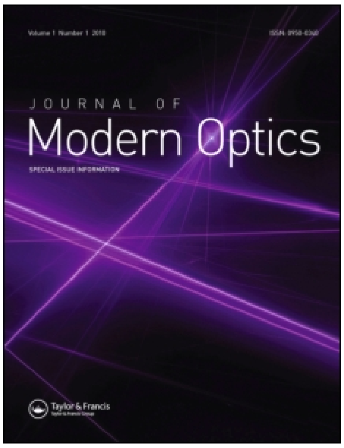

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An optical fibre sensor for dynamic deformation measurements based on the intensity modulation of a low-coherence source

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Letter
An optical fibre sensor for dynamic deformation measurements based on the intensity modulation of a low-coherence source

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Abstract. An optical fibre sensing technique for the measurement of dynamic deformations using a Michelson interferometer is reported. The method applied to interferometers with an initial path unbalance of around 1 cm is based on the rf intensity modulation of a low-coherence source. A large measurement range of 1 cm is intrinsic to the method and with an adequate demodulation process sensitivity better than 10 μm is obtained. This novel approach allows for measuring dynamic deformations with a bandwidth up to 100 Hz.

Michelson and Mach–Zhender configurations are often employed for small distance measurements with interferometric techniques. The phase modulation induced by the parameter to be measured is detected by comparing the phases of light in the signal and the reference fibre arms of the interferometer. A variety of signal-processing techniques employing both narrow-band and low-coherence sources have been developed to measure the induced phase change with interferometric sensitivity. A major difficulty in obtaining measurement of phase difference between the beams in the two arms of the interferometer resides in stabilizing the interferometric output at its quadrature point since random fluctuations in the ambient temperature tend to produce differential drifts in the arms of the interferometer. An active homodyne [1, 2], passive homodyne [3] and heterodyne [4], primarily developed for classical interferometry configurations, are key techniques developed to overcome this problem and to enable measurements of optical path changes that are shorter than the optical wavelength. On the other hand, techniques such as multiple-wavelength heterodyne interferometry [5], phase

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tracking [6] and white-light interferometry [7] have been developed, which allow for measurements of optical path changes in excess of a wavelength. By overcoming the phase ambiguity of 2π these methods have extended the range of path change measurements up to a few tens of millimetres. The operating principle of these methods, however, makes them basically suitable for obtaining only absolute measurements of the optical path differences in interferometers. The measurement range so obtained is thus equivalent to the maximum path unbalance that can be compensated for in the interferometric sensor.

In this letter we report an optical fibre sensing approach for the measurement of dynamic deformations using a path unbalanced (about 10 mm) Michelson interferometer. The concept, based on the rf amplitude modulation of a low-coherence source, is applied to a recently deployed fibre-optic configuration that has been installed in several large-scale civil engineering structures for long-term monitoring of static deformations [8, 9]. The objective of the study is to extend the use of the interferometric configuration to include monitoring of the dynamic behaviour of structures as well. From the viewpoint of the performance, output sensitivity in the range of a micrometer, a measurement range of few millimetres over the sensor length, and a measurement bandwidth of about 100 Hz are expected from the interferometer.

Beam modulation telemetry has been often employed to measure large distances. The amplitude or polarization of light modulated at high frequencies (a few hundred megahertz to a few gigahertz) is transmitted from the laser source to the reflector. A detector collects the reflected beam. The optical distance between the light source and reflector is determined through comparison of the phases of the modulated waveforms of the transmitted and reflected beams [10, 11].

A principle akin to that used in beam modulation telemetry is applied to a Michelson interferometer operated with a low-coherence source for obtaining dynamic measurements. The method consists of injecting amplitude-modulated radiation emitted by a low coherence source into a Michelson interferometer acting as sensor (figure 1). Assuming the amplitude of the light beam to be sinusoidally modulated, the intensity injected into the interferometer is given by

$$I_i(t) = I_0[1 + m\cos(2\pi f_m t + \varphi_0)]. \tag{1}$$

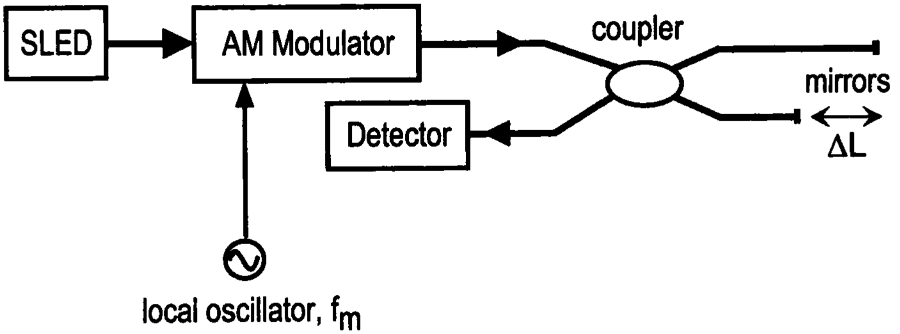

Figure 1. Schematic diagram of the path-unbalanced fibre optics Michelson interferometer for dynamic deformation measurements: SLED, superluminescent light emitting diode; AM, amplitude modulation.

where I_0 is the mean intensity, m is the modulation index of the amplitude modulation, f_m is the modulation frequency, t is the time and φ_0 is the initial phase of the modulated signal. The incident light is split into two beams that travel different distances in the interferometer. A coupler recombines the beams travelling through the two arms of the interferometer. The phase difference at the output is directly proportional to the optical path difference between the two beams in the interferometer. However, as the optical path difference in the interferometer is much larger than the coherence length of the source (about 40 μm), no interference effect is observed at the output of the interferometer. This also avoids taking into account the states of polarization of the interference beams. Hence, a detector placed at the output of the interferometer detects only the intensity superposition of the back-reflected signals. The intensity detected at the output of the sensor is given by

$$I_D(t) = \tfrac{1}{2}I_0 + \tfrac{1}{4}I_0 m\{\cos(2\pi f_m t + \varphi_0) + \cos[2\pi f_m(t-\tau) + \varphi_0]\} = A_0 + A(t), \quad (2)$$

where $\tau = 2n\Delta L/c$ is the flight-time difference between the two arms, ΔL is the initial path unbalance in the interferometer, n is the refractive index of the fibre and c is the velocity of light in vacuum. A_0 denotes the dc component and $A(t)$ is the amplitude modulation of the detected intensity. By changing the relative delay between the two beams, a succession of maxima and minima is obtained in the ac component of the signal, transforming the phase lag between the two reflected rf signals into an amplitude change. Because of the direct relationship existing between the modulation frequency and the phase lag, the same effect is obtained by changing the modulation frequency for a fixed value of τ.

Figure 2 shows the evolution of the detected amplitude modulation arising from the superposition of the two beams for $m = 0.5$ and for different values of the relative delay τ; values of τ are taken between zero and one half of the period of the

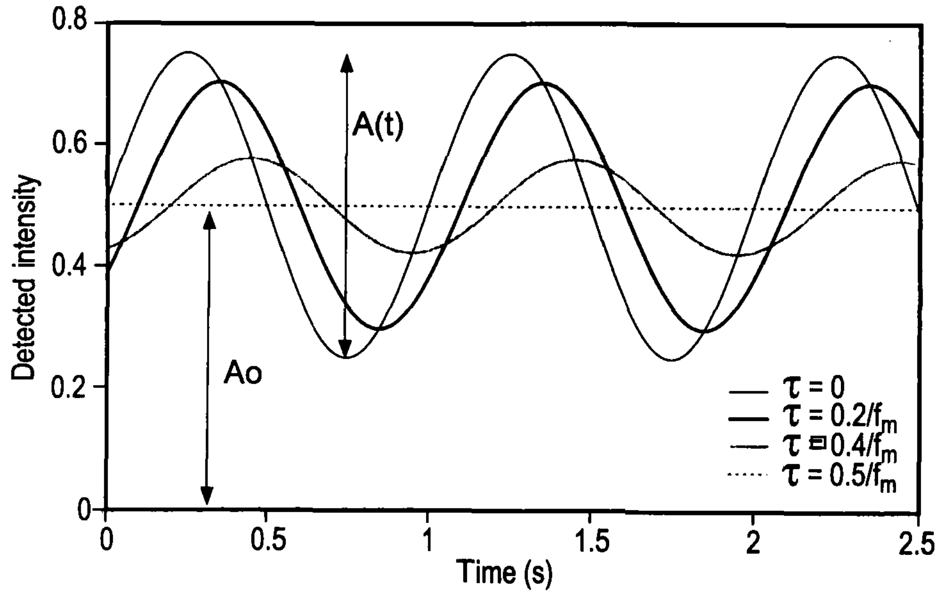

Figure 2. Plot of the detected intensity for different values of the relative delay τ; values of τ are taken between zero and one half of the period of the modulated signal.

modulated signal. One approach to retrieve deformation values is to detect phase changes in the modulated component. For an interferometer with initial path unbalance $\Delta L \approx 1$ cm, this would necessarily require working with modulation frequencies as high as 2 GHz in order to visualize these phase shifts. Such high working frequencies add an implementation difficulty to the system. In addition, in order to measure deformations of at least some hundreds of micrometres, the phase resolution requirements for the detection system, of the order of $\pi/500$, can be considered as difficult to fulfil at these high frequencies.

The effects of modulation can be quantified by calculating the rms value of the normalized ac component:

$$\text{rms} = \left[\left\langle\left(\frac{A(t)}{A_0} - \left\langle\frac{A(t)}{A_0}\right\rangle\right)^2\right\rangle\right]^{1/2} = \left[\left\langle\left(\frac{A(t)}{A_0}\right)^2\right\rangle - \left\langle\frac{A(t)}{A_0}\right\rangle^2\right]^{1/2}, \quad (3)$$

where

$$\frac{A(t)}{A_0} = \tfrac{1}{2} m\{\cos(2\pi f_m t + \varphi_0) + \cos[2\pi f_m(t - \tau) + \varphi_0]\} \quad (4)$$

and the angular brackets indicate the mean value. The rms value is obtained as

$$\text{rms} = \frac{m}{2}\,[1 + \cos(2\pi f_m \tau)]^{1/2}. \quad (5)$$

Equation (5) shows that the rms value of the normalized ac component is a periodic function in f_m. The value of rms is a minimum when the relative delay is an odd multiple of one half of the modulation period and is a maximum when the relative delay is a multiple of the modulation period. Since the position of the minimum depends only on the path unbalance in the sensor and on the modulation frequency, a good way for measuring deformation would be to monitor the deformation-induced frequency shifts of the minimum of the rms value and then to relate these shifts to changes in the optical path difference in the interferometer.

The solid curve in figure 3 shows the evolution of rms as a function of f_m for a modulation index $m = 0.5$. The broken curves in the figure shows the numerical simulation of the effect of shortening by 1 mm the initial path unbalance $\Delta L = 10$ mm, on the rms value of the normalized ac component. The minimum is seen to shift towards higher frequencies as ΔL decreases. For a given path unbalance in the sensor, the position of the minimum of the detected intensity is attained for a precise modulation frequency and vice versa (i.e. $f_m\tau = 0.5$ at the minimum).

Measurements were carried out by tracking the position of the minimum of the detected signal in the frequency domain. The principle of monitoring shifts of the minimum of the rms value consists of adding a frequency modulation, f_c, to the carrier frequency f_m. It can be shown that in this case the modulated intensity at the sensor output generates a sinusoid at the modulation frequency f_c with the amplitude proportional to the rate of change in the amplitude of the sensor response. At the minimum position, this sinusoid has an amplitude equal to zero.

The demodulation process includes an envelope detector, which eliminates the carrier frequency f_m. When deformation is applied to the measurement arm of the interferometer, the related shift δf_m in the position of the minimum is retrieved by comparing the output with a reference signal at f_c in a lock-in amplifier. The lock-

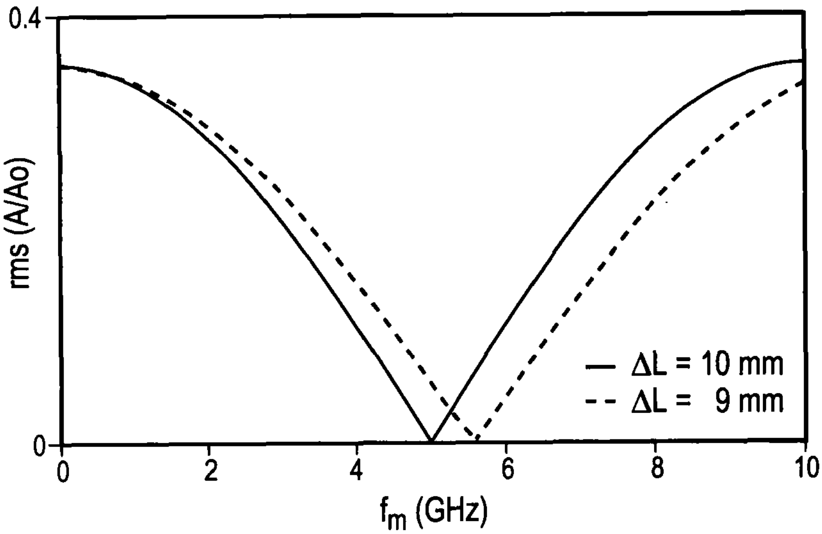

Figure 3. Evolution of the modulated amplitude as a function of the modulation frequency f_m.

in generates a signal proportional to the rate of change in the amplitude of the sensor response and consequently to the shift in the minimum position. This shift can be unambiguously related to the changes δL in the path unbalance in the sensor by using the expression

$$\delta L = -\frac{\delta f_m}{f_m}\,\Delta L = -\frac{\delta f_m}{f_m^2}\,\frac{c}{2n}. \tag{6}$$

A feedback loop is implemented in order to track and compensate the frequency shifts in the minimum position continuously. Continuous monitoring of these shifts allows for the determination of the dynamic deformation behaviour of the measurement arm of the interferometer. An advantage of this arrangement is that most of the processing that it involves is at low frequencies, which significantly contributes in simplifying the electronics needed to build such a system.

A modulator based on a Mach–Zhender configuration follows a 1300 nm superluminescent light emitting diode (SLED) with a mean power of 3 mW. The all-fibre sensor has an initial path unbalance of around 10 cm and the mirrors at the ends are achieved by silver deposition on the cleaved fibre ends. The sensing technique has been tested by applying a longitudinal sinusoidal deformation of 30 Hz to one of the sensor arms. A shaker driven with a sinusoidal signal at 30 Hz is used to apply the deformation. Figure 4 plots and compares measurements obtained with the minimum tracking system and those obtained with a commercial laser Doppler vibrometer. The peak-to-peak amplitude represents a deformation of 70 μm. The new technique shows a sensitivity better than 10 μm, a frequency response of up to 100 Hz and a measurement range of at least 1 cm. Furthermore, since both arms of the interferometer are at the same temperature and with no coherent interference taking place in the sensor, temperature variations are not observed to affect the measurements.

To conclude, a fibre sensing technique based on rf intensity modulation of a low-coherence source has been developed for measurement of dynamic deforma-

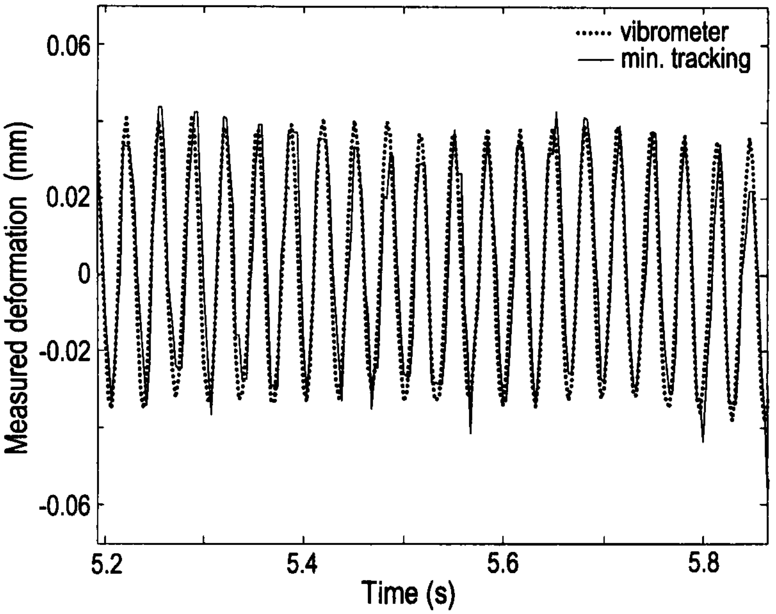

Figure 4. Comparison of measurements obtained with the minimum tracking system and those obtained with a commercial laser Doppler vibrometer to a response with an excitation of 30 Hz.

tions. It is insensitive to polarization of light, requires only a few optical elements and presents an intrinsic large measurement range. The main advantage of the proposed technique lies in its immunity to unbalanced reflectance values, which contributes to simplifying the production and calibration of the sensors.

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