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Thomas Durand-Texte, M. Melon, Elisabeth Simonetto, Marie-Hélène Moulet, Stéphane Durand

PAPER • OPEN ACCESS

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To cite this article: T. Durand-Texte *et al* 2018 *J. Phys.: Conf. Ser.* **1149** 012008

3D vision method applied to measure the vibrations of non-flat items with a two-mirror adapter

T. Durand-Texte[1,2], M. Melon[1], E. Simonetto[2], S. Durand[2] and M.-H. Moulet[3]

1 LAUM UMR CNRS 6613, avenue Olivier Messiaen, F-72085 Le Mans cedex 9, France
2 Laboratoire Géomatique et Foncier, CNAM, 72000 Le Mans, France
3 Centre de Transfert de technologie du Mans, 72000 Le Mans, France

E-mail: manuel.melon@univ-lemans.fr

Abstract. In order to measure low frequency vibrations with a stereo sensor, it is interesting to increase the angles between the cameras and the measured surface, as the out-of-plane displacements are then more visible on the images. Even if Digital Image Correlation has proven to be a valid tool to measure vibrations, the initial pairing process remains difficult, in this context, because of the large pan angle, all the more so if the measured object presents significant variations in depth (for example a loudspeaker). This conference paper thus presents a new method specifically designed to rectify images (referred to as the IRIs method), which successfully allows initializing the vibration measurement with a high number of measurement points. In the same way, the conventional single-camera pseudo stereo system with a four-mirror adapter, which is largely used to perform displacement measurement, remains rather complex to operate. This paper thus proposes a single-camera simplified system, with a two-mirror adapter only. The ensuing global protocol is more user-friendly, and even if the results obtained for vibration measurement are a little less accurate with the two-mirror adapter, the operational modal shapes have been successfully retrieved and match very well those obtained with the conventional set-up.

1. Introduction

The measurement of structural acoustic sources can be achieved by various means, that may be gathered together into two different branches: on the one hand, vibration measurement methods which focus on the vibration of the source; on the other hand, acoustic field measurement approaches which use microphones. The former are very popular because they usually do not require an anechoic chamber and thus can be performed in normal rooms. Two classical measurement devices are generally used in this context: accelerometers [1] and laser vibrometers [2]. However, these single-point techniques are not appropriate for sources that exhibit non-stationary or non-linear behaviours. In that case, full-field methods, for which all the points of interest are measured simultaneously, become particularly interesting. As a consequence, over the past decades, several optical full-field methods have been adapted to vibration measurements: deflectometry [3], digital holography [4] and dynamic photogrammetry [5] for example. While allowing performing full-field measurement, they present additional assets, such as non-intrusiveness or low sensitivity to the ambient acoustic noise. In a context of shape or vibration measurement, dynamic photogrammetry and more precisely 3D vision methods are at the core of the approach presented in this paper.

In order to perform shape and deformation measurement, Digital Image Correlation (DIC) is largely used [6]. Along with the development of high-speed cameras, its relevance to measure vibrations has been increasingly studied over the past decade [5, 7–13]. These cameras are also used by other vibration measurement techniques, such as videography [14, 15], stereophotogrammetry [16], digital holography [4] or fringe projection [17].

For the 3D vision methods, the protocol usually designed requires two views of the studied object to perform triangulation and obtain the data needed to retrieve the 3D shape and displacement of the object. Originally, two high-speed cameras were used [7, 8]. Because of the cost of these devices and the associated problems to synchronise them neatly, another set-up, originating from robotics [18–20] is very often used. It requires a single high-speed camera and a four-mirror adapter to generate two virtual cameras, and thus views, from a single real one. This pseudo stereo system with a four-mirror adapter has been validated several times to measure vibrations [21–25].

In this context, the use of large angles between the measured surface of the object and the cameras has proven to provide better precision for out-of-plane displacement [6] and thus to lead to better results for vibration measurement [25]. However, the initial pairing process, using DIC tools, remains difficult if the pan angle is large and if the measured object presents variations in depth (typically a loudspeaker). This conference paper thus presents a method designed for this specific context and a simplified set-up, in order to make the whole protocol more effective, user-friendly, while keeping a high degree of precision in the vibration measurement.

2. 3D iterative rectification of images (referred to as the IRIs method)

The usual image rectification methods, such as the epipolar image rectification [26, 27], are no longer sufficient to pair a high number of measurement points automatically, notably if a large pan angle is used (from 60° to 90° approximately) and if the studied object presents significant variations in depth (cf. figure 1). A new protocol has thus been designed in order to quickly and easily perform shape measurement with these specific parameters. The resulting synoptic diagram is shown figure 2.

An initial coarse shape measurement is performed with rectified images [26–28], with few measurement points, paired either automatically or even manually (cf. figure 3). From this initial shape, two ortho-images (one per view) are calculated by defining a pixel matrix in the 3D space of the object. The 3D positions of the matrix pixels are obtained by using the reference shape and are projected onto the initial images to perform image interpolation (cf. figure 4). As the ortho-images obtained display a higher degree of similarity, more points may be automatically paired. They are then projected onto the initial images in order to calculate a new shape, which can be used, in turn, to calculate new ortho-images, and so on...

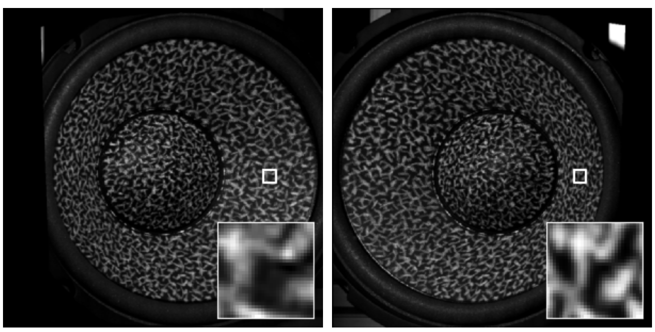


Figure 1. Rectified images: (*left*) from the left camera, (*right*) from the right camera.

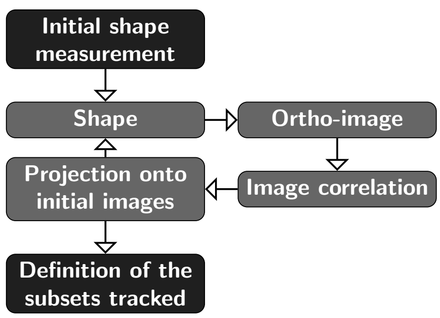


Figure 2. Synoptic diagram.

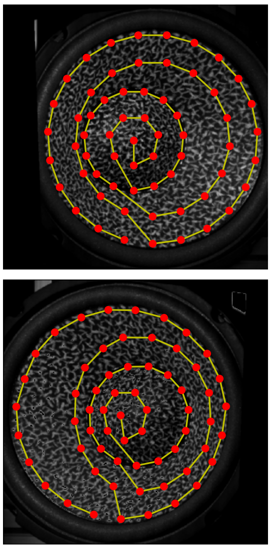


Figure 3. Initial paired points used to measure a coarse shape.

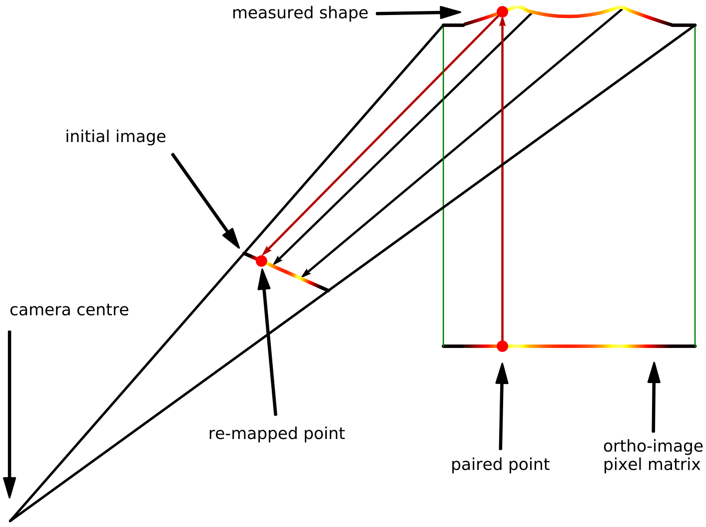


Figure 4. Sketch of the protocol used to calculate ortho-images.

After a few iterations, a large number of points can be paired (cf. figure 5) with an increasingly high precision as the ortho-images are increasingly similar. The correlation coefficient of the ortho-images directly indicates the degree of convergence of the process. For this experiment, when the third ortho-images are superimposed, ≈92% of correlation is achieved, with most of the differences coming from specular reflections (cf. figure 6).

In order to measure vibrations, pixel areas may now be defined. For this work, a few points have been chosen on a circle around each measurement point in the ortho-images. These points have been projected onto the initial images so as to calculate ellipses, whose areas define subsets tracked in the video. This protocol allows triangulating the full-field vibration signals of the object.

Once this technique established, it was tested on a loudspeaker, using the pseudo stereo system with a four-mirror adapter. This set-up was noticeably complex to manipulate, particularly because of the central mirrors. Moreover, the large pan angle clearly hindered the initial pairing process of the protocol presented in this paper. An attempt at reorganising the various elements differently was thus made, resulting in a new set-up requiring only a two-mirror adapter.

3. Pseudo stereo system with a two-mirror adapter

As mentioned previously, the pseudo stereo system with a four-mirror adapter (cf. figure 7) is not user-friendly, especially because of the central mirrors. Its use is all the more complex since it presents a shadow area in the middle of the image. The new set-up presented in this paper offers an alternative (cf. figure 8) : it requires only two mirrors and is specifically adapted to measure vibrations. Indeed, the real high-speed camera is placed on the side of the object and generates a view that is sensitive to out-of-plane displacement. The other, virtual, view is generated by the two mirrors and positioned in front of the object: it is thus sensitive to in-plane displacements. It may be noted that the principle of having a view set in front of the object is also used in trinocular stereo systems to initialise and facilitate the pairing process [29]. As a consequence, the pan angle is reduced by two, which simplifies the initial pairing process, while keeping a view that is very sensitive to vibrations. The whole system is more user-friendly, as there are only two large mirrors, and the shadow area in the image is reduced. The non-symmetry of the views

Figure 5. Measurement points re-projected onto the initial images: (*left*) first iteration, (*right*) second iteration.

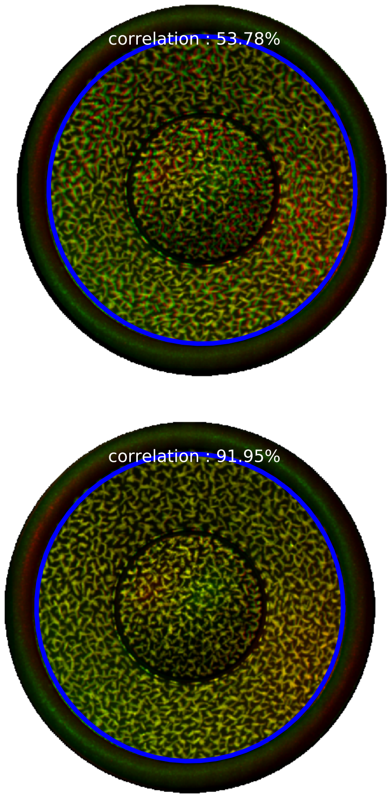


Figure 6. Ortho-images combined in two colors: (*top*) first iteration, (*bottom*) third iteration

induces biais in the shape measurement, but more pixels are available for the vibration-sensitive view.

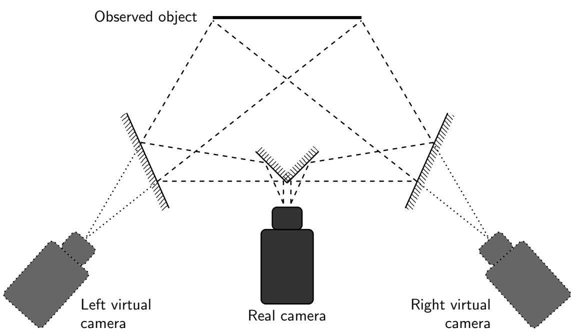


Figure 7. Sketch of the set-up with a four-mirror adapter.

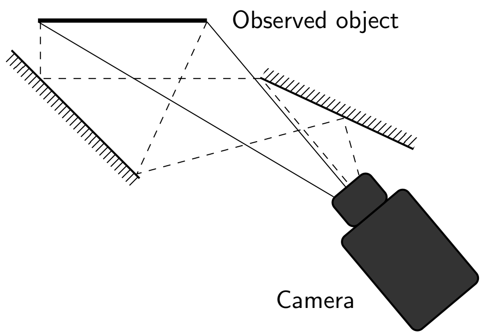


Figure 8. Sketch of the set-up with a two-mirror adapter.

A test on a loudspeaker has been carried out : the two-mirror adapter set-up has been used with the IRIs method to initialise the pairing process. The experimental set-up is presented figure 9. Figure 10 shows an example of image obtained with the new pseudo stereo system. The results have been compared with those obtained with the four-mirror adapter set-up for the full-field measurement, and with those obtained with a laser vibrometer (Polytec) for a single point measurement, in order to validate the whole protocol.

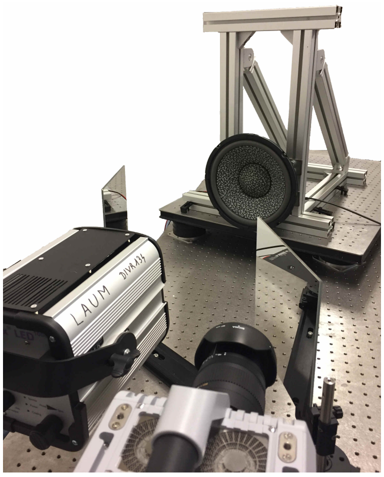


Figure 9. Picture of the experimental set-up.

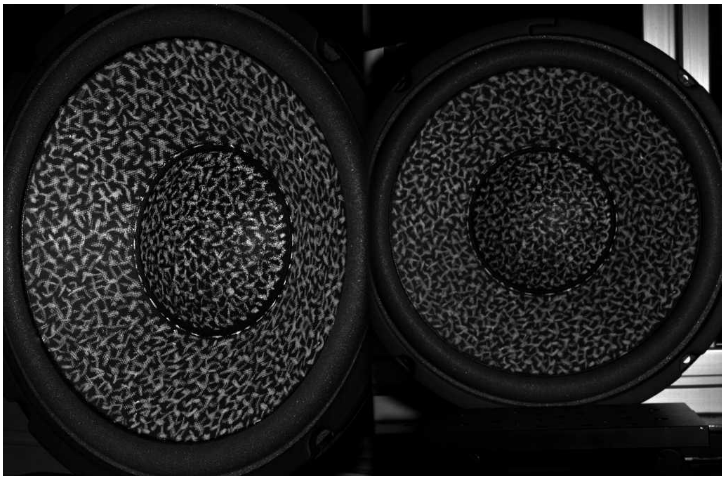


Figure 10. Example of image obtained with the pseudo stereo system with a two-mirror adapter.

The Frequency Response Functions (FRFs) of the central measurement point of the loudspeaker are calculated from the excitation signal at its terminals and from the resulting displacement signals measured with the two-mirror adapter and four-mirror adapter set-ups, and with the laser vibrometer. The results of the vision methods are shown figure 11 and match well those obtained with the reference technique, which validates the approach. The proposed set-up is a little less precise than the conventional one; yet the differences between the values obtained with the laser vibrometer and with the two-mirror adapter set-up are globally below 10%.

From the FRFs of all the points, the Operational Modal Shapes (OMSs) can be retrieved and displayed for both pseudo stereo systems (cf. figures 12 and 13). The images match neatly, which validates the technique once again.

4. Conclusion

In conclusion, firstly, large pan angles improve the precision of the vibration measurement but make it more difficult to pair initial measurement points if the object of study presents significant variations in depth. The IRIs method proposed here has been designed to perform this pairing process from a coarse shape measurement, while taking into consideration all the constraints mentioned above. It successfully allows initializing vibration measurement with a high number of measurement points. Secondly, if only one high-speed camera is at one's disposal, the conventional pseudo stereo system with a four-mirror adapter may be used to measure vibrations at the expense of the number of pixels available. Nonetheless, this set-up is not particularly user-friendly. Hence the attempt at designing a new set-up, which involves a different, simpler adapter with two mirrors. With this new system, the results seem to be a little less precise but the whole protocol allows retrieving similar operational modal shapes, which validates the technique presented in this paper.

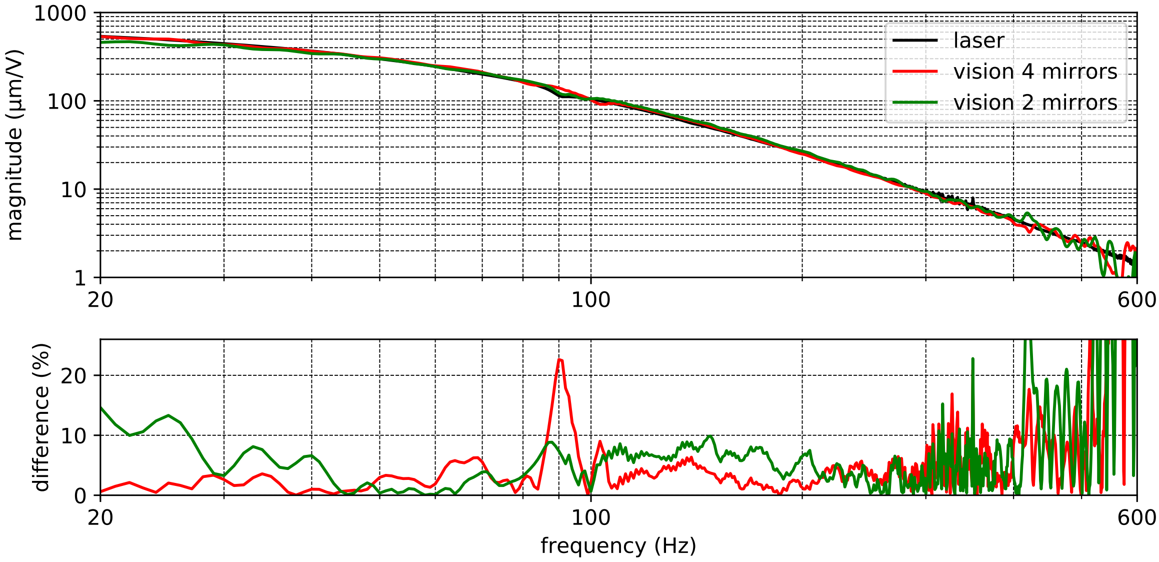
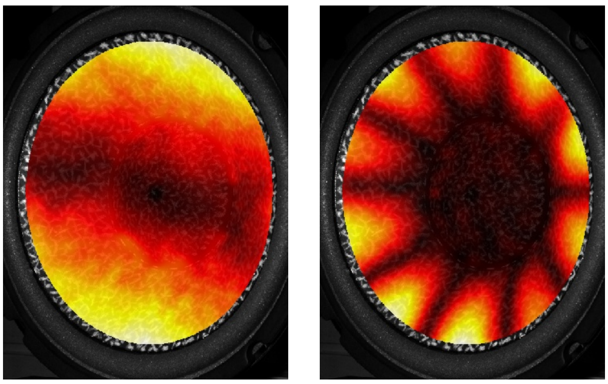
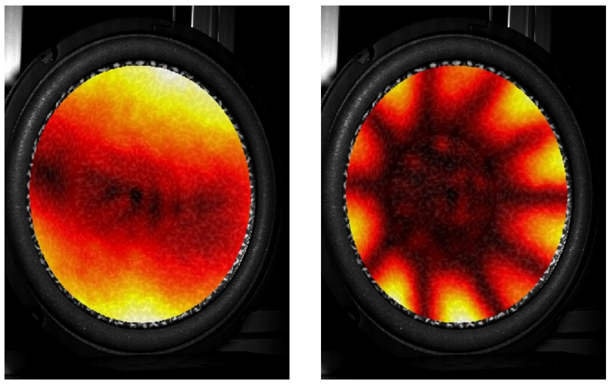


Figure 11. FRFs measured with the laser vibrometer and the vision set-ups



187 Hz 321 Hz

Figure 12. OMSs obtained with the two-mirror adapter set-up.



189 Hz 323 Hz

Figure 13. OMSs obtained with the four-mirror adapter set-up.

Acknowledgments

The work presented here is supported by the institute “Le Mans Acoustique” and funded by the “Pays de la Loire” region and the “European Regional Development Fund”.

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