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Contrast Enhanced and Phase Controlled Stroboscopic Additive Fibre Optic TV Holography for Whole Field Out-of-plane Vibration Analysis

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ABSTRACT

A new technique for real-time contrast enhancement and phase control of fringes in additive stroboscopic TV Holography applied to out-of-plane vibration analysis and its implementation on a fibre optic electronic speckle pattern interferometer (FOESPI) are presented. Synchronous stroboscopic illumination, firing two pulses per object’s vibration period, is combined with simultaneous interpulse (high frequency) and interframe (low frequency) phase modulation in the reference arm of the ESPI yielding a sequence of frames (interferograms) that are grabbed and processed in real-time. With this artifice both speckle and fringes phases are independently controlled by means of the parameters of modulation enabling speckle contrast inversion, as required to enhance the visibility of fringes by sequential subtraction, as well as dynamic fringe phase shifting to solve peak-valley ambiguity.

1. INTRODUCTION

Since its invention in 1971, television holography (TVH) -also known as electronic speckle pattern interferometry- has grown up and become a well established tool for whole field vibration analysis, among many other engineering fields. The incorporation of optical fibres, high performance solid state cameras and advanced image processing devices to the design of the electronic speckle pattern interferometer (ESPI) has resulted in a powerful instrument rough and compact enough to be portable to industrial environments.

The most usual technique for qualitative modal analysis by TVH is time-averaging; it yields fringes with brightness related to vibration amplitude through a Bessel function which are highly immune to environmental noise of frequency lower than video frame rate. The visibility of Bessel fringes decreases as the amplitude of vibration increases thus restricting the application range of this technique. Time-averaged correlograms map the amplitude of vibration, but phase and temporal shape information are lost. Heterodyne techniques can be used to solve peak-valley ambiguities but phase-shifting Bessel fringes involves applying optical phase modulation synchronized with object’s vibration in both frequency and phase and this makes its control and automation fairly complicated.

Stroboscopic techniques yield cosine fringes, of constant visibility, and provide full temporal resolution within the vibration cycle, i.e., instantaneous deformation of the object can be determined. This features can be exploited to analyse the shape of vibration across its period and to obtain phase-maps of amplitude and phase of vibration.

In single pulse subtractive stroboscopic TVH vibration is "frozen" at a fixed point of its period and compared by subtraction with object’s position at rest, as a result it can be treated as a static deformation field and phase-shifting is simply accomplished by changing the optical path in one of the arms between successive interferograms; but this technique shows very high sensitivity to low frequency mechanical noise and thermal drifts, that appear as a phase offset superimposed to vibration and are specially noticeable when fringes are observed for a long time using the same reference.
Twin pulse additive stroboscopic TVH, on the other hand, is highly immune to either low or high frequency environmental noise because it works comparing by addition\(^1\) two "frozen" deformation states inside the same vibration cycle and hence, there is no need of taking any reference with the object at rest, making this technique specially attractive for industrial and out-of-the-lab applications; but resulting fringes have rather low visibility compared with those obtained with subtractive methods and, being insensitive to low frequency phase changes, they can not be shifted just changing optical phase between TV frames.

In the following sections we shall present a technique that, combining twin pulse stroboscopic illumination with both synchronous and asynchronous phase modulations, yields stroboscopic additive TVH correlograms where phases of fringes and of speckle pattern can be individually shifted through two independent modulation parameters. A theoretical discussion of our technique is presented in section 2.1, a method to enhance fringe contrast is described in section 2.2 and how dynamic phase-shifting can be implemented to solve peak-valley ambiguity is disclosed in section 2.3. Section 3 describes the implementation of the technique on a fibre optic ESPI and shows some experimental results.

### 2. THEORY

#### 2.1. Independent control of speckle and fringe phases in additive stroboscopic speckle correlograms

The basic layout of an out-of-plane displacement sensitive fibre optic ESPI with amplitude and phase modulators is shown in figure 1. Its operation can be outlined as follows: a laser beam is split to get an object beam and a reference beam; the object beam illuminates the object under test and light scattered from its surface is collected by a lens that forms a speckled image on the sensitive area of a TV camera. This image of the object is then coherently combined with the reference beam to produce an interferogram.

Assuming for simplicity, and without loss of generality, normalized intensity and unity fringe visibility, the instantaneous incident intensity at an arbitrary point \(x=(x,y)\) on the face of the camera can be expressed as:

\[
i(x,t) = 1 + \cos[\Delta \phi_o(x,t) - \Delta \phi_r(t) + \psi(x)]
\]

being:

- \(\Delta \phi_o(x,t)\) the optical phase increment of the object arm due to the out-of-plane displacement \(z(x,t)\) of the point of the object imaged at \(x=(x,y)\). Assuming that illumination and observation are normal to the surface, \(\Delta \phi_o(x,t) = 2k z(x,t)\) where \(k=2\pi/\lambda\) (the wave number of light);
- \(\Delta \phi_r(t)\) an increment of the optical phase introduced in the reference arm by means of a phase modulator;
- \(\psi(x)\) a phase term with stochastic spatial distribution due to surface roughness.

![Figure 1.- Fibre optic ESPI with amplitude (AM) and phase (PM) modulators](image-url)
Under continuous illumination, if the surface of the object is vibrating in steady state with frequency $\omega$ much higher than the video frame rate, the interferogram $i(x,t)$ changes accordingly and its intensity is integrated by the camera during each frame period $(T_f)$ resulting in a time-averaged correlogram,

$$I(x) = \int_{T_f} i(x,t)\,dt$$

(2)

Illuminating the object with a train of short stroboscopic pulses synchronized with its vibration, the interferogram may be frozen at any instant $t_a$ of the vibration cycle and then the brightness recorded by the TV camera can be written as:

$$I_a(x) = I(x,t_a) = 1 + \cos[\Delta \varphi_a(x,t_a) - \Delta \varphi_r(t_a) + \psi(x)]$$

(3)

where $\alpha = \omega t_a$ is the phase delay between stroboscopic light pulses and object vibration.

In order to keep notation as concise as possible, we shall omit express references to spatial coordinates in succeeding, assuming that intensity and optical phase are functions of position; equation (3) is thus simplified to

$$I_a = 1 + \cos(\Delta \varphi_a - \Delta \varphi_r + \psi)$$

(4)

Firing two stroboscopic pulses with phases $\alpha$ and $\beta$ within each vibration period, as shown in figure 2.a, their respective interferograms will be incoherently combined on the camera yielding an additive correlogram where brightness is proportional to the sum of their intensities as given by (6).

$$I_{\alpha} = 1 + \cos(\Delta \varphi_{\alpha} - \Delta \varphi_{r} + \psi)$$

(5)

$$I_{\beta} = 1 + \cos(\Delta \varphi_{\beta} - \Delta \varphi_{r} + \psi)$$

(5)

$$I_{\alpha\beta} = I_{\alpha} + I_{\beta} = 2 + 2 \cdot \cos\left(\frac{\Delta \varphi_{\alpha} - \Delta \varphi_{\beta}}{2}\right) \cdot \cos\left(\frac{\Delta \varphi_{\alpha} + \Delta \varphi_{\beta}}{2}\right)$$

(6)

Figure 2.- Timing diagram: a) object vibration and stroboscopic pulses; b) phase modulation
Taking into account the premise of steady state vibration, \( \Delta \phi_{\alpha\beta} \) and \( \Delta \phi_{\alpha\beta} \) become constant for each point of the object once the values of \( \alpha \) and \( \beta \) have been chosen. In particular, their semisum is also a constant that added to the random term \( \psi \) results in a constant phase factor with stochastic spatial distribution too.

\[
\Psi_{\alpha\beta} = \frac{\Delta \phi_{\alpha\beta}}{2} + \psi
\]  

(7)

Substituting (7) and dividing by 2 to normalize brightness, equation (6) can be rewritten as follows.

\[
I_{\alpha\beta} = 1 + \cos\left(\frac{\Delta \phi_{\alpha\beta} - \Delta \phi_{\alpha\beta}}{2}\right) \cos\left(\Psi_{\alpha\beta} - \frac{\Delta \phi_{\alpha\beta} + \Delta \phi_{\alpha\beta}}{2}\right)
\]

(8)

Carefully looking at this expression, becomes obvious that the additive correlogram consists of a speckle field with its stochastic brightness distribution determined by \( \Psi_{\alpha\beta} \) and its contrast modulated by a function of \( \Delta \phi_{\alpha\beta} \). That is proportional to the displacement of the object between pulses. Speckle brightness distribution and contrast fringes can be shifted by means of \( \Delta \phi_{\alpha\beta} \) and \( \Delta \phi_{\alpha\beta} \). Changing any of these values individually should affect speckle and fringes at the same time, complicating unnecessarily the interpretation of the resulting correlogram. In order to separate both effects, we modulate the phase of the reference arm with a rectangular shaped signal \( \Delta \phi_{r}(t) \) satisfying:

\[
\begin{align*}
\Delta \phi_{ra} &= \Delta \phi_{ra} + \Delta \phi_{r}\delta \\
\Delta \phi_{oa} &= \Delta \phi_{oa} - \Delta \phi_{r}\delta
\end{align*}
\]  

(9)

Such modulation, as illustrated in figure 2.b., can be generated by the superposition of two basic components: one of them is a symmetrical rectangular wave of amplitude \( \Delta \phi_{r}\delta \) inverting its sign in synchronism with the stroboscopic pulses, and therefore synchronous with the vibration of the object, and the other is a phase offset that keeps the same value \( \Delta \phi_{r}\delta \) for both pulses, thus being asynchronous with the vibration. The implementation of the resulting modulation scheme, as we shall discuss in section 3, involves very simple electronic circuits.

The brightness distribution of the additive correlogram obtained with stroboscopic pulses in \( \alpha \) and \( \beta \) and modulating the reference arm with the proposed waveform is described by the final expression:

\[
I_{\alpha\beta} = 1 + \cos\left(\frac{\Delta \phi_{oa} - \Delta \phi_{o\beta}}{2}\right) \cdot \cos\left(\Psi_{\alpha\beta} - \Delta \phi_{rA}\right)
\]  

(10)

where:

- \( \Delta \phi_{r}\delta \), the amplitude of the synchronous component of modulation, controls the phase of fringes and can be used to implement either phase-stepping or phase-shifting evaluation techniques;
- \( \Delta \phi_{rA} \), the asynchronous offset, controls speckle phase, thus allowing fringe contrast enhancement by sequential subtraction and the implementation of speckle noise averaging techniques.
2.2. Contrast enhancement by sequential subtraction

Additive speckle correlograms as detected by the TV camera -equation (10)- have almost constant average brightness and the variations in correlation induced by the displacement of the object appear as changes in the contrast of the speckle pattern but not in its brightness (figure 3). Moreover, speckle noise arises as a multiplicative factor and can not be filtered out without removing the signal, for that reason such correlograms are not adequate by themselves for displaying or direct processing.

The usual way to improve fringe contrast\(^\dagger\) is to remove the DC component of brightness by high-pass filtering and then rectify the resulting signal. This technique can be implemented by direct manipulation of the video signal, without digitizing or storing correlograms, but fringes are often contaminated by electronic noise during filtering and rectification. Several methods\(^3,6\) combining additive formation with subtractive processing of the correlograms have been devised to get simultaneously good contrast and high environmental noise rejection, the basic idea is to acquire and subtract two consecutive video frames containing additive correlograms where the speckle field of the second has been either spatially decorrelated or its contrast inverted with respect to the first one.

As our technique provides full control over speckle phase, it makes really simple the implementation of a subtractive contrast enhancing algorithm for additive stroboscopic correlograms. Video frames are sequentially grabbed whilst asynchronous phase modulation of the reference arm is switched between \(\Delta \varphi_{rA} = 0\) and \(\Delta \varphi_{rA} = \pi\), or vice-versa, to invert speckle contrast of consecutive correlograms:

\[
I_{\text{seq}}(\Delta \varphi_{rA} = 0) = 1 + \cos\left(\frac{\Delta \varphi_{oa} - \Delta \varphi_{rA}}{2} - \Delta \varphi_{rS}\right) \cdot \cos(\Psi_{oa})
\]

\[
I_{\text{seq}}(\Delta \varphi_{rA} = \pi) = 1 + \cos\left(\frac{\Delta \varphi_{oa} - \Delta \varphi_{rA}}{2} - \Delta \varphi_{rS}\right) \cdot \cos(\Psi_{oa} - \pi) = 1 - \cos\left(\frac{\Delta \varphi_{oa} - \Delta \varphi_{rA}}{2} - \Delta \varphi_{rS}\right) \cdot \cos(\Psi_{oa})
\]

The last two frames are stored and the absolute value of their difference \(\Delta I_{\text{seq}}\) is calculated and displayed.

\[
\Delta I_{\text{seq}} = \left|I_{\text{seq}}(\Delta \varphi_{rA} = 0) - I_{\text{seq}}(\Delta \varphi_{rA} = \pi)\right| = 2 \cdot \cos\left(\frac{\Delta \varphi_{oa} - \Delta \varphi_{rA}}{2} - \Delta \varphi_{rS}\right) \cdot \cos(\Psi_{oa})
\]

The resulting subtractive correlogram (or additive/subtractive correlogram\(^6\)) exhibits improved contrast, good enough for real-time displaying purposes (figure 4). Each new frame grabbed replaces the older of the two currently stored and the subtractive correlogram is refreshed.

The synchronous component of the modulation \(\Delta \varphi_{rS}\) may be used to shift fringes in real-time and observe their migration in order to solve peak-valley ambiguity, as we shall disclose in the next section.

This technique is almost a natural extension of sequential time-average subtraction (devised by Davies et al.\(^3\)) and bears all its benefits - i.e., enhanced visibility and low noise fringes, background noise rejection and low requirements of mechanical stability- plus the added advantages, arising from its stroboscopic nature, of producing constant visibility cosine fringes instead of depending on amplitude like Bessel's and rejecting non synchronous environmental mechanical noise which, rather than appear as superimposed fringes, just degrades visibility. The main drawback is that exploitation of available light power is much less efficient. Figure 9 shows a comparison between the results of both techniques applied to the same vibration state of an object.
2.3. Dynamic fringe shifting.

Phase shifting of contrast enhanced fringes is accomplished in real-time by means of the synchronous component of phase modulation while the asynchronous offset is applied as stated in the previous section.

According with equation 13, as the amplitude of the synchronous component $\Delta \phi_s$ increases, fringes migrate from valleys (minima of $\Delta \phi \rightarrow \Delta \phi_{o \alpha}$ ) to peaks (maxima of $\Delta \phi \rightarrow \Delta \phi_{o \beta}$ ) revealing the actual slope of the deformation mapped by the fringe pattern. Therefore, $\Delta \phi_s$ may be slightly incremented from each video frame to the next to induce a dynamic shift of fringes producing a "pseudo heterodyne" effect; as rectified cosine fringes have a period of $\pi$, when the value of $\Delta \phi_s$ reaches $\pi$ it must return to 0 in order to get a continuous migration. In consequence, the phase of the reference arm of the ESPI must be modulated following the shape depicted in figure 5. Fringe migration speed is controlled by the amount that $\Delta \phi_s$ is incremented between frames.
3. EXPERIMENT

3.1. Experimental setup

We have incorporated our new phase shifting technique to a fibre-optic ESPI already in use at our laboratory in Vigo to assess the goodness of its behaviour. Conventional static subtraction, time average sequential subtraction, single pulse stroboscopic subtractive techniques and phase stepping algorithms were previously implemented; therefore, no substantial modifications were necessary, but only minor changes in phase modulator driving electronics and correlogram generation software routines. Figure 6 shows the current layout of our system, once modified to accommodate the new technique. We shall detail in succeeding the singularities of each component.

The light source is a 5mW He-Ne laser modulated by a rotating disk optical chopper synchronized with object excitation. It provides two equally spaced pulses within each vibration period, having each one a duty cycle of 1:20.

The laser beam is launched through a GRIN lens into a connectorized single mode 90:10 directional coupler (DC) that splits light into object (90%) and reference (10%) arm fibres. The object beam is guided through the object arm fibre and emerges from its cleaved end to illuminate the vibrating specimen. The reference arm fibre is wrapped around a piezoelectric cylinder (PM) that stretches it to modulate optical phase, it also incorporates a fibre optic polarization controller (PC) to match reference and object beam polarization states and a variable attenuation device (VAD) to balance reference and object beam intensities, both in order to maximize speckle visibility. Finally, an image of the object formed with a zoom lens (ZL) is combined with the reference beam (expanding from the end of its fibre) by means of a 50:50 non polarizing beam splitter (BS).

After chopping and launching only around 0.25mW remain available in the object beam and consequently the TV camera must be sensitive enough to deal with such tight conditions. We have chosen to use in our TVH system an Universal Technologies CV-252-C CCD camera which can operate with target illumination levels as low as 0.02lux rendering a maximum signal to noise ratio better than 52dB.
Figure 6.- Layout of the stroboscopic ESPI

Figure 7.- Phase modulator driver
Image grabbing, processing and displaying are implemented on a COMPAQ-386sx personal computer equipped with Data Translation's DT2851 "high resolution frame grabber" and DT2878-4 "frame processor" boards, interconnected through a high speed image bus (DT-Connect). The frame grabber has two 512×512×8 bit image buffers and a look-up table (LUT) processor that enables real-time operation on 4 bit images. The frame processor board is based on AT&T's DSP32C 25MFLOP digital signal processor (DSP) and boasts 4MB of RAM to store up to sixteen 512×512×8 bit images.

A second computer, equipped with a 12 bit digital to analog converter board, is entrusted to command the phase modulator. It generates two analog signals with appropriate values to drive $\Delta \varphi_{RS}$ and $\Delta \varphi_{RA}$ according with each operating mode of the ESPI. Synchronization between phase modulation and image processing is accomplished through an RS-232-C serial link running at 115200 Baud, which has proved to be fast enough for real-time operation.

The phase modulator driving circuit, depicted in figure 7, has been specifically designed to generate the wave form we need for phase-shifting stroboscopic additive fringes which is described by equation (9) and represented in figure 2.b. The circuit takes as inputs two analog voltages that applied to the piezoelectric tube would induce optical phase shifts of $\Delta \varphi_{pS}$ and $\Delta \varphi_{pA}$ respectively in the reference arm. A photodiode (PD) is placed on the spare input of the directional coupler to detect stroboscopic light pulses reflected back from its cleaved ends; falling edges of the resulting signal are counted by a T-type flip-flop and its output decides whether $\Delta \varphi_{pS}$ or $-\Delta \varphi_{pS}$ is applied to the tube. Doing so, the transition between both levels begins as soon as a stroboscopic pulse ends and thus the modulator has the longest attainable settling time until the next pulse starts. The voltage $\Delta \varphi_{pA}$ is finally added to $\pm \Delta \varphi_{pS}$ to be applied together to the piezoelectric tube.

All the sample fringe patterns presented herein have been obtained from a 4oz. tea can, measuring $3\times3\times3\frac{1}{2}$ inches, with its front face coated with retro-reflective tape and excited in resonance by a piezoelectric bimorph disk (PZ) stuck on its back. The object was placed ~0.7 m away from both the TV camera and the output of the object arm fibre with almost normal illumination and observation directions. The figures presented were taken with white fluorescent ambient light being the irradiance at the surface of the object $9\mu W/cm^2$ of ambient light versus $5\mu W/cm^2$ of object beam; but, as retro-reflective tape returns the illuminating laser beam back to the ESPI head, object to ambient intensity ratio at the face of the camera is dramatically improved.

### 3.2. Implementation of the sequential subtraction algorithms.

With our current image processing equipment we can choose between to options to implement the sequential subtraction technique described in section 2.2: using the LUT processing capabilities of the frame grabber board to get 4 bit correlograms at video rate and setting both boards, grabber and DSP, working together to produce 8 bit high resolution correlograms at a lower rate.

To process images with 8 bit resolution in real-time, they must be first transferred from the frame grabber to the DSP board and then the result moved back to the frame grabber for displaying. Although the DSP32C renders an operating speed of 25MFLOPS, its efficiency is low for operations as simple as finding the absolute value of a difference because moving data between memory and the processor takes much longer than the operation itself. This results in comparatively long processing times that, for our particular system, are:

<table>
<thead>
<tr>
<th>Process</th>
<th>Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame synchronization</td>
<td>0 to 40</td>
</tr>
<tr>
<td>Frame grabbing</td>
<td>80</td>
</tr>
<tr>
<td>Transference to the DSP board</td>
<td>100</td>
</tr>
<tr>
<td>DSP processing</td>
<td>~500</td>
</tr>
<tr>
<td>Transference to the frame grabber</td>
<td>100</td>
</tr>
</tbody>
</table>

Total time per frame: ~800 ms

resulting in a frame rate of 1.25 frames per second (fps).
Four bit LUT processing in the frame grabber board yields video frame rate operation (i.e., 25 fps or 30 fps in CCIR and RS-170 systems respectively) but with lower resolution. The process can be outlined as follows: each correlogram is digitized with 256 grey levels (8 bits) and passed through an input LUT to reduce its resolution to 16 grey levels (4 bits) before being stored. The last two correlograms are displayed simultaneously through an output LUT that calculates their difference.

In view of the fact that due to the limited visibility of speckle only a reduced range of grey levels appears in the image of a correlogram (~100 for well contrasted speckle, as shown in figure 8), we stretch the contrast to map with the four bits available only the quantization levels that are actually used. This is performed by our program that, either periodically or under request of the operator, calculates the histogram of the currently digitized eight bit image, finds the range of used grey levels and updates de LUTs accordingly. Hence, resolution and contrast of the resulting subtractive correlogram are automatically optimized.

3.3. Experimental results

The technique outlined in section 2.2 was used to analyse the vibration of a practical object: a tea can. The resulting contrast enhanced additive stroboscopic correlograms, as shown in figure 9.a, exhibit constant visibility fringes that have much better contrast for areas with large amplitude of vibration than the corresponding sequential subtraction time-averaged ones, shown in figure 9.b. The loss of illuminating power due to stroboscopic light chopping is compensated by the automatic gain control of the TV camera and so average brightness is the same for both correlograms.

Dynamic phase shifting and contrast enhancement have been successfully combined to induce fringe migration in real-time; figure 10 shows four successive positions of the fringes while moving from peak to valley.

4. CONCLUSIONS

A new phase-shifting technique for vibration analysis using additive stroboscopic TV holography has been presented. Fringe and speckle phases are shifted individually combining synchronous and asynchronous phase modulation, what is attained with very simple fully automated electronic circuits. There are no restrictions concerning stroboscopic pulse separation or vibration amplitude other than those imposed by amplitude and phase modulating devices. This technique has been implemented on a FOESPI and real-time contrast enhancement as well as dynamic fringe shifting have been demonstrated.

High visibility low noise correlograms are produced in real-time by sequential subtraction of speckle contrast inverted additive correlograms, thus sharing the benefits of both additive and subtractive methods. Dynamic phase shifting is accomplished in real-time by phase-stepping in synchronism with video frame rate; as long as no static reference is required, vibration can be analysed "in flight" and non-synchronous disturbances do not affect the results.
Figure 9.- Sequential subtraction correlograms of a tea can vibrating at 1080Hz.
   a) Stroboscopic, b) Time-averaged

Figure 10.- Successive fringe patterns of a tea can vibrating at 1080Hz while fringes are shifted from peak to valley.
5. REFERENCES


