The application of laser interferometry techniques to study the dynamic behaviour of structural components is described. Being a non contact field technique, it allows the measurement of a dynamic displacement fields without need of additional fitting of transducers, which would change the mass of the structure. Image processing techniques are already available to reduce the time invested in the results investigation. Results are available as numerical files that can be used for subsequent numerical processing of stress calculation.

1-INTRODUCTION

In the last forties Dennis Gabor[1] presented a technique that allows the recording of all the information contained in a wave front, what means; its amplitude and phase distributions. With this technique, that Gabor named holography (from the Greek holos = the whole), is possible to postpone reconstruct, from one hologram, the recorded wave front with all its characteristics. Some posterior works revealed that this technique can be very useful for experimental mechanics applications if interferometry between holograms were used to detect phenomena that can be codified in a wave front [2] [3]. If, at least, one of the wave fronts brought to interfere is reconstructed from one hologram, the technique is known by holographic interferometry. Although, after the discover of laser radiation [4], some spectacular holograms were recorded, holographic interferometry was looked as a scientific curiosity and most of its applications took place inside optical laboratories. Being the photographic emulsions the most used recording media, the holographic techniques usually imply an hologram developing using a chemical wet process. So, measurements with this technique were time consuming and poorly adapted to be used out of laboratories.

In the beginning of the seventies was introduced the electronic recording of the interferometric patterns [5]. The name of this set-up varies according to the research groups that participate on its development and can be ESPI (Electronic Speckle Pattern Interferometry) [5], DSPI (Digital Speckle Pattern Interferometry) [6], TV-holography [7] among others. After that, it was possible to use the target of a video camera to record the interferometric patterns with multiple advantages, being the principals the possibility of record 25 holograms per second (European video rate) with electronic reconstruction of the holograms.

With the recent developments in electronic industry, like the personal computers that became more and more powerful, the new hardware that allows the construction of image processing systems that can be plugged on its buses and the discover of new photodetectors like the CCD (Charge Coupled Device) that allow the construction of very compact video cameras, the holographic interferometry techniques became a very important tool for Experimental Mechanics.

Image processing techniques were developed to help in the analysis of the enormous quantity of information available in each interferogram [8]. Phase calculation routines, specially developed for this techniques, allow the increase of the measurements resolution by one order of magnitude. The result presentation was also improved becoming holographic interferometry more user-friendly and able to be applied on site with a quick analysis of results.

2-TV-HOLOGRAPHY

To record an hologram is necessary to generate two different beams from one polarised laser source. One of the beams, called the object beam, is used to illuminate the surface to be recorded in the hologram and the other, the
reference beam, is driven directly to the hologram plane. In TV-holography the recording media is an electronic photo detector, normally the target of a CCD camera. From the superposition of the two beams on the surface of the photo-detector results a pattern where the phase of the object beam is converted in an amplitude distribution by interferometric phenomena. This way, it is possible to record the object beam phase distribution with conventional quadratic detectors. A schematic representation of a typical holographic interferometry set-up with electronic recording of holograms is presented in figure 1.

Figure 1: Schematic representation of a TV-HOLOGRAPHY set-up.

The reference and object beams are described by the following equations;

\[ A_r = a_r \exp(i\phi_r) \]  \hspace{1cm} (1)

and

\[ A_o = a_o \exp(i\phi_o) \]  \hspace{1cm} (2)

where \( a_i \) is the amplitude, and \( \phi_i \) is the phase and the lower case i stands for reference and object respectively. From the combination of both beams in the plane of the photo-detector, one obtains an intensity distribution that is proportional to the square of the amplitude and can be described by the expression:

\[ I(x, y) = |A_o + A_r|^2 \]

\[ = a_0^2 + a_r^2 + a_o A_r^* + A_o A_r^* \]  \hspace{1cm} (3)

In the last equation, the first two terms represent the auto-correlation of both beams, while the last two are cross-correlation terms and have information of the object surface.

The term \( A_o A_r^* \) contains the information of the object beam and allows its postponed reconstruction. The ‘\( * \)’ represents the conjugate complex.

The intensity distribution described by equation (3) is recorded by the photo-detector, converted in an electrical signal and sent to an image processing board. This signal is sampled by the image hardware, converted in a grey level by the LUTs (Look Up Tables) and stored in the computer memory. Each image is represented by a matrix of pixels according to the image system resolution (in LOME/INEGI normally 512x512 pixels with a grey level in the range 0 to 255).

Holographic interferometry names the technique that uses two or more interferometric recordings to obtain information about the object surfaces. The correlation of the interferometric patterns can be done by one of the following techniques:

- Real time;
- Time-average;
- Double exposure.

In the first one a real time video signal is subtracted from the previous recorded image of the object surface. Any change in the surface can be detected because it will generate a fringe pattern, overlaying the object. These fringes represent points of equal displacement in the direction of the sensitivity vector [9].

To record holograms in time-average the object is harmonically vibrating in one of its eigenmodes during the exposure of the hologram. This way the object wave front is modulated by the object vibration and can be described by;

\[ A_o = a_o e^{i\omega \gamma \cos \omega t} \]  \hspace{1cm} (4)

In this expression \( \omega \) is the object vibration frequency, \( z \) is the vibration amplitude and \( \gamma \) depends on the directions of illumination and observation [10].

If the vibration period is much smaller that the exposure time, several cycles of vibration are recorded in each hologram. This way, by integrating along the vibration period one obtains, for the intensity distribution, the following equation;

\[ I(x, y) \propto |a_o|^2 J_0(k \gamma z) \]  \hspace{1cm} (5)

In this equation \( J_0 \) is the zero order Bessel function and results from the frequency modulation during the recording process. In figure 2 is represented the zero order Bessel
function and its square. In time average recordings each fringe represents points of equal vibration amplitude. The phase of the vibration is lost because several cycles of vibration are integrated in one hologram.

![Graphical representation of zero order Bessel function and its square.](image)

**Figure 2** Grafical representation of zero order Bessel function and its square.

Time average holograms have a peculiar aspect due to intensity modulation of the Bessel function. The first fringe is about five times brighter than the second as can be seen in the figure 3, where the brighter fringe represents the nodes (stationary points) of the vibration.

![Time average recording of an engine cover vibrating in one of its eigenfrequencies.](image)

**Figure 3:** Time average recording of an engine cover vibrating in one of its eigenfrequencies.

With this correlation technique is possible to assess the structure modal analysis scanning the exciting frequency and recording the fringe patterns corresponding to each eigenfrequency. These frequencies are easily detected by the increase in vibration amplitude when they are reached by the excitation.

Compared with conventional modal analysis, the interferometric holographic techniques have the advantage of being noncontact field techniques. Each eigenmode is recorded at once, carries the information about all the visible part of the object and there is no need to fix any transducer in the object surface.

In the correlation technique by double exposure two different instants of the object surface are recorded. The subtraction of the two interferograms is performed afterwards, resulting an interferometric pattern that describes the displacement distribution that the object undergoes between the two exposures. Representing the two recorded interferograms by $A_{01}$ and $A_{02}$, like in equations (1) and (2), after its addition one obtains, for the intensity distribution, the following expression [10]:

\[
I \approx K\{1 + \cos[k(\phi_{02} - \phi_{01})]\} 
\]

(6)

where $K$ is a constant term and $k$ is the wave vector that is equal to $2\pi/\lambda$. The cosine argument represents the phase difference between the two interferograms. In figure 4 is represented a double exposure hologram obtained for a transient phenomena due to an impact of a steel ball on the surface of a steel plate with 10 mm thickness [11].

![Double exposure hologram obtained for a bending wave propagation due to an impact of a steel ball against the surface of a steel plate.](image)

**Figure 4:** Double exposure hologram obtained for a bending wave propagation due to an impact of a steel ball against the surface of a steel plate.

In opposition to the time average fringe patterns, the ones obtained by double exposure have fringes that are linearly proportional to the displacements.

Using the set-up schematically represented in figure 1, operating in amplitude modulation, is possible to sample transient phenomena and obtain interferometric fringe patterns that represent the displacements occurring between the two exposures. However, this technique has a very low light efficiency.
Pulsed lasers can deliver high energies in very short periods of time. With this light sources it is possible to illuminate quick phenomena in a way that it can be considered frozen during the exposure time. The Ruby lasers are well developed and can deliver energies up to several Joules per pulse with a maximum pulsed frequency of about 4 Hz. These lasers were widely used in holography and when used with CCD detectors, have as major drawback its low repetition rate, not allowing real time fringe visualisation. However, the ruby laser is very easily synchronised by the phenomena to be studied, being this the major reason why it was used so widely.

Another laser that is now being developed and can be used for this application is the laser based in a Nd:YAG crystal. Nowadays these lasers can be operated at repetition rates up to 300 Hz with energies per pulse that can reach 100 Joules. Although their emission is in the infrared it can be brought to visible by Second Harmonic Generation which doubles its frequency.

Recent progress allow that the Nd:YAG crystals to be pumped by diode lasers. This way, it is possible to build up very compact laser systems with high energies per pulse. This laser is now being investigated to be included in holographic interferometry systems with CCD recording. As the laser is normally operated at a constant repetition rate, it should be used to synchronise the phenomena to be studied. Some results of TV-holography with a laser of this type have been already published [12].

When transient phenomena are studied, if they are non destructive, they can be repeated and, adjusting the time between pulses, scanned along its period.

3 - OPTICAL SET-UP

When a CCD is used to record the holograms, some special care should be devoted to the set-up. The maximum CCD resolution is about two orders of magnitude lower than the holographic emulsions resolution. So, the two beams that forms the interferometer should be aligned to obtain a primary fringe pattern compatible with the maximum spatial frequency that is resolvable by the photo-detector. The angle between the two beams shouldn’t be greater than 1° [13].

In this set-up, in opposition to conventional holography, an image lens is also necessary. This lens is used to keep the spatial frequency of the interferometric pattern inside the detector bandwidth, being its aperture used to control the size of the speckle, which should be adjusted to be resolved by the CCD.

In the figure 5 is represented the layout of a TV-holography set-up. There are several ways to introduce the reference beam inside the camera aligned with the object beam. In this set-up a monomode polarisation preserving optical fibre is used placed in the centre of the system lens.

![Figure 5: Layout of the TV-holography set-up](image)

The use of an optical fibre to guide the reference beam presents some advantages over other methods. This way the reference beam is immune to optical noise introduced by diffraction of the laser light from scratches and dust on the optical surfaces. The system can be designed more compact and more stable due to less optical components.

In this set-up a phase modulator device is provided and can be used to extend the system measurement capacities as will be described later. When an optical fibre is used, the phase modulation can be obtained by wrapping the fibre around a cylindrical piezotransducer (PZT). Changing the voltage applied to the PZT, one changes the tension in the fibre and consequently, the optical beam path [14].

The video signal obtained in the TV-holography set-up is introduced in an image processing hardware to obtain the interferometric patterns in a video monitor. In LOME/INEGI system, the image board is a DATA TRANSLATION DT 2861 that allows 8 bits real-time subtraction by feedback LUTs and has memory to store up to 16 images. The computer that operates the system has also an A/D-D/A converter that is used to control the PZT.

When time average correlation is used, the phase modulation can be applied to improve the analysis of the vibration. As was shown by Aleksoff [15] sinusoidal phase modulation (SPM) of the reference beam can be applied to obtain vibration phase maps. Other posterior works proved that SPM can also increase the
measurement range [16] or the measurement resolution [17].

Using a TV-holography set-up with time average correlation and lock-in detection, Høgmoen [17] claims to be able to measure vibration amplitudes of a few Å. To obtain this resolution the set-up was operated in the linear part of the zero order Bessel function that is represented in figure 6. In this figure the horizontal axis represents the amplitude of vibration measured with an Argon laser.

In this system an optical fibre coupler is used to substitute the beam splitter. As the reference beam is guided directly to the CCD detector, with almost no losses, the energy necessary in this arm of the interferometer is much less than the energy that should be used to illuminate the object. This way, in this set-up was used an 90/10 coupler delivering 90 % of the energy to the object surface.

As the object surface reflectivity may change from object to object the system is provided with an adjustable attenuator in the reference beam. When the object is changed the beam ration should be adjusted in way to optimise the object/reference beam ratio. In this case a micro-bending device is used to increase the losses in the fibre and so reduce the guided light. The optimum system setting can be detected by the fringe pattern contrast (normally a 3:1 ratio gives good results).

4 - IMAGE PROCESSING TECHNIQUES

The TV-holography system is also provided with specially developed software that extends the system capacities and helps in experimental data analysis. The set of routines to operate the system are collected in a package named Procim® that allows filtering, phase calculation, phase filtering, phase unwrapping and several different ways to present the measurement results.

With correlation by real time or double exposure the information concerning the object displacement is codified in the phase distribution of the interferograms. So, applying a phase calculation routine is possible to isolate the information that gives the displacement distribution. In figure 7 is represented a phase map obtained from the double exposure hologram that is represented in figure 4.

In phase calculation routines an arctangent function is involved to calculate the phase of each point [18], this leads to phase maps modulo $2\pi$, normally named wrapped phase maps. Several unwrapping algorithms are available to remove phase discontinuities and assess the continuous displacement distribution.

Image processing techniques can also be used to improve the results presentation, helping to speed up the measurement and becoming this techniques more user-friendly. In figure 8 is shown an eigenmode obtained from a composite rectangular plate that was acoustically excited by a loudspeaker.

After image processing is possible to present the results in a different way as in shown in figure 9. In this pseudo 3D presentation, is perfectly visible the way the plate vibrates. An animation showing the plate vibration in the computer monitor is also possible.
Although some routines can be used with different set-ups others should be specially developed for each application. For example phase calculation can be done in a few different ways depending on the way the interferogram is recorded [19]. The same stands for unwrapping algorithms which should be chosen accordingly to the noise quantity in the phase map.

5 - DISCUSSION AND CONCLUSIONS

Holographic interferometry have proved to be well adapted for Experimental Mechanics, allowing for measurements of structural displacements in static or dynamic loading conditions. Being non contact field techniques they are particularly well adapted to study dynamic phenomena. Modal analysis can be easily done by using TV-holography with time average correlation. In this case the eigenmode shapes of the objects can be assessed with no need to use any transducer mounted on the object surface. This characteristic is very important when low mass objects are being studied.

Being capable to obtain the whole mode shape, this technique can be very useful to detect structural characteristics that influence the dynamic behaviour of the objects. In figure 8 a thickness difference between the two free sides of the plate can be detect by the symmetry loss of the eigenmode. As shown by Martins et al the orthotropy directions can also be detected by this means [20].

An other very important application of time average holographic interferometry is in acoustic emission reduction. Vaz et al applied this technique to the study of an engine chain drive cover of an automobile [21]. In figure 3 is shown one of the images obtained for the modal analysis of the cover. As can be seen in the figure when the plate is excited by this frequency only part of it vibrates. This information can be very useful to study the best way to assess the vibration dumping.

In what concerns to double exposure correlation, this technique is well adapted to study transient phenomena. Used with pulsed lasers is possible to assess the displacement distribution between two known instants. Figure 4 is an example of a bending wave measurement in a steel plate. In this case only two recordings of the surface are available what demands special phase calculation routines to assess the phase map that is shown. In this case a sinusoidal fitting routine was used to calculate the phase difference between two holograms by decoding the primary fringes generated by placing the reference slightly shifted from the lens optical axis.

In all the applications of holographic interferometry techniques the resolution is of the order of the light wave length. When image processing techniques are applied is possible to increase the resolution by one order of magnitude, what means that displacement of the order of tenth of micrometers, or even smaller, can be easily measured.

ACKNOWLEDGEMENTS

The work presented in this paper has been supported by JNICT (Junta Nacional de Investigação Científica e Tecnológica), under the Pluriannual Research Funding programme, and by the Ministry of Defence (Portugal).

REFERENCES


