered the excitation is localized more accurately. When frequency band 1 is used, the localization coefficients for control points #8 to #9 are the highest, but localization coefficients for control points #1 and #6 are of the same order of magnitude. Hence the source localization using a high frequency band is not well defined. Using frequency band 2 allows one increasing the contrast between control points #9 and the others. The lowest frequency band gives the most accurate localization; control point #9 is clearly identified as the source location. This phenomenon could be explained by a higher variability of transfer functions between the excitation point and control point #9 for higher frequencies.

5. CONCLUSIONS & PERSPECTIVES

This paper illustrates the use of the virtual time-reversal technique for the localization of transient sources inside complex large-scale immersed structures. The virtual time-reversal technique consists in constructing a numerical model representative of the structure under consideration, and then in re-emitting recorded signal in this model to identify the source locations.

The structure considered here is a semi-cylindrical ribbed immersed shell equipped with machinery. Due

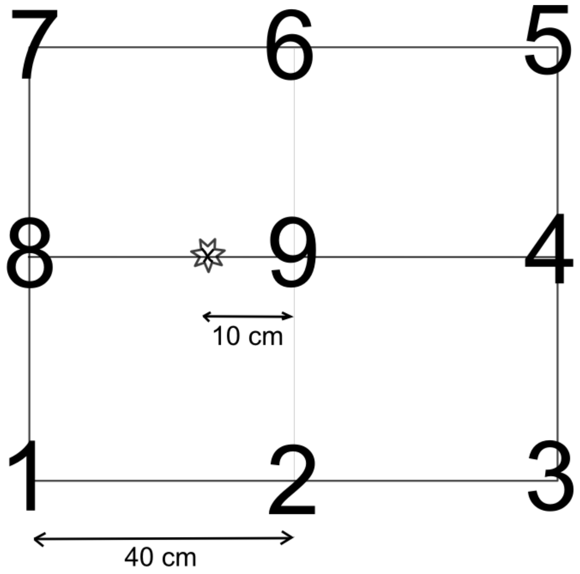

Figure 12 – Schematic view of the excitation and measurement points for test series D.

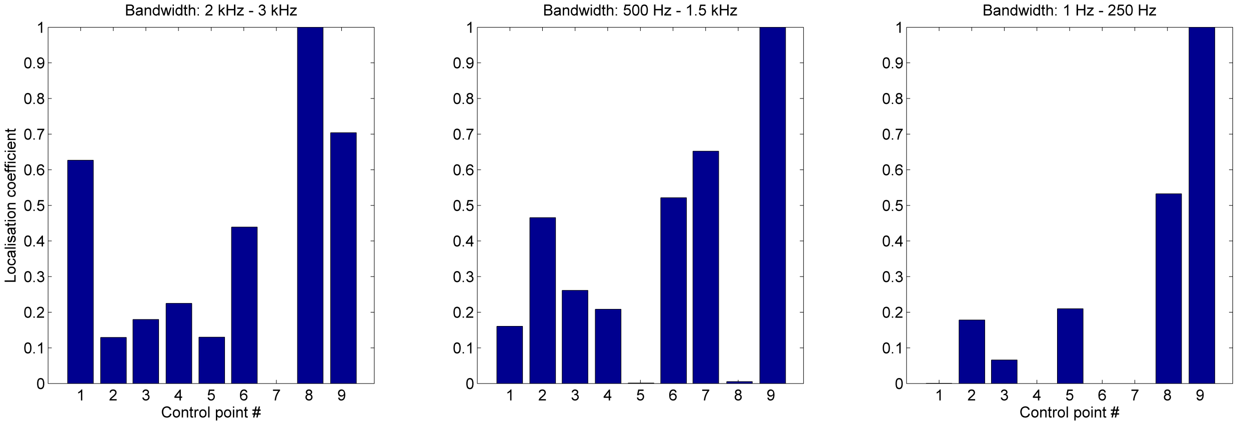

Figure 13 – Localization coefficients for test series D; excitation is located between control points #8 and #9, 10 cm away from control point #9 (see Figure 12). The bandwidths considered are 2 - 3 kHz (left subplot), 500 Hz - 1.5 kHz (middle subplot) and 1-250 Hz (right subplot).

to its complexity, it is decided to construct a numerical model based on point to point transfer function measurements.

Several tests are performed to illustrate the performances of the implemented localization method. It is shown that the time-reversal method successfully identifies the transient source localization in a variety of situations:

- large distances between excitation and measurements points,
- excitation and measurements points on different sides,
- excitation and measurements points on different compartments

Furthermore, it was shown that the method was successful in identifying the transient source location when it was applied in a different location than the one used for the construction of the numerical model of the structure.

In the experiments presented here, the localization system consisted in a small number of measurement points (2 accelerometers). In the future this system will be deployed on a larger scale, with a larger number of accelerometer distributed along the hull. This will allow a better assessment of the method performances, with an insight of its robustness regarding several parameters, such as the accelerometers meshing or the frequency band under interest.

ACKNOWLEDGMENTS

The authors gratefully acknowledge DGA for the co-financing of this project through the RAPID funding scheme.

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