Single pixel carrier based approach for full field laser interferometry using a CMOS-DSP camera

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ABSTRACT

This investigation describes the implementation of a Single Pixel Carrier Based Demodulation (SPCBD) approach on a digital CMOS-DSP camera for full-field heterodyne interferometry. A full-field vibration measurement system is presented as an alternative to a classical scanning Laser Doppler Vibrometer (LDV). The Heterodyne set-up, CMOS-DSP camera and the signal demodulation techniques adopted are described. Characterisation tests that describe the basic performance of the CMOS-DSP camera, in terms of acquisition rates and time response are presented. A simple experiment was performed to demonstrate the novel laser vibrometry system that consisted of determining the displacement of a point on the surface of a vibrating mirror. The measured velocity and displacement data were compared to the output from a commercial LDV. The integration of a CMOS sensor, DSP and a laser-doppler interferometer has lead to the development of a fully digital “functional” machine vision system that provides a flexible, compact and inexpensive tool for automated high-precision optical measurements.

Keywords: CMOS sensor, Laser Vibrometry, Heterodyne Interferometry, DSP, Analytic Signal

1. Introduction

Vibration measurements are carried out to identify the dynamic response of engineering structures and to identify the presence of any defects or damage\textsuperscript{1}. Optical methods offer a number of advantages over classical piezoelectric accelerometers for the determination of structural response in that they are non-invasive and provide full-field displacement and velocity data\textsuperscript{2}. Optical techniques are therefore suited to the rapid analysis of small and lightweight components that exhibit a complex dynamic behaviour. For this reason there has been a rapid uptake of these techniques in high-tech sectors such as aerospace engineering and MEMS\textsuperscript{3}.

The most popular optical method utilised for vibration measurements is scanning laser doppler vibrometry (SLDV)\textsuperscript{4}. A SLDV is usually based on a single-point laser doppler sensor that is coupled to an optical scanning servo-system. Although SLDVs can produce displacement or velocity maps in quasi real-time with impressive accuracy and stability, they are complex and costly\textsuperscript{5}. This is due primarily to the sophistication of the electro-mechanical components and controls that support the scanning action\textsuperscript{6,7}. In order to eliminate the requirement for a scanning system, some workers have extended full-field laser metrology techniques such as Electronic Speckle Pattern Interferometry (ESPI) to make dynamic measurements\textsuperscript{8,9}. The key element of such systems is a fast CCD camera that has an image-acquisition rate of 1kHz or more\textsuperscript{10}. A sequence of speckle interferograms is acquired and post-processed to extract displacement maps as a function of time\textsuperscript{11}. Although such an approach produces 2D data with no scanning, it suffers from the fact that high-speed CCD cameras...
are very expensive and relatively inflexible. Another disadvantage is that a large amount of image data must be acquired during a measurement and then post-processed on a computer to extract the relevant vibration data.

In this paper we propose a novel optical vibration measurement system that combines both laser doppler vibrometry and full-field imaging but avoids the use of any scanning hardware or fast CCD cameras. The system is built around a CMOS camera (model iMVS-135 from Fastcom*) that is combined with a digital signal processor (DSP). The DSP is a 40MHz, 32bit floating-point processor of the Shark™ family (Analog Devices).

The optical scheme employed is based on a heterodyne interferometer that produces an optical carrier which is frequency modulated (i.e. doppler-shifted) when reflected from a vibrating surface. As described below, the CMOS-DSP camera has a completely digital architecture that allows pixels to be randomly accessed at variable acquisition rates. Another important feature of the camera is the fact that very high acquisition bandwidths can be achieved (e.g. 10s of kHz) when the number of pixels interrogated is low. The approach described here exploits these features to allow the implementation of a Single Pixel Carrier Based Demodulation scheme that relies on the high-speed sampling of a frequency-modulated (FM) optical carrier and the subsequent determination of the instantaneous phase. Signal extraction is obtained through the implementation on the DSP of a classical and robust algorithm based on the Analytic signal argument via a pass-band filtering centred on the carrier frequency. Measurements of the velocity and displacement of a point on a vibrating mirror surface were obtained and compared with the output of a commercial LDV system. Characterisation tests that describe the basic performance of the CMOS-DSP camera, in terms of acquisition rates and time response, are also presented in this paper.

The integration of a CMOS sensor and DSP, combined with a laser doppler interferometer leads to a fully digital "functional" machine vision system that provides a flexible, compact and inexpensive tool for automated high-precision optical measurements.

2. Description of the CMOS-DSP camera

2.1 Features and benefits

One of the most important features of this CMOS-DSP camera, as mentioned above, is the true pixel random access, due to the Active Pixel Sensor (APS) architecture. In the CMOS sensors every pixel is independent and randomly addressable both in space and in time, i.e. any pixel can be accessed and read at any moment. A major advantage of the random access is the very high interrogation rate achievable to access a low number of pixels. A practical advantage of the spatial random access in the APS design is the opportunity to perform a fast electronic scan, jumping from pixel to pixel over the sensor, without moving mirrors and expensive micro-positioners.

An APS can be thought of as a digital single chip device, where the photocurrent generated by the incident light on the pixel surface is immediately digitally converted by an on-chip ADC. This process is continuous in time and the photocurrent to voltage conversion is logarithmic and inversely proportional to the light intensity. A CMOS pixel reacts like a first order electric circuit and its voltage output and its time constant are inversely related to the intensity of the incident light. This means that not only is the pixel able to detect high intensities, but also the dynamic pixel response becomes faster using higher intensities.

CMOS sensors are known to be affected by column Fixed Pattern Noise (FPN, also called spatial non-uniformity). Due to mismatches across the sensor, FPN is the spatial variation in the pixel output values under uniform illumination, in terms of offset and gain, and it is fixed for a given sensor. This problem for standard image based application can be overcome by calibration

* Fastcom Technology S.A., Lausanne, Switzerland.
procedures based on look up tables for a first-order correction of each individual pixel. On the contrary in interferometry, adopting a single pixel approach to retrieve, for example, phase information from carrier based optical signals, no calibration for FPN is needed because amplitude variations from pixel to pixel don’t affect the phase measurement.

2.2 Characterisation tests

Preliminary tests to evaluate practical performances and limitations of the CMOS-DSP camera are performed and described below. In particular, two fundamental aspects of the image sensor and the DSP integration are considered. Because the camera is designed for classical machine vision applications and not for dynamic measurements, not only the “electronic” acquisition rate is important, but also the sensor response, as described above, play a fundamental role being inversely related to the incident light intensity. In Fig.1 and Fig.2 the read-out time in terms of frequency (kHz), using different number of pixels, is presented. In fact, on the CMOS sensor a lower number of pixels interrogated correspond in an increasing of the acquisition frequency.

![Square Pixels Mode Acquisition](image1)
![Single Pixel Mode acquisition](image2)

The access time for reading a pixel is simply due to the time needed to reach the corresponding pixel address located in the DSP memory block. Typically, two functions are available to access the CMOS sensor in two different modes. The first one is associated with the classical approach adopted for displaying images in windows, called here, square pixels mode, and related to Fig. 1. Here, the acquisition rates for group of pixels starting from 256 by 256 pixels to the limit of one by one, are shown above in a logarithmic scale. The most remarkable values in terms of frequency rate are noticed for small windows of pixels such as 64 by 64, 32 by 32, to the limit of one pixel and are equal respectively to 500 Hz, 1.8 kHz and 200 kHz.

![Time response](image3)
![LDC 202 PD Power Output Zoom](image4)
The second acquisition mode concerns instead, the random access of single pixels and is presented in Fig. 2. For example, significant frequency rates for low number of pixels read are: 57 kHz, 112 kHz and 500 kHz respectively for group of pixels equal to 10, 5, and for a single pixel. In Fig. 3 and 4, two graphs present an example of the relation between the incoming light power and the corresponding pixel time constant $\tau$. The test was performed with diode laser (LD) at roughly 830nm (near infrared), controlled in current and temperature by a LDC202 system and amplitude modulated by a square wave using a digital signal generator. The CMOS-DSP camera and a calibrated photodiode (PD) (ThorLabs, DET210 model), used to calculate the LD power corresponding to the injected current value, were incorporated into a Michelson interferometer. As shown, the dynamic response of the sensor is in fact inversely proportional to the light power. Stronger is the illumination and faster is the response. This statement, as mentioned above, plays a primary part in the design of a dynamic measurement set-up. Especially in single pixel approach, the sampling time has to be calculated taking into account not only the DSP acquisition speed but also the effective power on the image sensor. Just to give an idea, in the test performed, under the conditions above described, at a power of 0.25 mW, 40 mA of drive current, the corresponding pixel response is in the order of 10 kHz.

3. Demonstration of laser vibrometry system

3.1 Set-up of laser doppler interferometer

The imaging laser doppler interferometer constructed to demonstrate the SPCBD approach is illustrated in Fig.5. It consisted of a double-Nd:YAG cw laser (532nm, Verdi, Coherent Inc.) as a light source, a Mach-Zender interferometer incorporating two 80MHz Acousto Optic Modulators (AOM1 and AOM2, model 3080-151, Crystal Technology Inc.) to generate the optical carrier and the CMOS-DSP camera to acquire the doppler-shifted carrier and to digitally demodulate the signal.

![Figure 5: Mach-Zender based Heterodyne Interferometer Set-up](image-url)
A variable Neutral Density Filter (NDF) was used to select the appropriate laser intensity in order to maximise the sensitivity of the CMOS sensor and ensure good modulation (visibility) of the interferometric signal, thereby maximising the signal to noise ratio.

The AOMs were driven by two stabilised RF drivers (model 1080-25, Crystal Technology Inc.), one driver being fixed at its nominal operating frequency of 80Mhz (fo) while the other was modified to allow tuning over a range of approximately 1kHz (fo+∆f). This allowed the generation of an optical carrier with a frequency (Δf) from a few Hz to 1kHz, significantly lower than the nominal operating frequency of a single AOM (80Mhz). To facilitate the selection of a particular carrier frequency and to compensate for any undesired drift in the RF drivers, an external locking circuit was constructed using a PLL and a digital signal generator.

A flat mirror mounted on a piezoelectric (PZT) actuator was chosen as the test object. A digital signal generator and a high-voltage amplifier (Physic Instrument GmbH) controlled the vibration frequency and amplitude of the mirror. It was placed within one arm of the interferometer, after AOM1. The lenses (L1 and L2) located after BS2 served to image the illuminated part of the mirror surface onto the CMOS sensor.

### 3.2 Experimental procedure

A simple experiment was performed to demonstrate the combination of heterodyne interferometry and a CMOS-DSP camera for laser vibrometry system. It consisted of determining the displacement of a point on the surface of the vibrating mirror. As shown in Fig.5, by locating the mirror in one arm of the heterodyne interferometer, the wavefront modulate by AOM1 experienced a second frequency-shift after reflecting from the vibrating surface. The carrier frequency (Δf) chosen for these tests was approximately 1kHz. Two tests were carried out for mirror vibration frequencies of 80Hz and 150Hz. The vibration frequencies and amplitudes were chosen in order to avoid over modulation and use classical demodulation algorithms.

The CMOS-DSP camera was set to acquire roughly 73ms of signal with a sampling frequency of 14kHz from individual pixels. A digital demodulation algorithm, implemented on the DSP, was then used to extract velocity and displacement data. The digital signal processing methods employed are described below. The vibration of the mirror was also measured using a commercial LDV system (model OFV-3000/302, Polytec) to verify the results obtained with the doppler CMOS-DSP system.

### 3.3 Signal processing and phase retrieval

The SPCBD scheme, as illustrated in Fig.6, is based on the Analytic Signal (AS) argument of a real signal. Also known as Complex signals (Gabor, 1946), Analytic Signals provide a direct route to determining amplitude and phase of a signal. The approach is commonly used in processing techniques employed in FM-radio communications and doppler-based measurement systems.

An AS is generated by simply suppressing all the negative frequency components in the original real signal. In our case, the real signal is a sinusoidal carrier, frequency modulated (FM) by the vibrating mirror, and acquired by a single CMOS pixel. The general expression of real signal in Euler’s notation is:

\[
s(t) = \rho(t) \cos(\omega \cdot t + \phi(t)) \rightarrow s(t) = \rho(t)e^{j(\omega \cdot t + \phi(t))}
\]

where \(\rho(t)\), \(\omega\) and \(\phi(t)\) denote respectively: instantaneous amplitude, rotational velocity equal to 2πΔf and instantaneous phase.
A conventional FM modulated signal has all its frequency components in the positive spectrum and a modulation bandwidth less than its carrier frequency \( \omega \) as summarised below:

\[
 s_{FM}(t) = \rho \cos(\omega \cdot t + \beta \cdot \int_0^t \phi(t)dt) \quad , \quad S(f)_{FM} \geq 0 \quad & \beta \phi(t) < \omega 
\]

where \( \beta \) is the maximum phase deviation, also termed modulation index.

An AS of a real signal corresponds to a complex signal with as imaginary part, the Hilbert transform of the original signal, and as real component, the original signal itself. The same effect can be obtained multiplying the signal's FFT by a band-pass filter (1kHz bandwidth) centred at the carrier frequency \( \Delta f \) equal to 962Hz and having zero response for negative frequencies. This so-called "gate filter", designed to produce the proper analytic signal \( \tilde{s}(t) \) while avoiding aliasing problems due to the sampling of a finite signal, has the following expression:

\[
f/\delta - 2[\sin(2\pi f/\delta)]/3\pi - [\sin(4\pi f/\delta)]/12\pi.
\]

Where \( \delta \) is the width of the rising and falling edges (200Hz). Owing to the rapid decreasing of the gate filter impulse response, undesired aliasing effects are avoided.

Suppose,

\[
s(t) \leftrightarrow S(f)
\]

Our analytic signal \( \tilde{s}(t) \), corresponding to \( s(t) \), is:

\[
\tilde{s}(t) \leftrightarrow \begin{cases} 
2S'(f) & \text{if } f > 0 \\
0 & \text{if } f = 0 \\
0 & \text{if } f < 0 
\end{cases}
\]

This analytic signal is just a complex function of time containing no more than the positive frequency components of the FM bandwidth of the original signal. The instantaneous frequency (IF) of the real signal, the argument \( [\omega + \beta \phi(t)] \), is retrieved as the imaginary part of the complex ratio given by the inverse FFTs of the AS time derivative, with the inverse FFTs of the AS itself (Fig. 6). The mean value of IF is defined as the carrier frequency \( \omega \) of the original FM signal. The vibration velocity is thus proportional to the IF minus this DC value \( \omega \) while the surface displacement is obtained by its time integration.

4. Results

Using a single pixel acquisition and quasi real-time demodulation within the CMOS-DSP camera, displacements measured from a point of the vibrating piezo-driven mirror surface (Vibrating Mirr in Fig.5) are presented in Fig.7 and 8. Approximately 73ms of signal acquired at a sampling rate of
14kHz was analysed. While, the heterodyne carrier frequency chosen was 962Hz (Δf, beat freq.), the two vibration frequencies were set at 80Hz and 150Hz.

![Displacement 80 Hz](image1.png) ![Displacement 150 Hz](image2.png)

**Figure 7**  **Figure 8**

Fig. 9 and Fig. 10 respectively illustrate the surface velocity of a point calculated from the IF, extracted through the demodulation algorithm and the associated displacement. During this acquisition the vibrating frequency was still 150Hz but with nearly half amplitude (i.e. 270mV) with respect to the test in Fig. 8. The digital phase demodulation based on the described Analytical signal argument analysis gives a very good agreement with those from the commercial laser vibrometer adopted (Polytec model OFV-3000) 12.

![Velocity](image3.png) ![Displacement](image4.png)

**Figure 9**  **Figure 10**

In fact, as shown in Fig. 11, the amplitude difference between the vibrometer and the CMOS-DSP camera system results less than 3%. This discrepancy, verified with accurate Polytec scanning screening, can be well explained as it matches exactly the spatial displacement distribution in the area around the spot imaged by the camera and in which a pixel of 12.5 microns is used as a photodiode.

As shown above in Fig. 7, 8, and 10, the amplitudes of the mirror translation are in the nanometers range with a bandwidth equal to roughly 1kHz, while in Fig. 9 the velocity range is in the order of micron/s.
5. Conclusions

A novel optical vibration measurement system that combines both laser doppler vibrometry and full-field imaging, avoiding the use of any scanning hardware or fast CCD cameras, has been proposed. This “functional” machine vision system, built around a fully digital CMOS-DSP camera, capable of spatial electronic scan at a very high rate, has been able to carry out high-sensitivity phase measurements, in terms of displacement in the order of nanometers and velocity in micron per second. Finally, the very good comparison with the output from a commercial high quality laser Doppler device has been presented. Although tough improvements can be still reached, the validity of this low-cost and versatile approach based on single pixel acquisitions and on-site demodulation in quasi real-time, has been confirmed.

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