# Temporal evolution measurement of harmonic vibration induced over a rectangular plate using a high-speed ESPI system

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The study of vibrations has taken a very important role in technological and scientific development. Some optical techniques have been used for this purpose. Examples of them are holography, fringe projection, Moiré Interferometry, Shearing Interferometry, Electronic Speckle Pattern Interferometry (ESPI) and Digital Holography, with the use of pulsed and continuous lasers. A limitation for vibration studies was the non-apparition of high speed cameras as well as continuous wave lasers with a higher power. Within the last year's evolution of technology, it is now possible to give a following of mechanical displacements with interferometric images. The purpose of this work is to get experimental data by the use of ESPI, a high speed camera and a continuous wave laser and compare this data with theoretical data to measure the temporal evolution of a complete cycle of vibration. A rectangular plate under harmonic vibration is used to classify the type of fringe pattern and to quantify the mechanical phase of this plate during vibrations. The influence in the fringe patterns acquired in high speed ESPI are investigated due to different exposure times, 1000, 2000 and 4000 frames per second for this case, because it has consequences in the natural recovering of the mechanical function induced for the harmonic vibration measurement.

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## 1. Introduction

For full-field measurements of deformations of mechanical components, TV Holography, also known as electronic speckle pattern Interferometry (ESPI) has been used [1, 2]. These measurements can be divided in two groups; dynamic measurements like flowing conditions, vibration and convection, and static measurements, like displacement, torsion, refractive index and pressure. The main advantage of using an optical technique is that it allows non-contact measurements on objects with rough surfaces. The base of measurements is a fringe pattern that can be produce by the interference between two or more wave fronts, all of them coming from the same source. For ESPI, two speckle interferograms are recorded, one without a deformation and other one with a deformation applied in the object. One pattern is then subtracted from the other one to obtain a fringe correlation pattern that will be processed by one of several techniques in order to identify the real deformation applied to the object. The study of object vibrations is one of the most interested applications of ESPI techniques [3, 4], unfortunately, these techniques have some limitations, for example, to study the entire deformation in the whole object due to transient vibrations, one experiment has to be repeated many times, that means that rapid non-repeatable events cannot be studied in detail. This work proposes a solution for this problem, a system that combines ESPI, a continuous wave laser and a high speed camera.

Some high-speed ESPI systems have been used before. The first practical system based on this concept was recording digital speckle interferograms at framing rates of up to 40 Hz, with phase shifting carried out by means of a mirror mounted on a piezoelectric translator [5]. In-plane and out-of-plane interferometers, recorded at 360 frames per second, were demonstrated by Joenathan *et. al.*, [6, 7]. A high-speed ESPI system that used a digital video camera running at 1 kHz was developed by Huntley *et. al.*, [8].

Our purpose in this paper is to present a high-speed ESPI system that uses a digital video camera running at 1, 2 and 4 kHz, a factor of 40, 80 and 160 times faster than can be achieved with the use of conventional video cameras, respectively [9]. The system will record a sequence of interferograms throughout the entire deformation history and with this information will be possible to recreate the entire evolution of the real deformation without the need of a repeatable experiments and the use of temporal or spatial carries. The sequence of interferograms will depend on the relation between the vibration frequency and the acquisition time of the camera.

## 2. Experimental set-up and theoretical description

The arrangement used to obtain the interferograms is an out-of-plane speckle interferometer, shown in figure 1. An out of plane sensitive ESPI is used. The beam coming from a Nd:YAG laser with 6-Watts maximum and 532 nm, is divided into object and reference beams by a beam splitter. The object beam is projected to the target under study by a 10x microscope objective and the reflection of this is recombined by a second beam splitter. The reference beam is re-directed to the second beam splitter and then to the sensor of the camera. The laser was set up from 2 to 5.5 Watts for the experiments described in this paper.

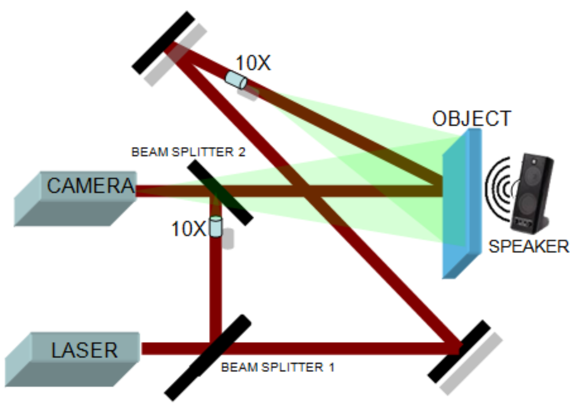



*Fig. 1. Optical set up for a high-speed ESPI system. Beam Splitters 1 is a 70/30, beam splitter 2 is a 50/50, microscope objectives are 10x. The object under study is a 140 x 190 mm rectangular plate.*

The object under study is a rectangular-metallic plate, which is exited by an external sine-wave generator, placed behind the object and plugged to a conventional speaker in order to generate vibration all over the plate. The first vibration modal for this plate is found at 320 Hz [10], which means that for a complete cycle of vibrations it is needed a time of only 3.125 ms. The evolution of the vibration is recorded by a high-speed CMOS camera and having an image lens with a focal length of 75mm in order to get the whole object into the CMOS sensor.

A continuous laser is used, it means that the intensity recorded by the camera sensor for each pixel ($x$,$y$) during the exposure time ($t$) caused by the interference between the object and the reference beams, can be shown as:

$$I_1(x,y) = \frac{1}{\tau}\int_0^{\tau}\left[a_1(x,y) + b_1(x,y)\cos(\psi + \phi_1)\right]dt \quad (1)$$

Where the first term is the DC component, the second term is the modulated interference term, $\psi$ is the random speckle phase and $\phi_1$ is the changed phase coming from the object. It is assumed that during the exposure time of the camera, the object suffers changes, in other words, the frequency at what the object is vibrating, has to be smaller than the camera exposure time in order to consider the integration time null. If this is the case, eq. (1) can be approximated to:

$$I_1(x,y) = a_1(x,y) + b_1(x,y)\cos(\psi + \phi_1) \quad (2)$$

Otherwise, Bessel fringe patterns are expected.
For a $n$–number of interference patterns, the intensity can be expressed in a general form as,

$$I_n(x,y) = a_n(x,y) + b_n(x,y)\cos(\psi + \phi_n) \quad (3)$$

## 3. Experiments

For the experiments done in this work, the camera was set up at 1000, 2000 and 4000 frames per second, it means that the capture time of the system was 1 ms, 500 ms and 250 ms respectively with the electronic camera shutter open for all the experiments at 512 x 512 pixels resolution and 8 bits dynamic range.

The relation between the frame camera rate and the frequency of the first modal vibration of the plate gives the number of fringe patterns that can be obtained in the experiment. Table 1 shows the above described .

*Table 1. Number of fringe patterns that can be obtained at different camera rates.*

| Plate First modal vibration | Fringe patterns obtained at | | |
|---|---|---|---|
| | 1000 fps | 2000 fps | 4000 fps |
| 320 Hz | 3.125 | 6.25 | 12.5 |

The first experiment consists in setting up the camera at a 1000 fps, it means, referring table 1, 3 complete fringe patterns are expected. The power used in the CW laser was 1 Watt.

Fig. 2 shows the theoretical suppose of time capturing and the real fringe patterns obtained at 1000 fps.

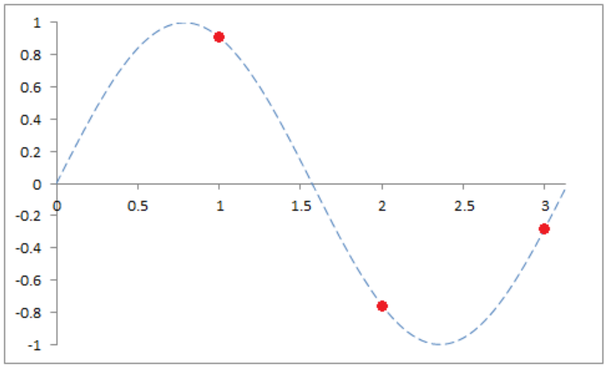
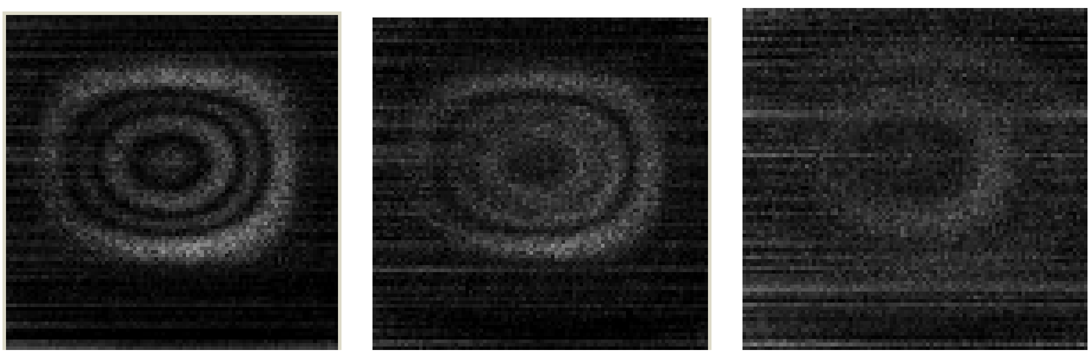



*Fig. 2. Three different intensity patterns are obtained by recording 1000 fps and having the object vibrating at 320 Hz. The x-axis is the time in milliseconds and the y-axis is the amplitude in radians.*

In order to get fringe patterns, as it was described above, one intensity pattern is randomly selected and three consecutive intensity patterns are subtracting from it. The resulted fringe patterns are shown in Fig. 3.



*1* *2* *3*

*Fig. 3. Three fringe patterns along a full vibration cycle. Each one is separated from each other by a phase of $2\pi/3$, this represents a space of time of 320 ms between each other.*

The second experiment takes, according to table 1, six complete fringe patterns; it means that the camera rate increases at 2000 fps. It is important to mention that the power of the CW laser used in this experiment was set at 2 Watts.

In Fig. 4, the expected fringe patterns at 2000 fps are shown

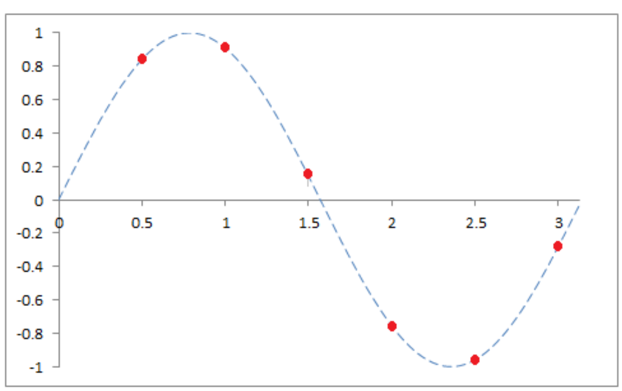



*Fig. 4. Six different intensity patterns are obtained by recording 2000 fps and having the object vibrating at 320 Hz. The x-axis is the time in milliseconds and the y-axis is the amplitude in radians.*

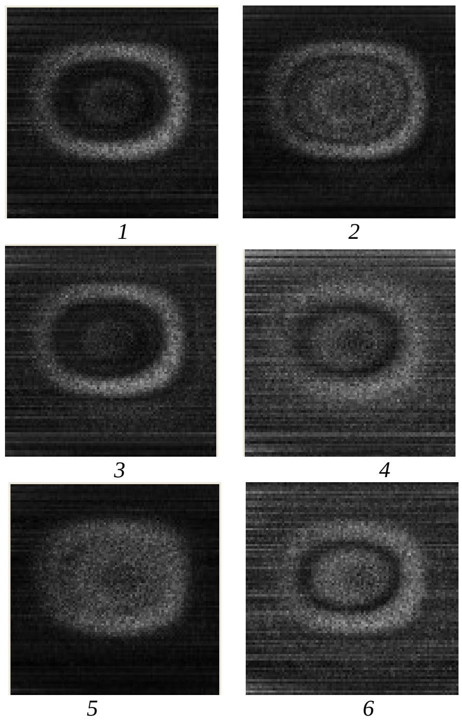



*Fig. 5. Six different fringe patterns obtained by recording 2000 fps and having the object vibrating at 320 Hz. Each fringe pattern is separated from each other in 160 ms.*

The final experiment is done at 4000 fps where 12.5 fringe patterns can be obtained.

In fig. 6, it is shown where the 12 intensity patterns are located along the time function. Fig. 7 shows the fringe patterns at 4000 fps. For this case, the power of the CW laser was set up at 5.5 Watts.

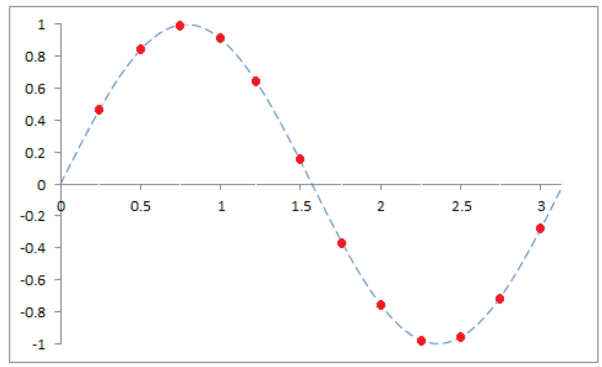



*Fig. 6. Twelve different intensity patterns are obtained by recording 4000 fps and having the object vibrating at 320 Hz. The x-axis is the time in milliseconds and the y-axis is the amplitude in radians.*

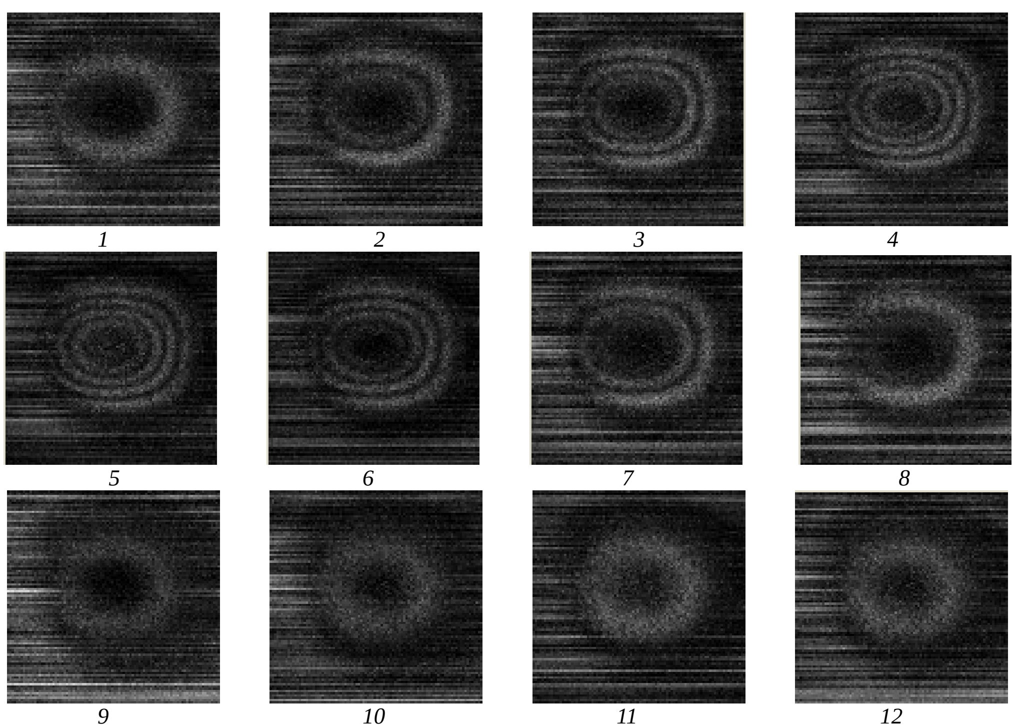



*Fig. 7. Twelve different fringe patterns obtained by recording 4000 fps and having the object vibrating at 320 Hz. Each fringe pattern is separated from each other in 80 ms.*

## 4. Results

In order to demonstrate experimentally that, with a small time exposure ($\tau$), eq. (1) can be written as eq. (2), the unwrapped phase of the fringe patterns obtained at 1000, 2000 and 4000 fps is used.

The procedure for this demonstration is as follows; the unwrapped phase of the fringe pattern is obtained by a computing process based in the Isotropic Quadrature Transform, which is widely described in [11, 12] which was previously used by the authors in [2]. A selected 3x3 kernel is fixed to be the information to follow along the time exposure of the system for each of the unwrapped fringe patterns obtained. The average of the 3x3 kernel is then plotted against time. The graphics obtained will show if the exposure time is small enough to be consider null and ensure that the fringe patterns obtained are sinusoidal.

For experiment 1, from Fig. 2, the wrapped and unwrapped phase is shown in Fig. 8.

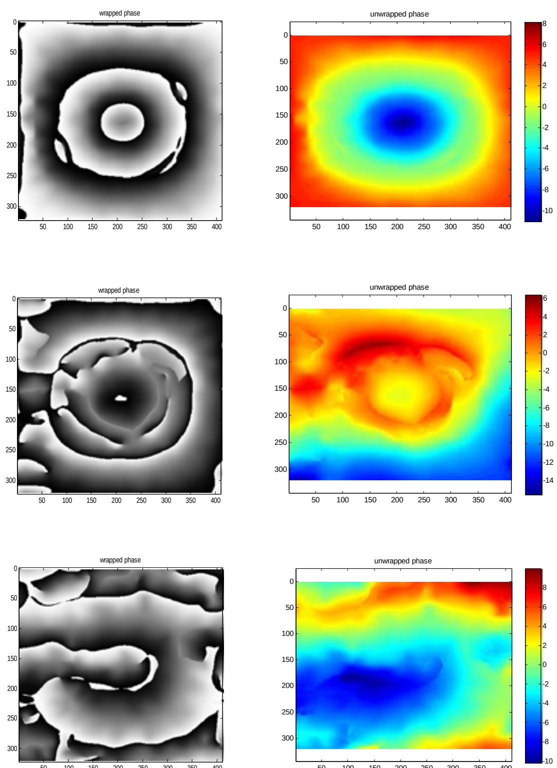



*Fig. 8. Three phase maps at 1000 fps separated one from the other in 320 ms.*

Choosing a 3x3 kernel of the unwrapped phase, where the pixel (170, 370) is the center one, the graphic along the time is as follows.

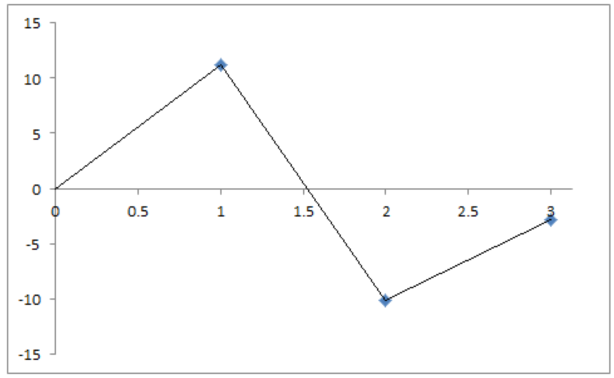


*Fig. 9. Graphics resulted of the experiment 1. The camera is configured at 1000 fps. The x-axis is in milliseconds and y-axis is phase in radians.*

Same procedure is done for experiments 2 and 3 giving the following results.

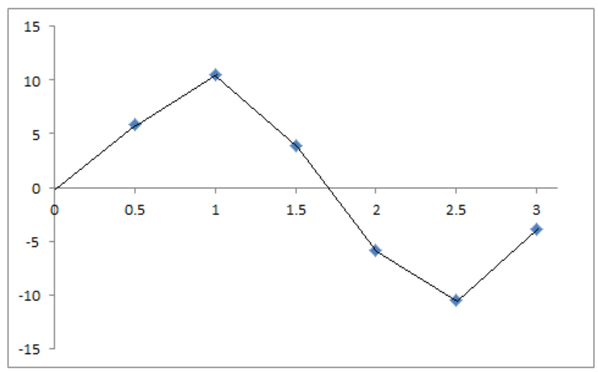


*Fig. 10. Graphics resulted from experiment 2. The camera is working at 2000 fps. x-axis is in milliseconds, y-axis is the phase in radians.*

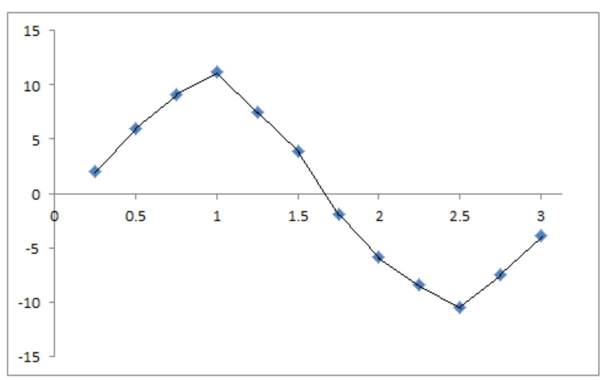


*Fig. 11. Graphics resulted from experiment 3. The camera records 4000 fps. The x-axis is in milliseconds and the y-axis is the phase in radians.*

As it is shown, when the exposure time of the CMOS camera is set up at 1000 fps, the behavior of the fringes patterns along the time is not defined; it means that for this experiment, the eq. (1) cannot be represented as eq. (2).

For experiment 2, when the exposure time runs at 2000 fps, the behavior of the fringe patterns along the time shows an approximated Bessel function (figure 7). Again in this case eq. (1) cannot be substituted by eq. (2).

In experiment 3, the behavior of the fringes patterns along the exposure time is represented by figure 8. Notice that the graphics is an approximated sinusoidal function. In this case, the exposure time of the CMOS camera is small enough and eq. (1) can be substituted by eq. (2).

In figure 9, 10 and 11 graphics of real data, without any fitting, is shown coming from the unwrapped phase obtained.

## 5. Conclusions

In this experiments the resulted graphics where not fitting to any interpolant function. The real data is processed and plotted.

The recovering of the excitation function of vibration coming from the experiment is near to the pure signal as long as the camera is setting to a bigger rate of frames per seconds.

This experiments shown that a same procedure can be done in transient events in order to get the signal of vibrations, with this there are a lot of possible applications to this technique.

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