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OPTICAL HEAD BASED ON A CALIBRATED FOCUS ERROR SIGNAL TO MEASURE VIBRATION AND DISPLACEMENT

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Abstract *In this work we present a study of an optical system based on the focus error signal technique to measure vibrations and surface displacement as a function of time.*
The device used was an optical head that focuses a laser beam onto the surface of interest and measure the position of the sample as a function of time by means of the focus error signal produced by the reflected beam.
Sample reflectivity and alignment are issues that condition its application range so different solutions are proposed and experimental configurations are presented.
The main characteristics that make such a device desirable in non-contact applications is that it offer measurement of the displacement as a function of time in a simple scheme. Two calibration techniques are included in the proposed system and testing results are presented.

Keywords: *Focus error signal, non contact measurement, vibration measurements*

1. INTRODUCTION

Nowadays vibration measurements rely on different techniques to measure its main parameters that are used in a wide number of applications. Between them accelerometers, interferometers and laser Dopler vibrometers (Castellini *et al*, 2006), perhaps the most common methods, measure acceleration or velocity of the sample of interest employing different principles and a variety of experimental schemes. In this work we introduce a system that uses the focus error signal (FES), an optical technique based in the measurement of the characteristics of a laser beam after a reflection on the sample surface. The central difference with conventional methods is the fact that this technique is able to measure position of the sample surface as a function of time, in a straight forward manner. That means that to get this magnitude only a previous calibration is needed but no deconvolution, signal integration nor other mathematical process is required. Another point of interest is that the frequency response, mainly limited by the detection system, is broad and with conventional detectors can reach the kHz range. Furthermore, the experimental set-up can be performed with inexpensive technology such as that employed in the DVD optical pick-up heads. The use of the FES has been explored and demonstrated by several authors (Hnilička *et al* 2002) (Cohen *et al*, 1984) in the measurement of diverse phenomena (Fan *et al*, 2000) (Quercioli *et al*, 1999) (Liu *et al*, 2009). In this work we summarize the workings of an optical head based on FES (OPH) and applied to measure vibration. An experimental set-up is presented employing two different calibration procedures proposed in a recent work. Some experimental results are also showed to validate the technique and to show the potential benefits in the application of this new technique.

2. OPERATION PRINCIPLES

The idea of the technique has been widely described in the bibliography (Goldwasser, 2011) (Weckenmann, 2006). For the sake of clarity we will summarize the most important aspects of its working principle and internal components. Fig. 1 depicts a simplified scheme of an OPH. It must be noted that some components have been excluded as these are not relevant to this paper. More detailed information can be found in the literature (Goldwasser, 2011). The output light beam of a laser diode is focused onto the sample surface by means of a lens system of a few millimetres focal length.

The light reflected back off the sample passes through an astigmatic lens after the reflection into a beam splitter and is directed to a four quadrant detector. This lens exhibits two different focal lengths. It could be said that the horizontal axis has a different focal length than that of the vertical axis. For a detailed description of this type of aberration refer to (Hecht, 2000).

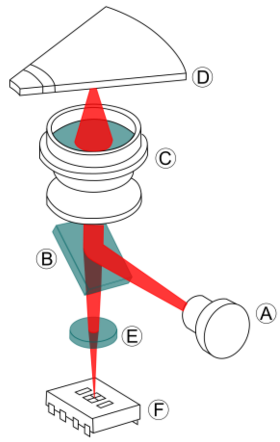

Figure 1: OPH internal components: A-Laser diode; B-Beam splitter; C-Objective lens; D-Sample; E-Astigmatic lens; F-Four quadrant detector. (Used with permission from Avago Technologies Fiber Austria GmbH.)

The aberration introduced by the lens is the key to the focus error signal generation. When the illuminated point of the sample surface is out of the focal plane, the image of the spot on the surface shifts from a circle (in focus) to an ellipse (out of focus). The ellipse's minor and major axes are aligned to the quadrant detector's diagonals. In this situation, the irradiance in two opposite photo detectors is larger than for the remaining two, Fig. 2a.

Commonly the detector outputs two signals: the focus error signal (FES) and the sum signal (SUM) that are defined, using the four voltages produced by each of the four quadrant that compose the detector (V_a, V_b, V_c, *and* V_d), as follows:

$$FES = (V_a+V_c)-(V_b+V_d) \tag{1}$$

$$SUM = V_a+V_c+V_b+V_d \tag{2}$$

In Figure 2b, a typical FES is shown; in this work the SUM signal was not used.

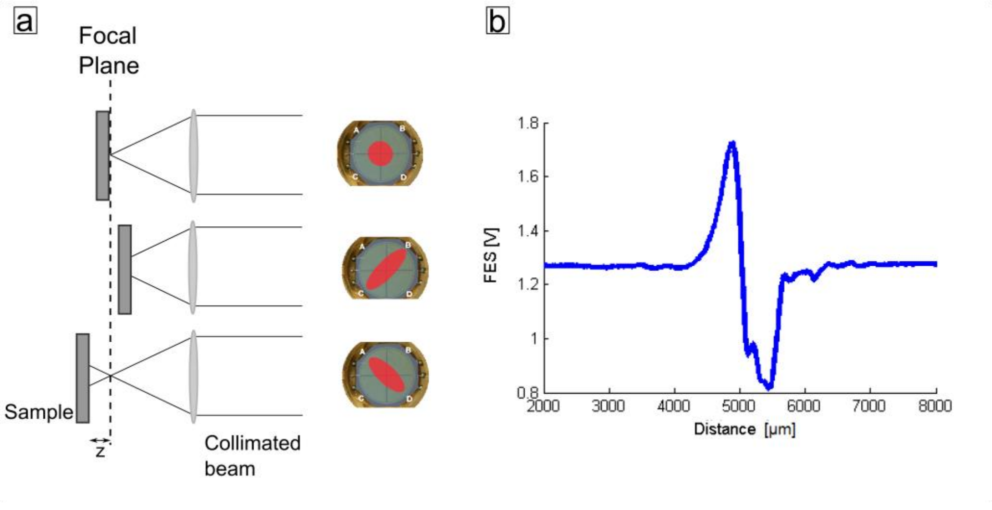

Figure 2: a-Sample and beam side view with the imaged spot on the detector. b-Typical FES curve.

3. VIBRATION MEASUREMENT AND CALIBRATION OF THE OPTICAL SYSTEM

The focus error signal measured can be related to the distance between the surface of the sample and the focal plane of the optical system that we assumed as a reference plane. It has been found that the focus error signal is dependent on many factors of the system, as the alignment between optical axis and the detector, the quality of the beam profile, the OPH angular alignment with the specimen surface and the sample reflectivity and roughness. These factors have been observed experimentally and its consequences can be found on several works (Cohen *et al*, 1984). To minimize this factor an alignment procedure and a calibration sequence was proposed in a recent work. In the same paper two different calibration techniques where tested; one using a piezo actuator with a strain gauge and a second one based on an interferometer. We present a brief description of the calibration procedure and some details that have to be considered to improve experimental results.

3.1 Piezo System

Similar methods have been used by some authors (Chie and Hung, 2009), which consist of using a closed loop positioning system driven by a piezo actuator to perform a scan of the FES by moving the sample in the range of distances in which the detector is linear. We decided to perform the calibration by steps, that is, we shifted the position of the sample surface (a mirror in our experiments) by discrete increments while keeping track of the FES and the elongation of the actuator measured with a strain gauge. In every step we waited some seconds to let the mechanical system settle and then, average over some extra time.

FES data was acquired using a DAQ Board from MCC (USB-2527), while elongation (GLG) data was acquired from the strain gauge output (TSG001 strain gauge reader from Thorlabs, inc). The set up is shown in Fig. 3.

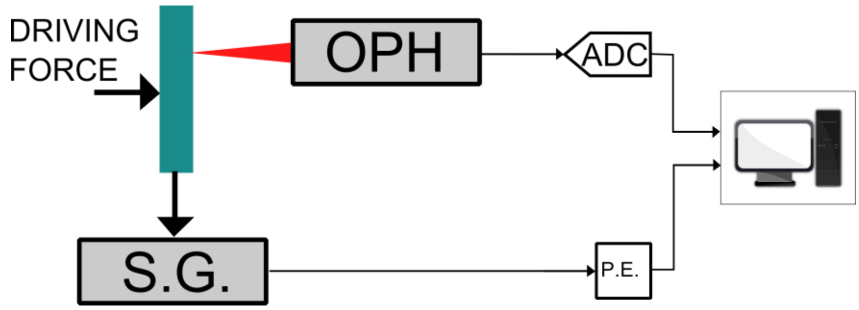

Figure 3: Strain gauge reference calibration set-up.

After a fitting process of the sequence of (FES, GLG) pairs measured following the previous procedure, the calibration function is obtained.

Special attention is required in the design of the set-up used for this scheme of calibration in order to avoid unexpected variation in the FES produced for random movement or drift in the mechanical system. These effects are portrayed in Fig. 4.

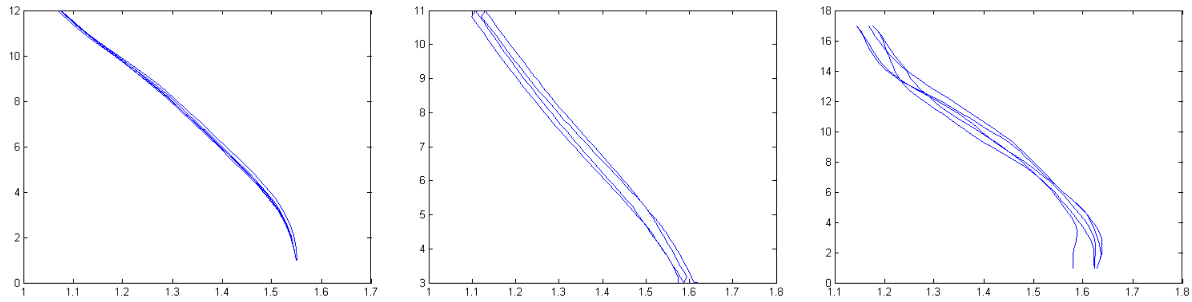

Figure 4: Left: Acceptable FES calibration curve; middle: drifted calibration curve; right: FES calibration curve affected by random movement produced by mechanical vibrations in the set-up.

3.2 Interferometric Method

An alternative calibration method proposed in (Liu *et al*, 2008) is based on a Michelson interferometer using a He-Ne laser as distance reference. The driving force was provided by means of a loudspeaker fitted with a ferromagnetic plate which provided easy mounting by attaching samples to a magnet; a schematic is shown in Fig. 5.

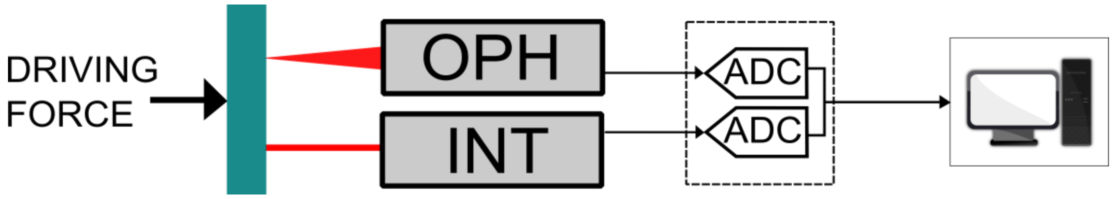

Figure 5: Interferometric reference calibration set-up.
Both ADC channels are embedded on a USB ADC board from MCC.

This method requires a more complex signal processing. The experimental procedure is analogous to the previous one, after the setup is aligned and ready to measure. In our configuration the vibration in the sample is produced by a loudspeaker and two datasets are logged simultaneously, the FES and the interference signal (INT).

I order to obtain the data that correspond to the reference distance measurement from the interference signals and the FES, it is follows these steps:

- Identify and separate the FES and the interference signal for each semicycle that correspond to the back and forth movement of the speaker.
- Normalize the interference signal and isolate the intervals for each semicycle.
- Crop both signals.
- Recover wrapped phase.
- Unwrap and scale the resulting interference signal.

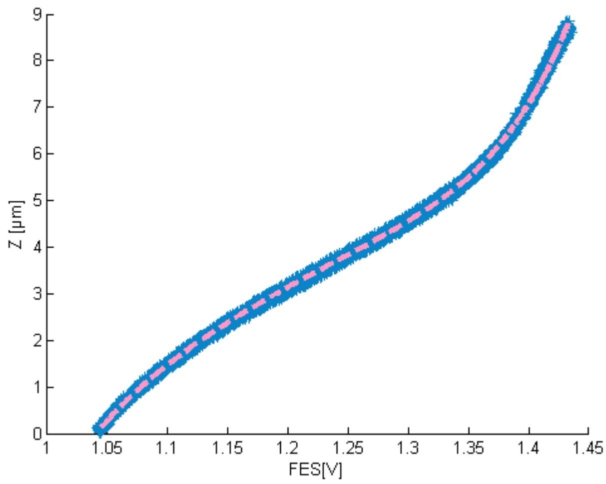

Figure 6: Top: interferometric reference calibration curve;
bottom: fitted-polinomial acquired data differences.

At this point we proceed to the polynomial fitting in the same way that in the previous calibration system. This method has the advantage of being extremely fast with very good results. Highly consistent correspondence between FES and the calculated displacement was observed in the experiments. The result of this method is shown in Fig. 6.

The processing of the interference signal can produce unexpected, and false, results after normalization, thus the need to crop it, Fig. 7. This and the fact that the interference signal is not direction sensitive prevent us from using the whole dataset.

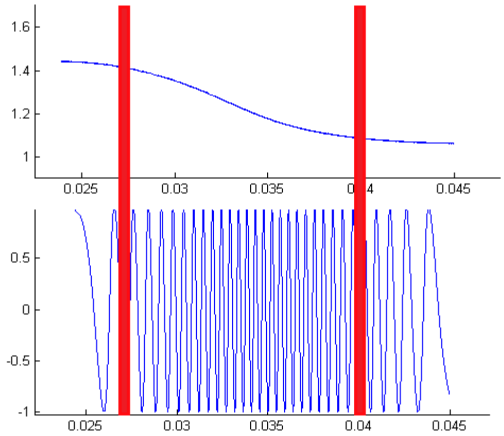

Figure 7: Top: FES, bottom: INT. Data points outside the vertical bars are excluded from analysis.

4. EXPERIMENTAL RESULTS

In this section some experimental results are presented on the measurement of vibration in different samples with the intention to show the possibilities in the use of the complete system. The results were obtained with the experimental set-up described in 3.1. In this example the results were obtained with a sample fixed to an open loop piezo actuator whose displacement was also measured with a strain gauge, Fig. 8.

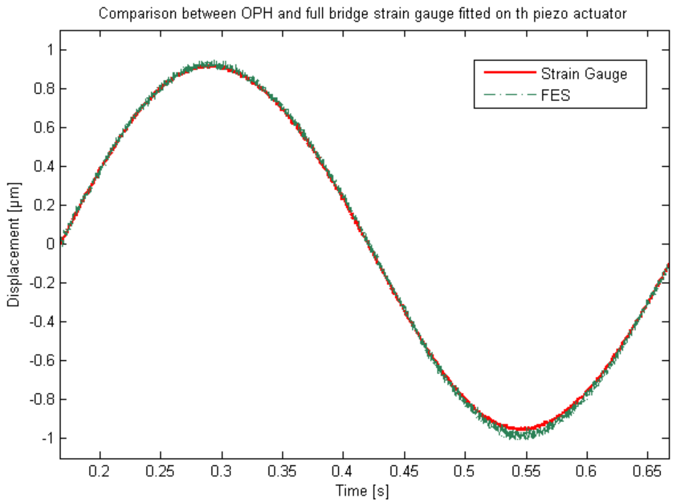

Figure 8: Oscillation movement measured simultaneously with a calibrated OPH system and with a strain gauge (fixed to the piezo actuator).

In a second example the natural vibration of a clamped end metal beam was measured with the OPH and a commercial accelerometer (303-A02 from PCB piezotronics) simultaneously. In this experiment the beam was excited by an impulse applied with a screwdriver at the clamp. In the transient, most vibration components were detected by both instruments. Results are shown in Fig. 9.

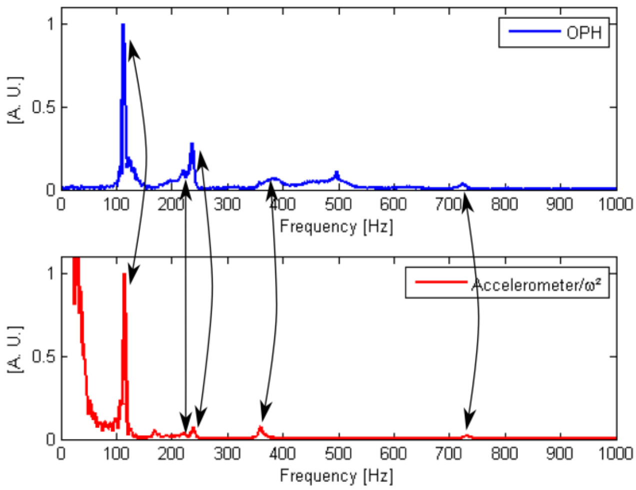

Figure 9. FFT of transient response of a single clamped end beam excited by an impulse and a constant acoustic excitation. Top: OPH. Bottom: Accelerometer

However, the OPH exhibits better response at low frequencies since there is no need for signal integration to obtain the displacement. This can be seen in a steady state oscillation of the same beam, Fig. 10. The beam is acoustically excited by a loudspeaker driven at 114 Hz. Additionally a high frequency component was present. This is detailed on the right side of Fig. 10.

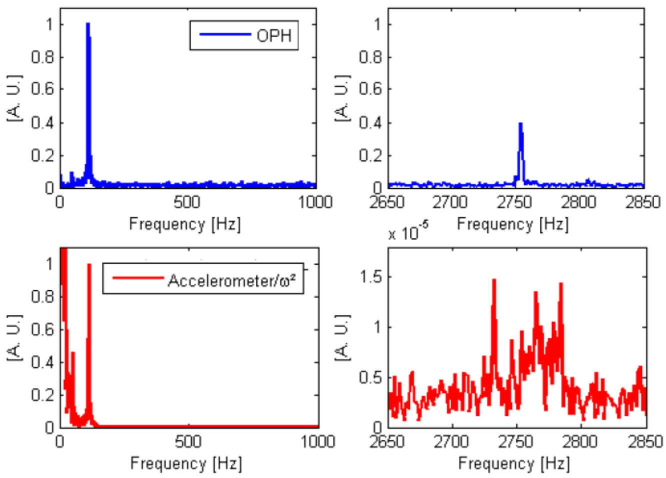

Figure 10. FFT of steady state of a single clamped end beam excited by an impulse and a constant acoustic excitation. Top: OPH. Bottom: Accelerometer

It is documented in some works (Feltrin *et al*, 2004) (Arraigada *et al*, 2006) that measurements obtained by numerically integrating the acceleration in order to get the displacement, can distort the calculated displacement signal. Particularly low frequency signals with extremely large amplitudes are present in the resulting integrated signal. This effect is intensified if there are components of low frequency and amplitude present in the original acceleration time series. This is evident in the integrated acceleration traces in Figures 9 and 10, but not in the OPH presented in this work, which becomes advantageous when trying to measure low frequency displacements.

5. CONCLUSION

It has been shown that the optical head based on the focus error signal with a calibration system is suitable for measuring vibrations and displacements. Measurements are presented in highly reflective surfaces such as mirrors or metal surfaces, and low reflectivity surfaces as non-polished metals or rough surfaces. In all cases it is shown that the system has similar results to those obtained with conventional techniques. While the technique has been tested previously by different authors in displacement and velocity measurements, we consider that this new experimental set-up offers considerable advantages, provided by the calibration system that gives the possibility of measuring with the same experimental system different materials or samples with different surface characteristics. Also this scheme has the advantage of allowing direct measurement of the position of the vibrating sample with little signal processing and in a wide spectral range of frequencies.

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7. RESPONSIBILITY NOTICE

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