A simplified Time Reversal method used to localize vibrations sources in a complex structure

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**Abstract**

The main issue while dealing with problems due to structural vibrations is the identification of the sources that create annoyance. One of the experimental processes that permit to tackle this reverse problem uses Time Reversal method to localize the origin of the vibration detected on the surface of a structure.

The Time Reversal experiment is based on a principle of time symmetry of waves propagation in a media. Using transceivers located on the structure, one can record its state of vibration. If all the signals recorded by the transceivers are reversed in time and reemitted from the position where they have been recorded, the resulting vibration will converge back to the point where it was originally emitted. In the standard approach, localization is observed both in time and space. We propose here a simplified localization process based on space localization only. We will apply this method on a complex industrial structure, stimulated with bursts. We shall show in the article the influence of certain parameters such as the number of transceivers or the structure complexity. Finally, all the tests presented hereby will allow us showing that the Time Reversal method is a very efficient and very easy to use method.

1. Introduction

Since it has been introduced by Mathias Fink during the 1980s [7], the Time Reversal experiment has been used in many fields. The main use of the Time Reversal method is made with ultrasonic waves, especially for medical applications. In this particular area two applications are for example lithotripsy [11] or medical imaging especially for in skull tumour localization [3]. It is also frequently used for under-water communication [9], non-destructive testing and crack detection [10]. Concerning all those applications, the Time Reversal method is used in the ultrasonic range. For some recent applications, it is used in the audible range [1] and for structural vibrations, in particular for tactile surfaces [4,8]. In this case, the Time Reversal method is used to localize the position of a finger impact on a surface.

The main purpose of this article will be to present one application of this method to structural vibrations of complex industrial systems and describe the parameters that increase or decrease the efficiency of the method. The application of the Time Reversal method in this particular context might be particularly useful when it is not possible to directly measure the vibration field on the structure, which would be the case for the testing of a working machinery. Indeed, we are frequently subjected to random phenomena that may not appear during the study but which can be recorder. With the recordings performed it is then possible, using Time Reversal, to recreate the state of vibration generated by those random phenomena to study them easily. By the way, for some safety reasons, it might not be possible to access the machinery while it is working (e.g. interaction with moving parts, high speed motion, high temperature, etc.). Once again, the recordings will allow the operator studying the vibrations while the machinery is off.

The results here shown are obtained while applying the Time Reversal method to a complex industrial structure. Furthermore they are to be measured by some particular transceivers using piezoelectric technology. The main goal of this study is to find a robust way of using the Time Reversal method in order to apply it as an industrial process for vibrations sources localization. Therefore, there would not be any particular development in the theory itself. This article is mainly supposed to introduce the combination of the theory and those piezoelectric transducers in a robust and innovative method to find vibrations sources.

2. Particularities of the Time Reversal method

The Time Reversal method has two main advantages and two main drawbacks for the application we are concerned with. The advantages are those of the reflective environment and of the complexity of the structure. Drawbacks are those of damped structures and precision of the localization.
This method is based on the principle of time symmetry of wave propagation in a media. Considering that there is no damping in the media, this formulation is true. The limit that appears now is that damping cannot be time-reversed. Otherwise this would mean that when reemitted to focus to the source, the different waves should see their range increase with regard to time, which is unlikely.

Secondly, when the wave is reemitted in the structure, it first merges to the exact place of the original burst. This wave will then divert, thus creating interferences with the merging wave. The superposition of these two waves implies that the source localization will not be possible under the half of the wavelength [1]. Actually, this may not be such as a penalty as the method will here be used to localize burst sources. Those broadband signals including high frequency and having small wavelength will then lead to a correct precision. The accuracy of the Time Reversal method as been improved by introducing the concept of Time Reversal sink [1]. By emitting the original signal at the exact point of the merging, it permits to suppress the diverting wave, thus reducing the interferences it creates. This process allows increasing the accuracy of the Time Reversal method, but at a numerical cost that is too high for the industrial application we intend to in this article. Furthermore, such a high precision should probably be a disadvantage, as it will require using a thinner mesh to localize the maximum.

In order to give its best results, the wave emitted by a source point must be recorded at every location surrounding the source. One may easily admit that this cannot be conveniently performed, thus the notions of Time Reversal mirror and Time Reversal cavity have been introduced [7,2,5]. As it is impossible to cover the whole surface with transceivers, only a small area of it is covered, and the recorder signal is an approximation. However, when returned back to the source, the approximation is good enough to give a good idea of the source position. It has been shown [5,6] that when applied to a reflective environment, the borders of the structure can be considered as many virtual sources, allowing the user using only one real source. Results may be improved by using two sources, but we shall see that the amelioration is perhaps not worthy compared to the cost of a second source. We can see here that this property of the reflective environment is in accordance with our will to build a robust process.

The more complicated is the structure, the more reflection and diffraction phenomena will occur. Those events will extend the recorded signal in time. A longer signal is then more able to localize a source. We can see here what is probably the major particularity of this Time Reversal method. It is one of the few taking benefit of the structure complexity. Once again, as we are willing to build a process that can be used on industrial components this advantage will be of great interest.

3. Experimental device

3.1. Using piezoelectric patches

The experiment hereby presented uses emitters and sensors made of smart materials. Some ceramic patches having piezoelectric properties are used for many reasons among which one can explain the following. The piezoelectric effect is reversible. That is piezoelectric materials can be used both as sensor and as actuator. This guarantees the simplicity of the experiment we want to develop as the same material can be used either to record signals or to reemit time-reversed signals. Secondly, piezoelectric patches are easy to use. Once they are wired, it is just required to glue them on the structure and they are ready to use. This is still regarding the fact we are willing to build a robust and easy to use method.

For this application, we used squared patches, having the size 0.03 × 0.03 × 0.001 m, made in zirconate and titanate with copper and nickel electrodes. The patches were bonded to the structure using a two-part epoxy adhesive.

3.2. A mower body frame

The method we introduce here is to be applied on complex industrial structures. Thus we have chosen to make its first application on the mower body-frame shown in Fig. 1. It depicts the two parts of the structure in light and dark gray. The positions of the two piezoelectric patches used are pointed out with a solid arrow, while the scanning areas are pointed out with a dashed arrow.

3.3. Measurement

The Time Reversal experiment is a set of two steps that could be named recording and focusing. This section shall list the devices used for both steps and the experimental setup is detailed in Fig. 2.

During the recording step (Fig. 2a), each piezoelectric patch is used as a sensor. So as to be able to detect the vibrations of the structure, they are plugged on a load conditioner and ICP converter whose output is connected to a 8-channel FirePod multiplex then on a computer to record the signals.

During the focusing step (Fig. 2b), each piezoelectric patch is used as an actuator. Piezoelectric actuators need a high voltage input to create enough displacement to rebuild a propagative vibration in a structure. Due to that requirement, it is not possible to plug the patch directly on the multiplex. It is necessary to use a high voltage amplifier able to deliver up to 500 V with an average current of 100 mA. The scanning is made by a PCB accelerometer plugged on the load conditioner. The scanning is performed on a 1 × 1 cm mesh so as to cover the surfaces shown in Fig. 1 and detailed in Fig. 3.

The maximum of vibration is searched in the records made by the accelerometer. Once again, we want to present an easy to use method. We decided to use no particular post-processing to search for the maxima. The results given might then be blurred by local maxima due to noise. To avoid this, a time window averaging is usually applied. In the method we are introducing here, we decided to do this averaging while printing the cartography instead of while searching maxima. Indeed, a linear interpolation with spatial averaging is calculated with the data measured by the accelerometer. This allows us producing better cartographies in which it is easier to determine the area of maximum vibration.

4. Localization of excitation point

In the Time Reversal theory it is said that the time-reversed wave is merging at the source location at a particular time after...
excitation point. Thus, if one wants to search the localization of the source in space and time, it is first required to look for the maximum of acceleration measured at all points during the observation window. At the instant it occurs, a map of the scanned area is displayed, presenting the values of the vibrations at all point at the time of the merging. This post processing methods produces some very effective results as shown in Fig. 5a. For further references, it will be named space-and-time localization.

To reduce the number of steps in the localization process, the previous post processing method has been simplified. The algorithm we introduce in this article extracts from the recording at each point its maximum with no regard to the instant it occurs. All those maxima are then displayed on the map. Thus, we have a map that is not a representation of the vibration pattern at a given instant. Fig. 5b shows the map obtained using this post processing method, which will be named space-only localization.

For this first experiment, the initial impact has been applied at point (5; 2). We can see in Fig. 5 that both post processing methods give the right position of the excitation point. While the first gives a very precise result, the second is a bit blurred by additional high values due to the fact that the reemitted wave is diverting back after the focusing. The map drawn with space-only localization is obtained in a very simple way suitable for industrial purpose and it is the method that will be used to present the results of next experiments.

As said in paragraph Section 2 and in [1], for space-and-time localization, the localization cannot be done under the half of the wavelength in the media. We can see in Fig. 5a that the focusing spot is approximately 2 cm wide. We can then compare this size to the wavelength in the mower body frame. The wavelength can be calculated using the velocity of bending waves in the media.

\[
\lambda = \frac{c_b}{f}\]

(1)

The bending velocity can be calculated using the following equation:

\[
c_b = \sqrt{\frac{Eh^3}{12(1-v^2)\rho}} \sqrt{2}\pi f
\]

(2)

We know the physical properties of our material

\[
\begin{align*}
E &= 2.1e11 \text{ Pa} \\
h &= 0.0025 \text{ m} \\
v &= 0.3 \\
\rho &= 7800 \text{ kg m}^{-3}
\end{align*}
\]

The frequency is estimated in Fig. 4d. We can see that the most important part of the signal has a frequency of 17.5 kHz. We can then calculate the wavelength in the media:

\[
\lambda = 0.038 \text{ m}
\]

The diameter of the focusing spot should be of 0.019 m (the half of the wavelength calculated), which is totally coherent to the focusing spot observed in Fig. 5a.

5. Number of patches in use

The first experiment that has been performed was to determine whether or not the number of patches used was important. To find this out an experiment has been conducted in this way. During the first step of the Time Reversal experiment two patches were used to record the signal. For the second step, it has been first refocused with only one patch, then with the two of them so as to be able to evaluate the increase in accuracy provided by the second patch. The time reversed signal and its spectrum are given in Fig. 6a.
and b. It is important to notice here that even if this experiment is the same than the one performed to produce Fig. 5b, it has been made using a different impact, explaining the difference between Figs. 7a and 5b. The results obtained are shown in Fig. 7.

One can see here that the focusing area (the black surface) is not significantly narrower in Fig. 7b than in Fig. 7a. That means that the localization is not particularly more precise when using two patches, and the difference is certainly not worth the cost of a second patch (1.3 sq. cm with one patch, 0.9 sq. cm with two patches). As said in paragraph Section 2, and in [5] or [6], when applied to a reflective structure, the boundaries of the structure act as virtual sources, allowing using as few as one patch. This is verified here, as the number of patches has not such a particular influence.

By the way, it is still interesting to use a second patch for this reason: on the left hand side of Fig. 7a the acceleration of the structure is growing up. It means that the Time Reversal method may give some local maxima that could confuse the user. In Fig. 7b this local maximum is attenuated. Using a second patch is then not needed to increase the precision of the method, but more to prevent from finding unreal sources due to local maxima.

6. Structure complexity

It has been said in paragraph Section 2 that structure complexity is an advantage to the Time Reversal method. In this experiment we tested this property. In the structure we used, the upper part is fixed on the lower part by four screws. As both patches are placed on the upper part, if the burst is given on the upper part, a short straight path from the burst to the patches exists. If the impact is produced on the lower part, we force the wave to propagate through those four screws. The path between the source point and the patches is then much longer and the recorded signal contains more information generated by a high number of reflection or diffraction during the propagation.

The test made on the upper part has been done using the impact of which the time recording and spectrum were displayed in Fig. 6. The test made on the lower part has been done using an impact whose time recording and spectrum are depicted in Fig. 8.

The results given by this experiment are shown in picture Fig. 9, considering that the burst is given at point (5; 2) on the upper part, and at point (0; 2) on the lower part.

In Fig. 9a, the surface covered by the maximum value is of 0.9 sq. cm while in Fig. 9b, it is of 0.2 sq. cm. It is known that the precision of the Time Reversal method depends deeply on the wavelength of the material, that is on the thickness of the media. One could think that this narrower distribution is due to different thickness in the upper and lower part but both parts are made of
the same 2.5-mm thick material. It then appears clearly that the focussing is more efficacious in the case of a complex path. This corresponds to what was expected and is probably an advantage of the Time Reversal method: it is benefiting from the complexity of the structure.

7. Robustness of the experiment

The behavior of the Time Reversal experiment has been tested in case of a structural modification. A first experiment is conducted to get the reference result. The structure is then modified and a new focussing is made with no prior recording, that means using the signals of the first focusing. Adding mass at a particular location as depicted in Fig. 10 has made the modification. The impact is the same as for the experiment presented in paragraph Section 6 and having time reversed signals displayed in Fig. 8. The results are given in Fig. 11.

In the second case, the exact place of the source could not have been found using the first recordings. It is to be noticed that the modification is extremely important as the mass of the pulleys is equivalent to the mass of the upper part. If considering this, and
is time symmetry of waves propagation in a media. As this propagation is advantage of a mechanical property of the structure that is intrinsic to the media, there is no need to build any model of the structure, e.g. finite elements model. Furthermore setting up the required material is quite simple. Especially, using piezoelectric patches reduces problems as they just have to be glued on the structure to work properly both as sensor and actuator.

The Time Reversal method with space-only localization has proved to be very simple to use, that render possible industrial applications. We have seen that an important structural modification was not responsible for a great modification in the results, thus proving its robustness. Making all those experiments lets see that there is no particular importance neither of the position of the piezoelectric patches, nor of the quality applied to the scanning of the structure. In summary, it is working on complex industrial structure with no particular preparation.

For further development, one has to remind the most important gain permitted by this method. When looking for a default in machinery, one usually searches on the structure while it is working. Using the Time Reversal method could make possible to record the state of vibration of the structure while it is working, then play time-reversed signal when the system is off to detect sources.

A particular problem, that has not been studied yet, is that in reality, and for most of the applications, we will be confronted to multiple sources. Further researches have been undertaken to tackle this problem while predicting the source position and shall be presented in a following article.

As a sum up, one can yet retain some of the main advantages of this method: simplicity of use, time gain while performing tests, possibilities of work on a complex structure, no complex calculation and no model required.

Appendix A. Supplementary data


References