

# Vibration Isolation Techniques Suitable for Portable Electronic Speckle Pattern Interferometry

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## ABSTRACT

Electronic Speckle Pattern Interferometry (ESPI) and Digital Shearography are optical interference techniques, suitable for non-destructive inspection procedures. Due to the stringent vibration isolation conditions required for ESPI, the technique is mainly suited for laboratory based inspection procedures, as opposed to Digital Shearography, which is suited for on-site industrial applications. On the other hand, the interference patterns obtained using ESPI exhibit better fringe definition and contrast than those obtained using Digital Shearography. The image quality of Digital Shearography can be improved by introducing phase stepping and unwrapping techniques, but these methods add a level of complexity to the inspection system and reduce the image refresh rate of the overall process.

As part of a project to produce a low cost portable ESPI system suitable for industrial applications, this paper investigates various methods of minimizing the impact of environmental vibration on the ESPI technique. This can be achieved by effectively 'freezing' the object movement during the image acquisition process. The methods employed include mechanical and electronic means to strobe a continuous wave laser beam. The effect of using a variable shutter speed camera in conjunction with custom written software acquisition routines is also studied.

The techniques employed are described and are applied to selected samples. The initial results are presented and analysed. Conclusions are drawn and their impact on the feasibility of a portable ESPI system discussed.

## 1 INTRODUCTION

The contemporary world has witnessed the development of such innovations as the nuclear-powered submarine, jet aircrafts, satellites and space stations. All of these products are high-value systems where the correct operation of the individual components needs to be guaranteed in order for the whole system to function correctly. To this effect it is necessary to perform numerous quality control inspections; first during the manufacturing phase and then at routine maintenance intervals. Electronic circuits very often include self-diagnostic routines and critical mechanical components are either replaced at regular intervals or alternatively exposed to a sequence of non-destructive evaluation techniques to determine their integrity.

Two of the many non-destructive evaluation techniques available are Electronic Speckle Pattern Interferometry and Digital Shearography. The applications of these optical interference techniques include the detection of material defects such as cracks in manufactured components; debonds and delaminations in composites; internal voids; pitting and corrosion to name but a few<sup>1,2,3,6</sup>.

Over the last 10 years these two techniques have enjoyed much research in the Department of Mechanical Engineering at the University of Cape Town, and the application of these optical interference techniques and their ability to detect the above-mentioned flaws have been published in numerous papers<sup>2,3</sup>. Both techniques have the ability to detect the displacement of an object in response to an applied stress. Due to the optical configuration and interference process, Digital Shearography is less sensitive to global vibrations and is therefore more readily suited for on-site applications. Due to interest from industry, a project was initiated with the primary aim of developing a non-destructive inspection system, which could be liberated from the laboratory environment and used on site. Because of the stringent vibration

isolation requirements for ESPI to be successfully applied, Digital Shearography was chosen as the preferred inspection method. The outcome of the project was the successful manufacture of a prototype Portable Shearography Inspection Module, which was presented at a previous SPIE conference<sup>3</sup>.

Although the project was successfully completed, the results indicated that, depending on the method of object stressing selected, the quality of the produced fringes were not of a high calibre. By reducing the image refresh rate and applying appropriate image post-processing routines<sup>4</sup>, the image quality could be significantly enhanced. In addition, by applying phase stepping routines<sup>5</sup> followed by unwrapping techniques, the image quality could also be improved. This however would only be achievable by adding another level of complexity to the system and reducing the rate at which resultant images could be generated. The phase stepping technique would also increase the vibration stability requirements of the whole system.

A further observation made by industry technicians when exposed to both the Digital Shearography and ESPI techniques, was that the interpretation of fringe patterns produced using Digital Shearography was more difficult than the interpretation of fringe patterns obtained using ESPI.

As a result, it was decided to begin a new project, the aim of which is to develop a small portable Electronic Speckle Pattern Interferometry Inspection System. As mentioned previously, the strict vibration isolation requirements of ESPI has necessitated that the application of the technique be mainly restricted to laboratory-based procedures. The first aim of this project was therefore to address this problem and investigate methods aimed at reducing the impact of this restriction. This paper presents the methods investigated and results obtained.

## 2 THE PRINCIPLE OF ELECTRONIC SPECKLE PATTERN INTERFEROMETRY

ESPI is a non-contacting optical interference technique, which is able to record an object's surface displacement in response to an applied stress. This is achieved by using a monochromatic laser light to illuminate the object being inspected. Using the diagram in Figure 1, the process can be described as follows:

The emitted laser beam is first split into two separate beams via a beam splitter. The first beam, which is called the object beam is expanded and then used to illuminate the object. A CCD camera, coupled via a digitiser card to a computer, is then positioned in front of the object and focused onto the illuminated object. A second beam splitter is then placed between the CCD camera and the object, and the second beam, which is called the reference beam, is focused onto this beam splitter. Due to the monochromatic nature of the laser light, the two beams produce an optical interference pattern. By positioning the beam splitter in such a way that the reference beam is also focused onto the CCD of the video camera, the speckle interference pattern is captured and stored in the computer.

If the object is then stressed mechanically, its surface will deform. This causes the path length of the optical beam to alter. The speckle pattern produced by the interference of the object and reference beam, which remains unaltered, changes accordingly. This new Speckle interference pattern is also captured and stored. The 2 stored images are then compared with each other and areas of correlation and de-correlation identified and mapped into a final image, where areas of correlation are represented as black and areas of de-correlation as grey to white, the level being directly proportional to the magnitude of de-correlation. This process produces an image, which contains the decidedly familiar zebra-like black and white fringes and can be described by equation<sup>7</sup> (1) below.

$$d = \frac{n\lambda}{[\cos\alpha + \cos\beta]} \quad (1)$$

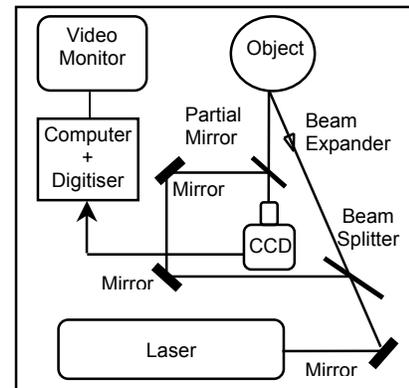


Figure 1. Typical ESPI Layout

where:  $d$  = out of plane displacement of the object due to the applied stress,  
 $\alpha$  = angle between the direction of object displacement and camera viewing angle,  
 $\beta$  = angle between the direction of object displacement and object beam, and  
 $n$  = number of fringes.

These black-and-white fringes are a direct indication of the magnitude of surface deformation, which is represented by  $d$  in the above equation. Equation (1) also indicates that each fringe of magnitude  $n$  represents a region of constant deflection and that as the object deflection increases, so does the number of fringes. If a flaw is present in the area under inspection, its presence weakens the material structure. When stressed, the area of the object where the flaw is present will deflect abnormally. This can directly be detected in the resultant interferogram as an increase in fringe density or fringe irregularity.

Because the formation of the fringes is directly related to the difference in beam path length change between the object and reference beam during the inspection process, any environmental disturbance that will cause either an optical component or the object to resonate, will destroy the image acquisition procedure.

In order to make the ESPI procedure more robust, the researchers associated with this paper investigated methods of reducing the influence of environmental disturbances on the inspection technique. The approaches adopted can broadly be split into two categories. The first was to investigate the use of a variable shutter speed camera and the second was to investigate methods of producing a strobed laser light source.

### **3 VARIABLE SHUTTER SPEED IMAGE ACQUISITION**

Most of today's CCD cameras offer variable shutter speed control settings. The standard camera used in the laboratory for the image acquisition routines was a monochrome Sony camera with a composite video signal output. The camera had seven different shutter speed settings ranging from one 50th of a second to one 10 thousandth of a second. The camera also had an automatic gain control (ACG) routine, which could be engaged or disengaged via an on-board micro switch.

The investigations were conducted in the department's non-destructive testing laboratory and all optical set-ups were arranged on a steel table using optics with magnetic bases. The object used for the evaluation process was a section of a composite aluminium helicopter blade, which was placed on a conventional wooden 2-step ladder on the floor adjacent to the table. In addition, a compressor was placed in the room and switched on in order to simulate environmental disturbances.

The optical configuration used was similar to the one indicated in Figure 1. The rotor blade used for the inspection incorporated a man-made surface tear of the aluminium skin and was illuminated with laser light obtained from a 35 mW helium neon laser. Thermal heating was used to stress the object. All video acquisition, comparison and processing was performed using a Matrox digitising card and custom written software routines. By operating the software in real-time mode, the operator was given the ability to obtain fringe pattern results immediately. This was achieved by recording an initial image of the object in its unstressed state. By placing the digitiser into a continuous acquisition mode, all successive frames recorded by the computer were then compared to the initially stored image and the results presented on the screen for viewing. The operator had, at any point in the procedure, the ability to stop the comparison sequence and record the last generated image.

#### **3.1 Variable Shutter Speed Results**

The tests were conducted by systematically operating the camera and software program through each of the available shutter speed settings and recording the interferograms produced in response to the thermal stressing of the rotor blade.

Figures 2 through 7 depict the ESPI results obtained. The irregular fringe formation in the centre of the interferograms in each of the images clearly reveals the location of the flaw. The tests revealed that for shutter speed settings below

1/1000<sup>th</sup> of a second, the fringes produced by the inspection process often lacked definition and had to be repeated numerous time in order to get good results.

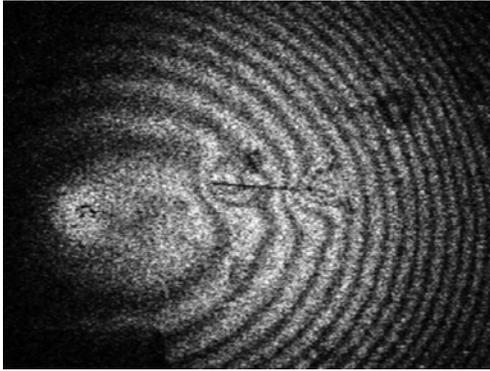


Figure 2. ESPI Result, 1/250<sup>th</sup> sec shutter.

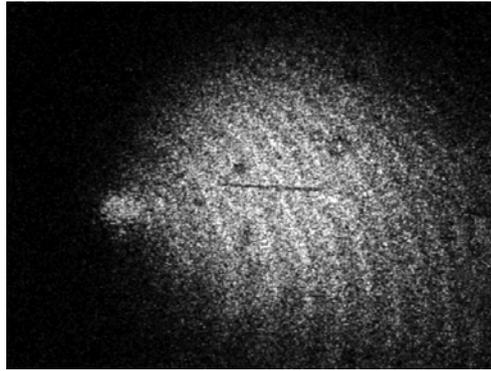


Figure 3. ESPI Result 1/250<sup>th</sup> sec, Compressor on.

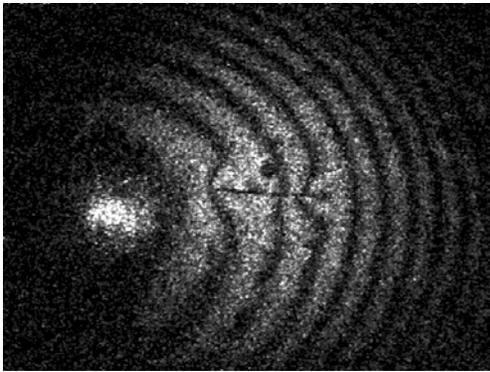


Figure 4. ESPI Result, 1/4000<sup>th</sup> sec shutter

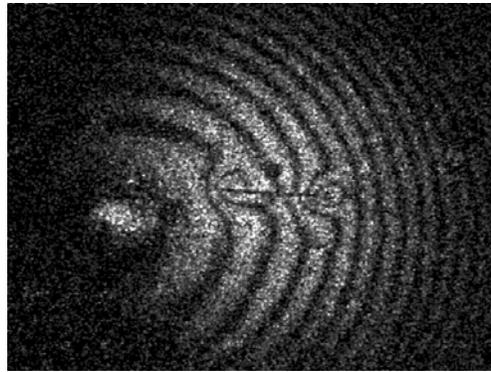


Figure 5. ESPI Result, 1/4000<sup>th</sup> sec, Compressor on

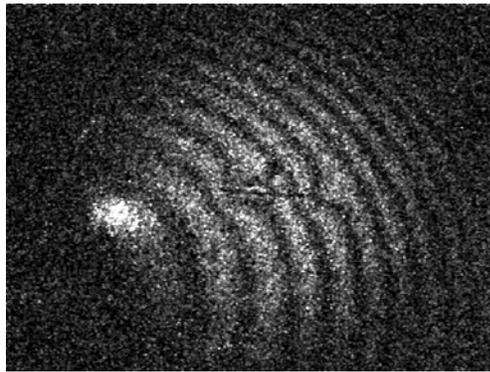


Figure 6. ESPI Result, 1/10 000<sup>th</sup> sec shutter

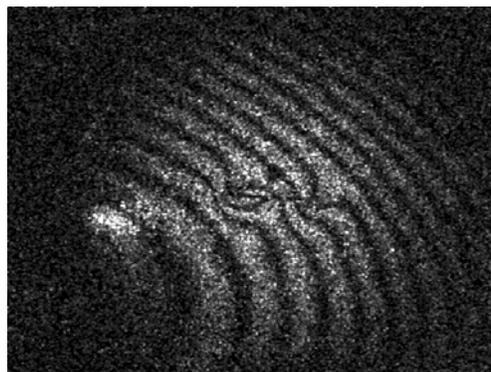


Figure 7. ESPI Result, 1/10 000<sup>th</sup> sec, Compressor on

The fringe patterns in Figures 3, 5 & 7 were obtained with the compressor switched on. For the 1/4000<sup>th</sup> and 1/10 000<sup>th</sup> sec exposure results one can see that the fringe formation is clear, indicating that the environmental disturbance created by the compressor is eliminated by the reduced integration period of the CCD camera. This cannot be said for the result in Figure 3, where at 1/250<sup>th</sup> the influence of the compressor destroys the fringe visibility.

For images captured at 1/1000<sup>th</sup> of a second and less, it was necessary to use the camera's ACG function. Due to the shorter integration period, the 35mW laser simply did not deliver enough laser light to provide a sufficiently saturated

image. By manipulating the camera gain setting, this effect could be reduced, but with a resultant increase in noise in the final image. This is particularly evident in Figures 6 & 7, which were recorded at 1/10 000<sup>th</sup> sec.

## 4 PULSED LASER ILLUMINATION

By manipulating the exposure time of the CCD camera, the system effectively freezes the object motion during the image acquisition phase. As an alternative to this approach, the project also set out to explore means by which the duration of object illumination could be controlled. Typically this can be achieved by switching a laser on and off according to a predetermined voltage modulation sequence or alternatively by chopping a continuous wave laser beam using optical shutters.

The first part of this investigation was to explore the feasibility of modulating a laser diode's injection current. A square wave signal generator was used to provide the timing signal for the modulation port of the diode laser power supply. Initial tests revealed that the quality of the pulsed laser light was poor and that intensity correlation between successive images was a near impossibility. It was noted that by modulating the power supply, both the average laser intensity as well as the laser light wavelength fluctuated over time. It also immediately became apparent that the modulation frequency was critical. This was due to the composite signal produced by the CCD video camera. Because the video format used was PAL, the frame rate was 25 frames per second and the camera integration period 20ms per field. If the modulation frequency chosen was not a common multiple of 50 Hz, a visible beat was noticeable in the digitised image sequence. This was particularly evident if the frequency was less than 25 Hz, at which point intermittent black images would be produced. The literature<sup>8</sup> also reports on the problems associated with modulating the supply voltage and continues to point out that frequency chirping cannot be entirely eliminated.

### 4.1 Mechanical shutters

After having eliminated the possibility of modulating the laser supply voltage, pulsed laser illumination via the use of mechanical shutters was explored. In order to test the feasibility of this approach, it was decided to use a rotating circular disk with machined radial slots. By letting the rotating disk intersect the laser beam path between the laser and the first mirror of the set-up shown in Figure 1, laser light would only pass through the disk via the slots and otherwise be blocked by the opaque disk.

The first disk used was a 150 mm disk with two 9mm wide slots diagonally opposite to each other. In order to synchronise the illumination frequency with the camera field acquisition rate, the disk was rotated on the shaft of a DC motor at 1500 rpm, which produced the required 50 Hz. Tests however revealed that the motor speed on average fluctuated by 10 rpm, which produced unwanted beats in the fringe pattern image on the monitor. The setup was replaced with a second disk, 120 mm in diameter. The disk had 12 equally spaced radial slots and each slot was made up of a 12mm inner slot, which tapered down to a 4 mm outer slot. By mounting this disk onto a stepper motor and setting the speed to a constant 250 rpm, the beat problem experienced with the dc motor was eliminated. Changing the radial distance at which the laser intersected the disk controlled the object illumination pulse length.

Figures 8 & 9 depict two of the many results obtained. Due to the laser position on the disk, the illumination period was 10 ms (1/100 sec) and 2.7 ms (1/370 sec) respectively. Both images contain clear fringe patterns and the flaw can be identified via the fringe irregularities. The compressor was not used, because the camera shutter investigation had shown that this illumination period was still too long to effectively eliminate the produced environmental vibrations. In order to produce the required 0.25

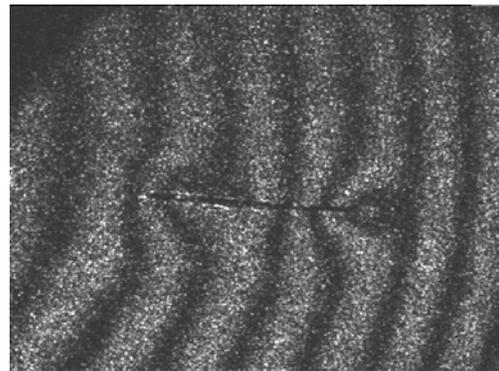


Figure 8. ESPI Result, mechanical shutter, 10ms

ms illumination pulse, as observed in the camera shutter tests, a 305 mm disk with 12 1mm slots on the outer perimeter would be required. This was not considered viable, especially when considering that the system was to be small and portable. The vibrations produced by the first disk also required that the disk and motor had to be separated from the optical table. The second disk and low rpm stepper motor combination however didn't require additional vibration isolation procedures.

#### 4.2 Optical shutters

The use of optical shutters is an appealing alternative to mechanical shutters, as there would be no moving parts and associated vibrations to isolate from the interferometer optics. There only were two types of optical shutters available to the researchers and both were investigated. The first was a liquid crystal modulator (LCM), as used in 3D computer glasses, and the second a lithium niobate crystal.

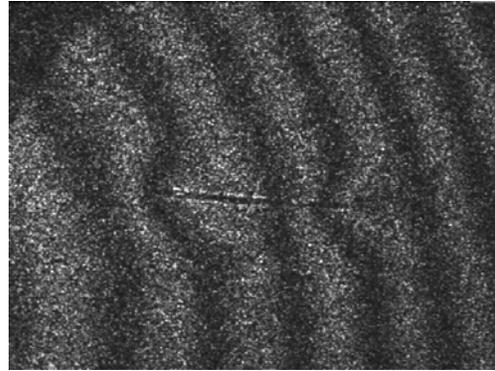


Figure 9. ESPI Result, mechanical shutter, 2.7 ms

#### 4.3 Liquid Crystal Modulator

The liquid crystal modulator (LCM) consisted of liquid crystal molecules sandwiched between two crossed polarizers<sup>9</sup>. By applying 12 V across the embedded terminals and passing the laser beam through the LCM with the polarization orientation of the panel in line with the polarization state of the laser, the shutter would be closed and not transmit light. Switching off the LCM would open the shutter and allow laser light to pass through. A square wave generator with a 12 V output, was connected directly to the LCM. The modulation frequency was set to 50 Hz, so that the cycle time would match the CCD integration period. With this configuration, adjusting the 12 V pulse width within the 20 ms cycle allowed the laser illumination time to be controlled.

The results of the inspection of the same flawed helicopter rotor blade are listed in Figures 10, 11, 12 & 13 below. As can be seen, the vertical fringes deviate in the central region of the image, indicating the flaw location. One can see that the fringes in Figure 10 are not as defined as those in Figure 11. This is, in all probability, due to the reduced exposure

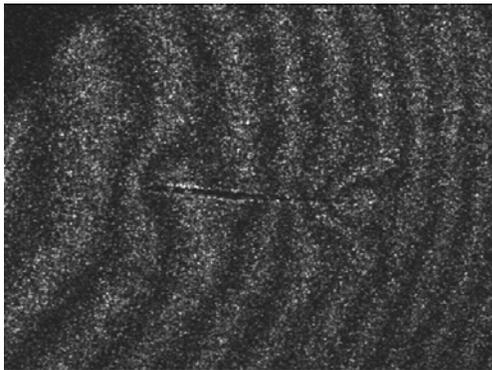


Figure 10. ESPI Result, 12ms LCM exposure time

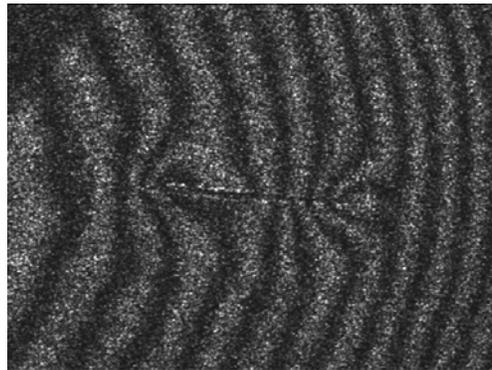


Figure 11. ESPI Result, 8.13ms LCM exposure time

time used in Figure 11 (8.13 ms vs 12ms). Another likely contributing factor was that the inspection process had to be repeated a couple of times on a hit and miss basis in order to obtain a stable fringe pattern. Both these factor point to the need for shorter exposure times in order to effectively freeze potential object movement. But the results in Figures 12 & 13, which were recorded using a 3ms (1/333 sec) and 2ms (1/500 sec) exposure time respectively, should have reduced the problems associated with the results of Figure 10 and 11. However, the fringe quality in Figure 13 was unsatisfactory and pointed to underexposure.

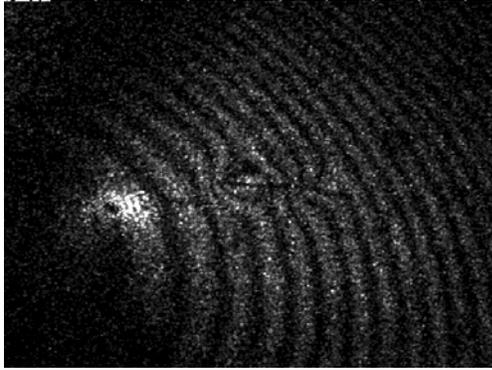


Figure 12. ESPI Result, 3ms exposure time

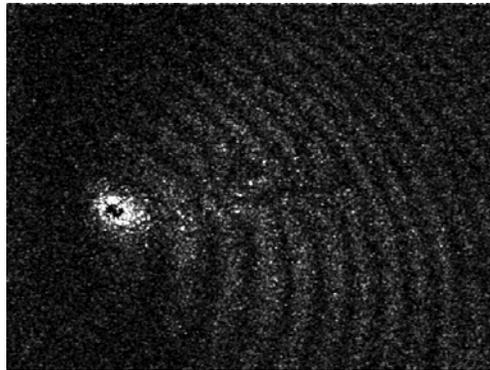


Figure 13. ESPI Result, 2ms exposure time

As a result of the above, the performance of the LCM was analysed. This was done by focussing the laser beam transmitted through the LCM onto a photocell connected to an oscilloscope. The on-off and off-on switching times were recorded and are presented in Figure 14. The graph shows that the on-off switching response time was greater than 5ms and the off-on switching time approximately 1ms. Because the laser light only passed through the LCM when the applied voltage was switched off, this graph reveals that for pulse widths less than 5 ms, which is equivalent to a 1/200 sec exposure time, the liquid crystal molecules do not have sufficient time to re-orientate completely. The effect of this is a reduced peak optical power and resultant loss in image quality. This explains why the image quality in Figure 13 is so poor.

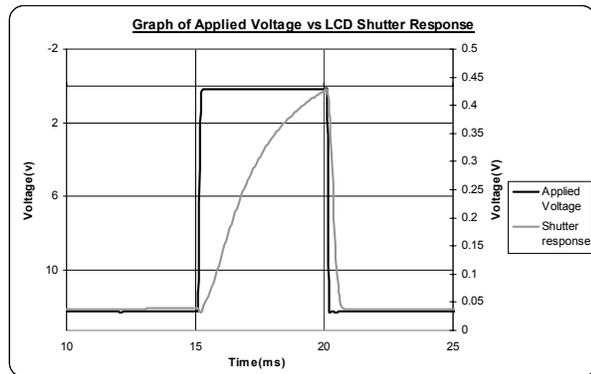


Figure 14. Graph of Applied Voltage vs LCM Response

#### 4.4 Lithium Niobate Crystal

A company called Eloptro informed the research team that an optical shutter with fast response times could be manufactured using lithium niobate crystals. When applying a high voltage across the crystal, the polarization orientation of a linearly polarized laser beam passing through the crystal can be made to rotate by 90°. By placing a polarizer at the exit face of the crystal, either crossed or parallel to the polarization state of the laser beam, the setup could be used as an electronic shutter.

A lithium niobate crystal was kindly donated to the research team by Mr Steyl of Eloptro. The Electrical Engineering Department at UCT assisted with the design and manufacture of the crystal's power supply. The power supply consisted of a step-up transformer, rectifier and high voltage switching circuitry. A square wave generator was used to trigger the switching circuitry. In order to determine the required driving voltage, a helium neon laser beam was passed through the electronic shutter and focussed onto a photocell connected to an oscilloscope. The results showed that a driving voltage of 1800 – 2000 V produced the largest peak laser power. For shutter periods in excess of 0.2ms, higher voltages produced undesirable laser power spikes when the switching circuit opened. For shutter periods less than 0.2ms, higher voltage levels could be tolerated. Figure 15 represents the shutter's response to a 0.1ms pulse width. The graph shows that the off-on and on-off switching times for the crystal are approximately 0.1ms and 0.2ms respectively.

Figures 16 and 17 below are the interferograms obtained using the lithium niobate optical shutter in the ESPI set-up with the compressor switched off. Switching the compressor on made no difference to the image quality. The fringes for both the 1ms (1/1000 sec) and 0.1ms (1/10 000 sec) illumination period are well defined and clearly visible and the flaw location can be easily located via the fringe pattern. In Figure 17 one can notice that the left edge of the image was under illuminated, indicating that a higher-powered laser should be used if the illumination period were to be reduced further.

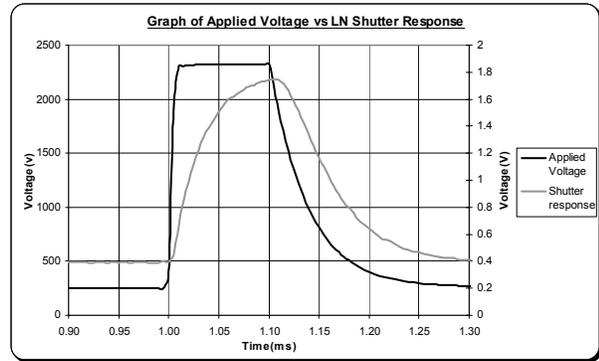


Figure 15. Graph of Applied Voltage vs Lithium Niobate Crystal Response

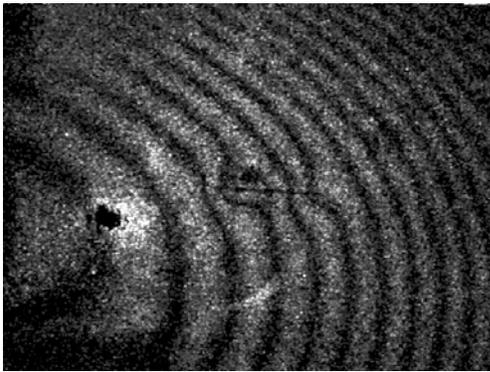


Figure 16. ESPI Result, 1ms Illumination, Lithium Niobate Shutter

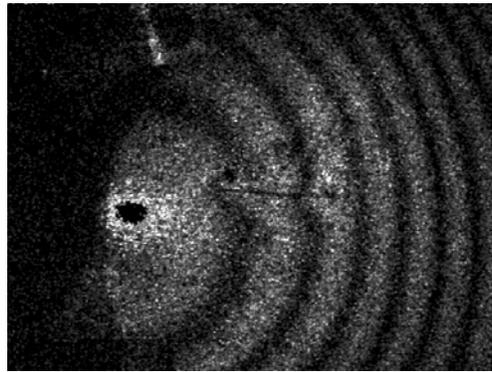


Figure 17. ESPI Result, 0.1 ms Illumination, Lithium Niobate Shutter

## 5 CONCLUSIONS

From the results, the following conclusions can be drawn.

With the exception of directly modulating a diode laser, all laser strobing techniques presented, were successfully integrated into an ESPI set-up and produced good interferograms.

The high-speed camera shutter option was effectively used for ESPI inspection routines. Short integration periods in excess of  $1/4000^{\text{th}}$  of a second were able to remove the effect of induced environmental vibrations from the inspection procedure and produce reliable interferograms with clear fringe definition.

The stepper motor driven mechanical shutter proved to be a suitable chopping technique with no noticeable vibration influences when operating at 250 rpm. In order to produce sufficiently short laser pulses, a 305 mm disk with 1 mm slots would have to be used. This is not considered viable for a small portable inspection system.

Because of the relative slow response time, the LCM can only operate effectively as an optical shutter at speeds of  $1/300^{\text{th}}$  of a second and longer. These speeds are too slow to significantly reduce the impact of vibrations on the ESPI technique.

The ESPI set-up incorporating the lithium niobate crystal and power supply produced clear interferograms at shutter speeds up to 1/10 000<sup>th</sup> of a second. At these speeds, the induced environmental vibration effects were eliminated and clear interferograms with good fringe visibility were captured.

Due to the reduced amount of laser light available to illuminate the object and beam splitter, a more powerful laser is needed for an ESPI system incorporating a high-speed optical shutter.

## 6 RECOMMENDATIONS

From the research presented in this paper, the high-speed camera shutter option or the lithium niobate electrical shutter would be the most suitable method of removing vibration influences from the ESPI inspection procedure. The variable camera shutter appears to be a likely choice, as the system is already integrated into the camera electronics. However, the limitation of this choice is that there are only 8 speed settings and 1/10 000 of a second is the fastest available. A survey needs to be undertaken to determine if there are suitable alternative cameras with more and faster speed settings.

The lithium niobate electrical shutter is a small device and could be incorporated into a portable system. As the shutter is controlled via the square wave generator, it is easy to select any desired shutter speed. Further work would have to be undertaken to investigate the influence of the driving voltage on electrical components such as video cameras and laser diodes. The shutter timing could also be configured to generate two laser pulses within one camera frame integration period, which would make the system suitable for additive ESPI work or object vibration studies.

In closing, the researchers would like to acknowledge Armscor for supporting this project.

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