Dual beam pulsed ESPI system for measuring out-of-plane displacements

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ABSTRACT: The development of a new dual beam illumination ESPI system is presented. This system is based on a Liquid Crystal Retarder to generate two optical beams orthogonally polarised. With this technique it is possible to illuminate an object with two different beams creating a spatial carrier in the secondary speckle pattern interferogram. This allows the use of Fourier transform techniques and only one interferogram is necessary to get a phase map of the displacement field. Experimental results obtained with an He-Ne laser are presented as well as the way this technique can be used with Nd:YAG pulsed lasers to investigate transient phenomena.

1 INTRODUCTION

Conventional holographic interferometry and Ruby lasers were used, for long time, to study transient phenomena in structural mechanics (Fallstrom, 1989; McBain, 1979). Nowadays, these techniques are being implemented with video recording and Nd:YAG pulsed lasers, with the main advantage of recording 25-pulsed holograms/sec with no need for wet processing. Although the output energy per pulse available with Nd:YAG lasers is less than the obtained with Ruby lasers, its repetition rate can be adjusted to match the video frequency (25 Hz European video standard). With double pulsed T.V.-holography, two laser pulses are used to record a pair of speckle patterns, closely separated in time, this allowing the measurement of the object displacement that occurs between the two pulses (Spooren, 1992).

The enormous quantity of information available in each measurement was used, over a long time period, for qualitative evaluation or time consuming sets of discrete quantitative measures.

The introduction of image processing techniques in experimental data analysis allows for fast and quantitative continuous measurements. These techniques are normally based upon the calculation of the spatial phase distribution of the object wave front, which corresponds to the object deformed shape.

Different image processing algorithms were developed to access the phase maps of interferometric measurements. These algorithms can be classified in two categories: temporal and spatial (Creath, 1994). In temporal techniques several recordings over time of the deformation pattern, obtained after stepping the phase with a phase modulator, are involved in phase calculation. In this case three or more recordings of the same deformation are used to calculate the phase. This demands set-ups that should be mechanically stable during the time involved in the interferograms recording. So, if one wants to study dynamic phenomena, a double-exposure double-reference set-up should be used (Crawforth, 1990). With this set-up it is possible to step the phase between the two reference beams and record the three interferograms necessary to calculate the phase. However, this technique can't be used with an ESPI system because it requires the double exposure hologram to be recorded in a different media. In spatial techniques phase maps are obtained from the demodulation of a spatial carrier introduced in the interferometric patterns.

When transient phenomena have to be studied temporal phase calculation techniques are not the best approach because they demand set-ups that are difficult to adjust due to the presence of a double reference in the reconstruction process. In this case good results can be obtained using pulsed
techniques with spatial phase algorithms. These techniques rely upon the use of a spatial carrier to codify the modulation induced by the object deformation. Depending on the set-up used the carrier can be introduced in the primary or in the secondary fringes, several different ways having been proposed to generate the carrier (Harihar, 1973, Matthey, 1988, Pedrini, 1993).

If the carrier is in the primary fringes, its demodulation leads to the phase distribution of each wave front that, after subtraction, leads to the deformation pattern. When the carrier is in the secondary fringes, the demodulation involves only one interferogram and leads directly to the deformation.

The traditional spatial techniques used to access phase maps with ESPi are sinusoidal fitting (Pedrini, 1993), digital holography (Schmars, 1994) and FFT phase calculations (Morimoto, 1988). In all of them, the carrier should be adjusted to have a frequency that can be resolved by the detector. As the speckle must also be resolved by the detector, its presence in the interferometric pattern imposes some limitations in the maximum carrier frequency that can be demodulated properly.

When a secondary carrier is used, its frequency should also be adjusted according to the object modulation, because the object modulation bandwidth should not include the continuous term in the frequency domain (Judge, 1992). Although this last limitation implies that the maximum displacement amplitude should be previously known, the necessary optical set-up can be very simple. In the present work a novel technique is presented which uses the spatial phase calculation based on a secondary carrier. This is introduced by changing the illumination direction with no need for moving parts. In the set-up proposed the beam polarisation is used to change the light path and so introduce a carrier in the secondary patterns.

2 PULSED Nd:YAG ESPi

The substitution of Ruby lasers by Nd:YAG allowed the construction of an ESPi system that can display real-time double pulsed holograms (Spooren, 1992). These lasers have been used for a long time with a single cavity double pulsed with a time delay that could vary from 20 to 400 μs. When Nd:YAG pulsed ESPi system is used to study mechanical phenomena, like vibrations, this time delay could be too small. In this case, injection seeded twin systems with time delays that can go up to 1 ms should be selected. Because this system corresponds to two completely different lasers it is possible to vary the polarisation of each one to spatially separate both beams. In this work we propose a technique that uses the separation between beam paths to generate a secondary carrier for FFT phase calculation from one single interferogram. Because the carrier direction is well known, there is no π ambiguity in the selection of the FFT side lobe containing the object modulation.

As the Nd:YAG lasers used for holographic interferometry usually have both lasers working with the same polarisation, some modifications have to be done to adapt the laser for this technique. Figure 1 represents the layout of a twin laser converted for this application. The modifications introduced were necessary due to the polarisation characteristics of the second harmonic generation (SHG) which doesn't allow the use of the same crystal for both polarisation directions (Koechner, 1988). So, two different SHG have to be used, being the beam combination done after the frequency doubling. This problem can also be overcome by using a Pockel cell in the output side synchronised with the laser, without any modifications.

![Figure 1. Twin laser layout after modification to deliver pulses with orthogonal polarisation.](image)

As far as two pulses are available with orthogonal polarisation it is possible to separate them spatially by using polarisation sensitive beam-splitters. The set-up used is represented in figure 2, where a linear polariser in the reference beam, oriented in the bisector of both polarisations, ensures the same reference intensity for both pulses. In this way, it is possible to adjust the frequency of the carrier by changing the angle between the two illumination
paths. The pitch of the carrier can be calculated by the well known formula:

\[ p = \frac{\lambda}{\sin \left( \frac{\gamma}{2} \right)} \]  

(1)

where \( \lambda \) is the laser wavelength and \( \gamma \) is the angle between the two directions of illumination.

Figure 2. Double illumination system proposed.

To test this technique, a set-up was built based on a He-Ne laser and a Liquid-Crystal Light Control System, Newport 932C. Using the liquid-crystal retarder (LCR) with a polarised beam-splitter (PBS), one has a configuration with a behaviour very similar to a Pockel cell, and thus it is possible to generate two orthogonally polarised beams. The relative intensity of both beams can be controlled by changing the electrical voltage applied to the LCR. In figure 3 a schematic representation of the set-up used to generate the two beams is shown.

Figure 3. Schematic representation of the set-up used to generate two orthogonal polarised beams.

The output of this set-up is dependent on the applied voltage to the LCR, as illustrated in figure 4. The drive voltage applied to the LCR changes its birefringence, thus the polarisation delivered to the PBS. So, the PBS can create two different paths for the illumination beam. To make the two illuminating beams with the same polarisation, a \( \lambda/2 \)-plate retarder is used in one of the beams to rotate the polarisation by \( \pi/2 \). Both outputs 1 and 2 will have the same polarisation, equal to the reference beam.

Figure 4. Voltage VS Intensity for the two beams delivered from the LCR+PBS.

By a careful adjustment of the drive applied voltage and the introduction of an attenuator in one of the beams, to compensate for the losses introduced by the retarder plate, it is possible to have the same intensity in both beams, thus better fringe contrast.

3 PHASE CALCULATION WITH ONE INTERFEROGRAM

As explained previously, the best way to access the phase maps with pulsed techniques is using a spatial carrier. The phase calculation is obtained by demodulating the carrier. Although the method based on the introduction of the carrier in the primary fringes has the advantage that its frequency is independent of the object deformation, the set-up proposed in this paper, using secondary fringes, is very easy to implement and adjust, without moving components. Using this technique, the modulation induced by the object deformation is demodulated with conventional Fourier techniques (Morimoto, 1988).

Figure 5 represents one of the spatial carriers used, the modulation introduced by the object
deformation and the speckle pattern obtained after superposition of both. It should be mentioned that the fringe pattern represented in figure 5c) is close to one limit of this method: the deformation imposed is too big for the carrier being used. Here, the presence of almost horizontal fringes shows that the bandwidth of the modulation is close to zero, making its demodulation difficult. Nevertheless Kreis has proposed a method that can make the demodulation even with a signal around the continuous term (Kreis, 1994).

![Figure 5](image1.png)

Figure 5. a) Variable carrier fringes. b) Modulation due to the object deformation. c) Carrier + modulation fringes.

As regards the maximum spatial frequency for the carrier, a limit is imposed by the detector resolution. Furthermore, the presence of speckle in the fringe patterns decreases substantially the capability of the detector to resolve those patterns. Because the speckle noise is spread all over the Fourier plane as the signal bandwidth increases more noise is included.

4 EXPERIMENTAL MEASUREMENTS

In order to evaluate the performance of the technique proposed, several interferometric patterns were recorded with four different displacement amplitudes and four different carrier frequencies. For that propose, a circular steel plate 1 mm thick assembled in a rigid support was chosen. A micrometer screw was used to impose a central displacement in a direction normal to the surface. All the deformations were measured with the object standing still.

According to the optical set-up, presented in figure 6, an 18 mW He-Ne laser was used as the light source, and the reference beam is delivered by a polarisation preserving optical fibre. The double illumination is obtained by changing the LCR drive voltage. Different carriers can be generated by slightly changing the angle between the two directions of illumination. To ensure that the two illumination wave fronts have the same curvature, both beams are driven through the same objective (Dandliker, 1985).

![Figure 6](image2.png)

Figure 6. Representation of the experimental set-up used to validate the technique.

As the imposed displacements were not cross-checked, some variations appear in the imposed amplitude which can be clearly seen in the interferometric patterns presented in figure 7. The results presented correspond to different displacement measurements obtained for different spatial carriers. In row 1 it was used a carrier with 16 fringes with displacements varying between 0.5 μm and 5 μm. In rows 2, 3 and 4 the same displacements are imposed with carriers of 26, 36 and 46 fringes respectively. In row 1 it is possible to see that the carrier is too low to allow the demodulation of the 5 μm displacement. In the Fourier plane the object modulation bandwidth includes the continuous term, meaning that there is no phase calculation in regions corresponding to
Figure 7. Carrier and phase maps obtained for different displacement amplitudes.

closed fringes.
By increasing the carrier frequency the demodulation becomes possible, as for the same bandwidth the continuous term is excluded. In the following rows it can be seen that, for the same displacements, the quality of the phase maps improves with increasing carrier frequencies.

Figure 8 represents a phase map obtained with a displacement of 9 μm and a 46 fringes carrier. Here, the fringe shape is still clear, nevertheless, the phase map has a lot of errors, meaning that another limit was reached. The deformation induces a large bandwidth in the Fourier plane, thus including a large amount of noise that destroys part of the information.

Figure 8. Phase map for 9 μm displacement and respective modulation in the Fourier plane.
This noise is due to the presence of speckle in the initial fringe pattern. As this technique is based upon the video recording of fringe patterns, the speckle must be resolved by the photo-detector, thus it will be always present in the patterns.

5 CONCLUSIONS

A new technique to generate a spatial carrier in the secondary interferometric patterns in an ESPI system is available. The implementation of this technique was tested by using a CW laser and a Liquid-Crystal Light Control System to generate two illumination beams. The set-up presented uses no moving parts thus being well adapted to be used in pulsed ESPI, as far as one can generate two orthogonal polarised beams. Either a Pockel cell can be used or a twin cavity Nd:YAG can be adapted to obtain the two illumination beams. In this paper an adaptation of a twin cavity Nd:YAG laser was described for achieving this goal. As this type of laser is being increasingly used in Experimental Mechanics, the technique could be very promising in future pulsed ESPI systems.

It should be mentioned that the carrier frequency is easily adjusted by tilting and displacing external mirrors used to guide the illumination beam. The set-up described is easy to adjust, simple and allows phase calculation with one single interferogram. As the introduced carrier is perfectly known, there will be no ambiguity in its demodulation.

When compared with other techniques based on the introduction of carriers in the primary fringes, this has as main drawback the influence of the deformation in the carrier demodulation. In this technique when the deformation increases in two problems can arise:

- The modulation bandwidth can include the continuous term, implying that the complete demodulation is impossible;
- Increases in the noise contribution for the calculations, thus causing more errors in the final result.

In conclusion, when using this technique it is necessary to know previously the maximum amplitude of the deformation to adjust the carrier frequency.

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