Full field laser vibrometry employing a novel CMOS-DSP camera

Mauro V. Aguanno$^{1,2}$, Michael J. Connelly$^1$, Maurice P. Whelan$^2$

$^1$Dept. of Electronic and Computer Engineering, University of Limerick, Limerick, mailto: michael.connelly@ul.ie ; mauro.aguanno@ul.ie

$^2$Institute for Health and Consumer Protection (IHCP), European Commission Joint Research Centre (JRC), Ispra, Italy mailto: maurice.whelan@jrc.it

ABSTRACT

This study concerns the application of a novel digital CMOS-DSP camera in full-field interferometry for vibration analysis and quasi real time processing in optical metrology. Characterisation tests on the digital camera have been performed. Both quasi-static and carrier-based approaches have been considered and will be presented in this paper. The CMOS-DSP camera is a primary component of a compact and low cost system for classical image processing and an innovative element for full field vibration measurement using a single pixel carrier based approach.

1 Introduction

In this paper we investigate the efficacy and the benefit of introducing a novel CMOS camera with an integrated DSP in interferometry-based optical metrology. For this purpose, several interferometric techniques$^1$ can be adopted depending on the field of application. Typically, these techniques are characterised by very high resolution, non-contact and full-field measurement capability. Two different interferometric schemes for optical metrology employing a novel CMOS-DSP are presented here, namely, classical Digital Phase Stepping Interferometry (DPSI) and a new Single Pixel Carrier Based Demodulation (SPCBD) technique. The main difference between the DSPI and SPCBD schemes is that DSPI is suited mainly to static or quasi-static measurements while SPCBD is targeted at dynamic measurements, such as vibration analysis.

DSPI$^3$ is a full field optical method that can be used in conjunction with several interferometric schemes to achieve accurate shape or micro-deformation measurements. A phase map of a surface illuminated by a coherent light source can be reconstructed from the interference patterns obtained from an interferometer set-up. Quantitative data can be extracted using this method with a precision greater than a factor of ten to one hundred with respect to simply analysing digitised fringe-images, or interferograms. The computation of the phase maps can be performed directly within the DSP on the camera obtaining a versatile, compact and portable low cost system for classical image processing dedicated to static or quasi static applications.

Heterodyne interferometry$^8$ is one of the optical techniques that can be chosen for SPCBD as it is a powerful non-invasive technique for vibration measurement and the study of dynamic processes. Typically, two mutually coherent monochromatic wavefronts at slightly different frequencies interfere to produce a beat signal, termed the carrier signal. This carrier signal has a significantly lower frequency with respect to the frequency of the light used. The beat signal can be modulated by a vibrating surface and measured by a photo-detector. In our case, the detectors are all the pixels in the CMOS sensor. Velocity and displacement information are obtained by demodulating the pixel generated beat photocurrent. Used in laser Doppler velocimeter (LDV) systems$^4-5$, this technique replaces measurements of lengths by measurements of frequency or phase with very high precision. Working in the frequency domain allows more information to be acquired than is possible with time domain analysis. Our approach takes the advantages of the CMOS image sensors and their active pixel architecture coupled with a digital signal processor (DSP). The most important feature of CMOS cameras is their random pixel access meaning that the frame-rate is determined by the number of pixels sampled. So, the lower number of pixels sampled, the higher frame rates that can be obtained. It is also possible to access different pixels at the same time independently facilitating a fast electronic scan and process within the DSP camera. Using appropriate digital signal processing algorithms and only a small number of pixels, we can execute a real-time carrier-signal based demodulation technique.
2 Description of the CMOS-DSP camera

Until recently, Charge Couple Devices (CCDs) were typically the only image sensors used in optical metrology. In full field metrology applications they capture light on small photosites on their surface and an analog signal is produced and then digitised inside a PC using a frame-grabber card. CCDs have been well developed through their use in astronomical cameras, video camcorders and scanners. These photosites, consist of photodiodes or photogates. A current of photons generates a charge, which is accumulated during a certain period of time. An electronic shutter determines this exposure or integration time. Due to the integrating characteristic of this procedure, the relation between the output voltage and the light intensity is linear. The charge on the first row of pixels is transferred to a read-out register and once the row has been read, the charge on the register is deleted, and the next row enters the read-out register. The charge on each row is coupled to the row above and thus the name ‘charge coupled’ devices. In this way, each row can be read, one row at a time. However, there is a new immersing technology, CMOS-based Imaging, which offers advantages over CCD-based imaging.

CMOS stands for Complementary Metal-Oxide Semiconductor, the architecture of most computer CPUs and memory modules. High performance CMOS image sensors use active pixel architectures and the same manufacturing technologies as microprocessors and memory modules, and thus they are easier to produce and less expensive. Each pixel contains the photo-detector element (photo-diode) and the amplifier element (active transistor circuitry) and the photocurrent is continuously converted to an output voltage. The relation between the output voltage and the light intensity is highly non-linear. The effect of this non-linearity is a very high dynamic range but unfortunately also a strong presence of high frequency noise. Another feature of CMOS cameras is the possibility to randomly access their pixels. As we mentioned above we can think of such a camera as a kind of RAM memory and thanks to the continuously conversion process we can access every pixel at any sequence and any moment and get the corresponding grey level once the relevant address is fed in to the camera in the form of row and column index. This random access means that the frame rate is determined by the frequency of the pixel clock and the number of pixels that define the frame. Since the pixel clock is constant, the interrogation of a low number of pixels can be conducted at high frame rates. Moreover, integrating the CMOS image sensors with a digital signal processor we can have a pure digital camera with all the CMOS features but with less cost because most of the technology involved is already well developed. The benefits of using this camera with a DSP and a CMOS image sensor system coupled together are examined here for applications in full field laser metrology.

3 Materials and methods

3.1 Characterisation Tests

Preliminary characterisation tests have been performed on the CMOS-DSP camera: FASTCOM iMVS-135 model (Fastcom Technology S.A., Lausanne, Switzerland). These tests were carried out to check the camera performance in terms of acquisition speed, image quality and computation time. A simple program was written to calculate the time necessary to acquire intensity values from the image sensor using both the standard acquisition and the single pixel random acquisition modes. In the first mode, called “square window” mode, images composed by groups of pixels, starting from the limit of 1x1 to 512x512 have been acquired, giving an idea about the frequency rates using the classical way to display images in windows. Then, the single pixel acquisition mode was tested to present a frequency response plot of the CMOS image sensor, accessed reading only the chosen pixel. Due to the pixel random access feature, intensity values were also read from a number of selected random pixels and their number have been increased to calculate the acquisition bandwidth for a carrier based approach. After the calibration process of the CMOS sensor to the specific light conditions used, a test image printed on a paper and white light illuminated, has been acquired and compared with the same image taken from a CCD camera.

3.2 Digital Phase Shifting Interferometry

Interferograms of object surfaces contain information relating to the deformation or the displacement taken place, if a suitable interferometer is used. To get quantitative data with very high precision from no more than a map of local brightness, a phase shifting analysis is required. As mentioned above, phase stepping techniques have many advantages over the simple recorded and digitised interferogram. Phase shifting is based on the introduction of a known amount
of shift in the interferometer pattern, called the phase-step, with the resulting effect of the movement of intensity peaks across the pattern. The phase change in one arm of the interferometer can be implemented for example as a linear displacement of a mirror stepped in N equal and controlled steps, so that the total phase shift is equal to $2\pi$. In particular, we adopted an algorithm based on a Four Step technique ($N = 4$). DPSI can be applied with many different interferometric techniques such as Digital Speckle Pattern Interferometry (DSPI), Grating (Moire’) Interferometry and Holographic interferometry. The adopted set-up (Fig.1) was arranged to implement the DPSI algorithm following the block diagram in Fig.2. Four stepped images corresponding to a phase shift of $0^\circ$, $90^\circ$, $180^\circ$ and $270^\circ$ were sequentially acquired with the CMOS camera by moving synchronously the PZT mirror. Consequently, a phase map was achieved and displayed onto a monitor. A standard CCD camera connected with a frame-grabber card and a dedicated image processing software (IDEA) completed the same process with the beam sent by the beam splitter 2.

Typically the resultant intensity distribution for a captured image can be expressed as,

$$I = I_o + I_r + \sqrt{(I_o I_r)} \cdot 2\cos \phi$$  \hspace{1cm} (1)

Where $I_o$, $I_r$ are the intensity distributions for the object and the reference beam, respectively, and $\phi$ is the relative phase between the two before the deformation. Surface deformations translate points on the surface inducing a change in the relative phase angle $\phi$ by an amount $\Delta \phi$ such that the new intensity distribution $I'$ is given by:

$$I' = I_o + I_r + \sqrt{(I_o I_r)} \cdot 2\cos(\phi + \Delta \phi)$$  \hspace{1cm} (2)

To calculate this optical phase change, $\Delta \phi$ and quantify the related displacement, a minimum of three measurement sets of fringe intensity data needs to be acquired. Since there are three unknowns in the interference equation (1), by combining the resulting three equations we can solve the system for $\phi$ for every pixel. In our case, four images ($N = 4$) are grabbed at the different phase offset steps of $0$, $\pi/2$, $\pi$, and $3\pi/2$. The four-step technique was chosen because it’s less affected by errors than the three-step technique. In particular, a second-order non-linear response from a detector like CMOS image sensors and CCD arrays can introduce phase errors and the measured optical irradiance $I_e$ can be written by:

$$I_e = I + \epsilon I^2$$
Where $\varepsilon$ is the non-linear coefficient. In this case a minimum of four measurements is necessary to obtain an accurate phase calculation. For a third-order distortion ($I_N = I + \varepsilon I^3$) an algorithm with a minimum of five steps is required to reduce most effects of detector non-linearity\(^1\). Working with speckle images, a fifth image $I'$ is required to get the four fringe patterns images by subtraction between the last image (live) and the previous four-stepped reference images. Assuming that $I_o = I_r$, the intensity profile $I_N$ of the image after the subtraction is given by

$$I_N = |I - I'| = 2 \sqrt{I_o I_r} \cdot \left[ \cos \phi - \cos(\phi + \Delta \phi) \right]$$  \hspace{1cm} (3)

Where here $N = 0 \div 3$, and $\phi$ can be calculated for every pixel by the following:

$$\phi(x, y) = \arctan \left( \frac{I_3(x, y) - I_1(x, y)}{I_0(x, y) - I_2(x, y)} \right)$$  \hspace{1cm} (4)

Where $I_0$, $I_1$, $I_2$ and $I_3$ are the intensity (or optical irradiance) of the four correlation images every frame updated to get the phase map in quasi real time proportional to the displacement. This yields a calculated phase map lying values between $-\pi$ and $\pi$ because the presence of the arctan. A procedure called phase unwrapping must be carried out to restore the unknown multiple of $2\pi$ to each pixel. This can be achieved by comparing the phase difference between adjacent pixels. Specifically, when the phase difference is greater than $\pi$, $2\pi$ are added to the remaining pixels in the row and the process is then repeated along the columns. Then, the surface displacement $d_z$ at the location $(x, y)$, can be determined once the phase is know, from the follow equation:

$$d_z(x, y) = \frac{\phi(x, y)\lambda}{2\pi}$$  \hspace{1cm} (5)

Where $\lambda$ is the wavelength of the illumination\(^2\).

---

**Fig.2 PHASE.C Block diagram, implemented for speckle P-S on the Analog Device SHARC family DSP of the camera.**
3.3 Single Pixel Carrier Based Demodulation

Carrier-signal techniques (e.g. heterodyne demodulation) are used in single-point systems\(^4\) (e.g. laser Doppler velocimeter) and offer very good stability and high sensitivity. Many imaging metrology systems available are scanning-based especially for experimental modal analysis purposes and structural monitoring. However, mechanical scanning is complex and costly. As described above, one of the most important features of CMOS cameras is their random pixel access meaning that the number of pixels used determines the frame rate and that every pixel can be accessed as a single photo detector. The internal DSP of the camera can be programmed to perform a fast electronic scan and compute the data set from a number of random pixels. For dynamic analysis such as vibration measurements, a simple Michelson interferometer (Fig.3) was employed to test if the camera can be used as a multi-photo detector coupled with a digital signal processor. A laser source (Diode Laser, 740nm) was amplitude modulated (AM) by a high frequency signal to simulate a heterodyne beat frequency. This was produced in a range of frequencies between 500Hz and 5kHz. A silicon photodiode was introduced in one arm of the interferometer to check the laser modulation. A second amplitude modulation at a lower frequency was then applied to the simulated beat frequency signal. This composed signal was detected and then demodulated inside the DSP of the camera. The same algorithm used has been validated in a computer simulation with a C executable file and Matlab routines. The method adopted is based on the digital version of a simple analog synchronous detection scheme. The following step will be the implementation of a frequency demodulation scheme to extract the modulating vibration from the heterodyne beat signal.

![Fig.3 Michelson interferometer set-up for carrier based simulated vibration detection](image-url)
4 Results

4.1 Characterisation tests

The frequency rate for the “square window” mode is presented in Fig.4. For 512x512 pixels, the minimum rate value of 8 Hz was found.

A zoom of the above plot for very small square windows is shown in Fig.5 using a logarithmic scale in the Y-axes. A maximum frequency rate of 250kHz was recorded for the smallest window (1x1) and only 5 msec are needed to acquire a single frame of 64x64 pixels.
In the “single pixel” mode (Fig.6) a frequency response gives a maximum value of 500kHz for a single pixel acquisition.

![Single Pixel Mode Graph](image)

**Fig.6 Frequency acquisition rate plot for “single pixel” mode**

A test image of a simulated fringe pattern was printed on a paper, illuminated by a white light and then observed with both the CCD camera and the CMOS camera. The two recorded images side by side are shown in Fig.7 and the fixed pattern noise in the CMOS image appears as a de-sharpening in the fringes contours.

![Test Images](image)

**Fig.7 Test between the CCD and the CMOS camera image**

### 4.2 Digital Phase Stepping Interferometry

An example of calculated wrapped phase map of a tilted mirror surface and the corresponding four step images with a phase value equal to $\Phi_1=0^\circ$, $\Phi_2=90^\circ$, $\Phi_3=180^\circ$ and $\Phi_4=270^\circ$, is shown below in Fig.8.
In this first part of the work, using the C code illustrated in Fig. 2, the calculation time including acquiring times for all the images needed and all the computation for a complete loop of a 64x64 image of wrapped phase map (four step technique) is 81ms that correspond to 11.8 frames per sec.

### 4.3 Signal Carrier Based Demodulation

A screenshot of the monitor image dumped from the camera to the PC is presented in Fig. 8. It shows the demodulated signal of the acquired beam from a single pixel located in the centre of the image sensor affected by the presence of a very low frequency component due by a very little difference between the acquisition frequency and the generated internal local oscillator timing. This little difference between the two periods appear as a multiplication between a very low frequency cosinusoid and the demodulated output. In particular this figure shows the 30Hz signal extracted from laser source modulated at 800Hz.

Fig. 9 Demodulation output from the camera of a detected 800Hz carrier laser modulation amplitude modulated at 30Hz
5 Discussions

Preliminary tests on the ‘smart’ digital camera have shown good results in terms of acquisition and computation speed. For this purpose, acquisition 'frame rate' tests with different numbers of single pixels were conducted. Although the calibration of the CMOS camera could be still optimised and the image quality significantly increased, we can have an idea from Fig. 7 about the high frequency noise added by the CMOS sensor with respect to a very good CCD image. In particular this effect is noticed as de-sharpening in the fringes contours. The frequency rate in Fig.4 and 5 concerns only the acquiring time of different group of square pixels while the display time is negligible. In the “single pixel” mode (Fig.6) we can take the advantage of reading the values of single pixels straight from the memory. So, we can choose only the selected pixels we are interested on from the sensor as simple addresses. In this way we can get higher rates and in particular, for a single pixel, working as a single photodiode, a maximum frequency rate of 500 KHz has been achieved.

A simple Michelson interferometer has been arranged and a four-step algorithm has been implemented in C language within the DSP camera. The wrapped phase map has been realised and a result of 12 frames per second was obtained for a 64x64 pixel image test. Finally, a heterodyne system has been simulated using an AM carrier from a laser diode source at 740 nm and detected with quasi-real time demodulation performed within the camera using a single pixel acquisition. Although, the demodulation result (Fig.8) has been affected by a low frequency cosineoid, the detection has been achieved and verified for a wide range of carrier and modulating frequencies. The low frequency cosineoid is the effect due to a little difference between the acquisition frequency and the generated internal local oscillator timing. The result is a multiplication between the demodulation output and the cosineoid having a frequency equal to this difference value. A precision of at least greater than one over a thousand in terms of difference in frequency has to be reached in order to reduce this multiplication effect. This simulation was completed before beginning to perform a frequency or phase demodulation of a carrier signal from a vibrating object surface.

6 Conclusions

The consequence of the high frame rate in the read-out of a number of strategically located pixels on the test body combined with a very high precision measurement made in frequency domain, allows us to be optimistic in the use of the SPCBD approach for full field vibration analysis. In particular, the results from the characterisation tests performed are reasonable, although improvements can be still achieved by further optimisation in the signal processing algorithms and the demodulation techniques adopted.

Acknowledgements

The authors would like to thanks Dr. Fereydoun Lakestani (EC JRC) for the helpful discussions during this first part of the work. This project is supported through a collaboration contract (# 18487-2001-10 SOFD ISPIE) between the IHCP European Commission Joint Research Centre (Ispra, Italy) and the Department of Electronic and Computer Engineering of the University of Limerick (Limerick, Ireland).

References