Improved Demodulation Algorithm for Spatial-Frequency Multiplexed Fibre-Optic Fizeau Strain Sensor System

Author/Contributor:
Wong, Allan; Phillips, Christopher; Peng, Gang-Ding

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Improved demodulation algorithm for spatial-frequency multiplexed fibre-optic Fizeau strain sensor system

Allan C.L. Wong, C.J.E. Phillips and Gang-Ding Peng
The University of New South Wales, Sydney, NSW, Australia,
Phone: (612) 93855534, Fax: (612) 93855993, allanw@student.unsw.edu.au

Abstract

An improved algorithm is proposed to demodulate signals acquired from a spatial-frequency multiplexed fibre-optic Fizeau strain sensor system. We have demonstrated that this algorithm, which includes wavelet signal-processing techniques, reduces noise and increases strain resolution.

Introduction: The spatial frequency multiplexed fibre-optic Fizeau strain sensor system is a novel design proposed by Rao *et al* [1]. In principle, the sensor is demodulated using a Fourier transform (FT) method to find the cavity length, and hence the strain values. However, in their system, instead of using the direct FT method, a method called the discrete gap transform was used to avoid poor strain resolution and transforming from spatial frequency to cavity length. The direct FT method has been used by others to find the strain values [2 – 5], but in most cases either only the phase information or a technique called FT spectroscopy was used. Here, we present an improved demodulation algorithm utilising wavelet denoising together with a simple FT peak detection method to calculate the strain values, as well as to increase the strain resolution and reduce the noise associated with the sensor signals.

Sensor demodulation algorithm: The demodulation algorithm is depicted in Fig. 1. The intensity distribution of the sensor signal, $I(\lambda)$, is of the form [1]:

$$I(\lambda) = A(\lambda) + G(\lambda)\cdot r_1 r_2\{1 + V\cdot S(\lambda)\cdot\cos(4\pi d/\lambda)\}, \qquad (1)$$

where $A(\lambda)$ is the incident light source intensity, $G(\lambda)$ is EDFA small signal gain, r_1 & r_2 are the reflection coefficients of the two fibre ends, V is the fringe visibility, $S(\lambda)$ is the light source spectral profile, and d is the sensor cavity length. In practice, the sensor signal is acquired from an optical spectrum analyser (OSA), and is represented as a discrete signal.

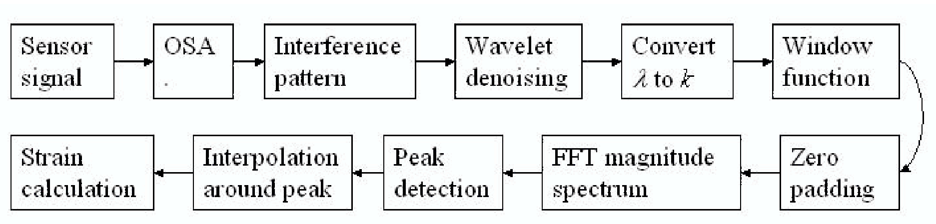

Fig. 1 Schematic diagram of the demodulation algorithm.

The sampled discrete version of Eq. (1) is given by:

$$I[n] = A[n] + G[n]\cdot r_1 r_2\{1 + V\cdot S[n]\cdot\cos[4\pi d/n]\}, \qquad (2)$$

where $n = \lambda/\Lambda$ is the sampling number, and Λ is the sampling interval (in wavelength). The raw sensor signal acquired has broadband (white) noise associated with it due to the light source, sensor head, fluctuations of the ambient temperature, and finite resolution limit of the OSA. Since it is difficult to remove white noise using conventional filtering, wavelet denoising [6] is applied to reduce the noise. Let the signal be represented as: $I[n] = \sum_{i,j}\alpha_{i,j}\psi_{i,j}[n]$, where $\psi_{i,j}[n] = 2^{-i/2}\psi[2^{-i}n - j]$, $i, j = 0,\ldots,N-1$ is the wavelet basis. A Fourth-order Daubechies wavelet was used as it generally works better than other wavelets in signal denoising. The wavelet coefficients are obtained by taking the discrete wavelet transform (DWT) of $I[n]$: $\alpha_{i,j} = \langle I[n], \psi_{i,j}[n]\rangle$. Then we apply hard-thresholding to the wavelet coefficients, such that any noise components below the threshold h are suppressed: $\alpha'_{i,j} = \xi_h[\alpha_{i,j}] = \begin{cases} \alpha_{i,j}, |\alpha_{i,j}| > h \\ 0, |\alpha_{i,j}| < h \end{cases}$.

Finally, we take the inverse DWT to reconstruct the signal: $I'[n_\lambda] = \sum_{i,j} \alpha'_{i,j} \psi_{i,j}[n_\lambda]$.

Having reduced the noise, we convert the variable from wavelength to wavenumber ($k = 2\pi/\lambda$), so that the FT variable becomes the optical path difference (l) of the cavity, rather than the spatial frequency. The cavity length is simply given by $d = l/2$. We take an N-point discrete FT of the denoised signal assuming that the mapping is approximately linear; as the wavelength sampling range is only 20 – 50 nm, the effect of nonlinear mapping on the FT is negligible. Ideally the DFT requires the signal to be periodic, but since the acquired sensor signal is often either non-periodic or not an integer multiple of the signal period, there will be discontinuities at the edges of the signal period leading to spectral leakage. The Fourier magnitude spectrum is affected in both the amplitude and frequency. It appears as a smeared Gaussian-like peak instead of a single line (delta function), with the energy being leaked to other frequency bins. In order to minimise the spectral leakage, a window function can be applied to the signal to smooth the signal edges. Our aim is to reduce the sampling interval width (Δl) in the l-domain as much as possible, so that we can resolve and track minute changes in the cavity length. One way to reduce Δl is by increasing N, which can be done by zero padding the signal in the original domain. This reduces Δl evenly for the whole Fourier magnitude spectrum, and that is effectively the same as increasing the strain resolution. However, since only the Fourier peak location and the amount shifted due to an applied strain are of interest, we can further reduce Δl around the Fourier peak. We consider a set of neighbourhood data points about the peak centre and apply some kind of interpolation, such as a cubic-spline, to this region. Once we know d from the magnitude spectrum, the strain value is simply given by: $\varepsilon = (d - d_0)/L$, where d_0 is the initial cavity length and L is the gauge length (~40 mm).

Results: The Fizeau sensor system utilising the demodulation algorithm was simulated using MATLAB. The sensor signal was generated by Eq. (2) for a particular cavity length. An additive Gaussian white noise was added to the sensor signal. A typical sensor signal obtained from the OSA is shown in Fig. 2. The simulation for determining the strain values using our demodulation algorithm and the direct FT method is compared and shown in Fig. 3. The applied strains ranged from 1 – 4 με with a SNR of 15.2 dB. Although it cannot be seen from the FT magnitude spectrum, there are actually four peaks overlapping one another, each corresponds to an applied strain value. As seen from the figure, by just using the basic FT method without our algorithm it is impossible to determine the applied strain correctly and accurately. By using our algorithm, we can determine strains as small as 1 με with an error of 7 %, or 1.00 ± 0.07 με. Such strain

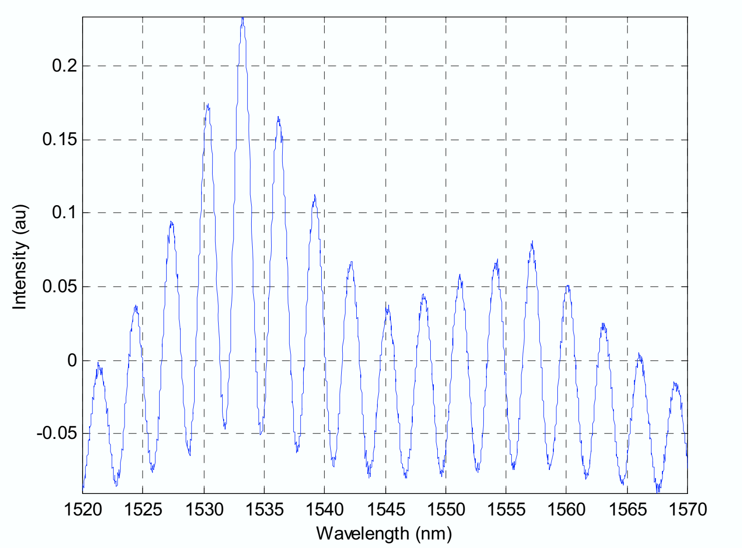

Fig.2 Typical interference pattern of the Fizeau strain sensor with Gaussian white noise. The sensor cavity length is 400 μm.

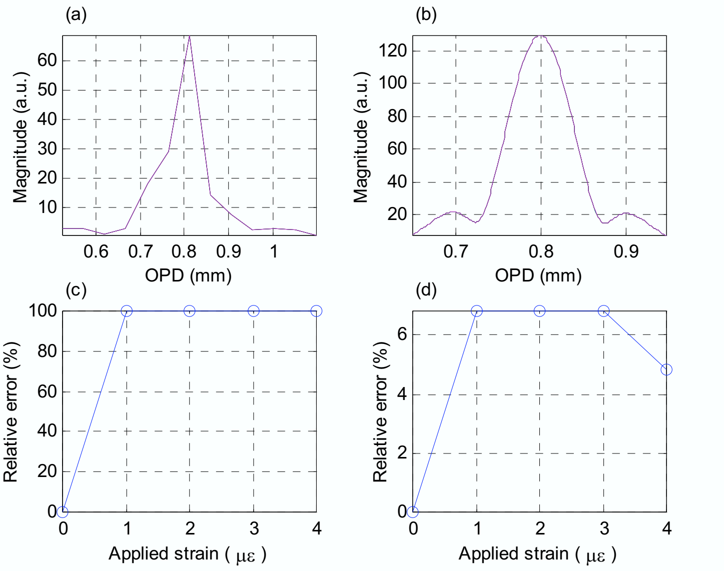

Fig.3 Fourier magnitude spectrum of the signal (Fig. 1) with applied strains of 1 – 4 με and a SNR of 15.2 dB, using (a) direct FT method, (b) our demodulation algorithm. The respective relative errors for the calculated strains are shown in (c) and (d).

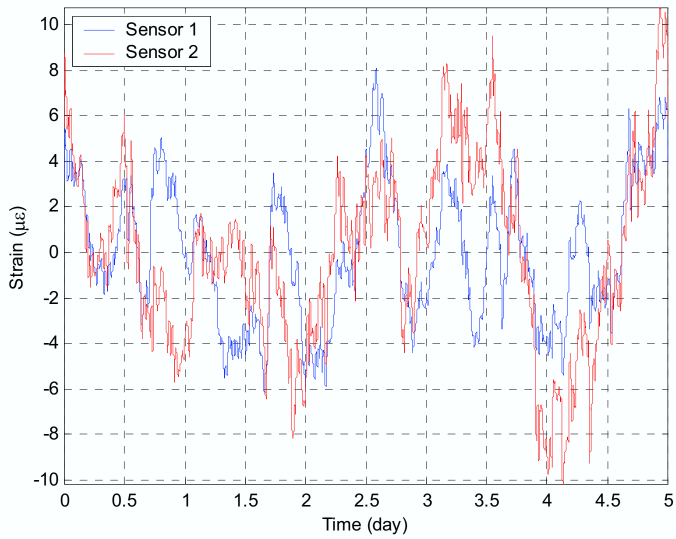

Fig.4 Strain logs of two multiplexed Fizeau sensors for a 5-day cycle.

resolution is adequate for most quasi-static strain detections in structural health monitoring (SHM) of large structures such as concrete bridges. It is found that by just using the basic FT method, a strain of at least 50000 με is needed in order to resolve the applied strain at a reasonable accuracy (<40 %). Such a large strain range is beyond the tolerable limit for concrete bridges (~20000 με), making this sensor system impractical for ordinary SHM.

Our demodulation algorithm is applied experimentally in real-time strain sensing. The generic experimental setup is described in Ref. [1], except that the two multiplexed sensors were placed vertically next to each other on the edge of a workbench. A LabVIEW program was written to acquire and process the sensor signals in real-time. Preliminary results for the two multiplexed sensors were obtained. Fig. 4 shows the mean-removed strain logs for a 5-day cycle. The degree of correlation between the two sensors was 0.5863. The strain variations were mainly due to ambient temperature change.

Conclusion: We have proposed an improved demodulation algorithm that employs the wavelet signal processing techniques, in combination with the usual FT peak detection method, in Fizeau strain sensor systems. We have demonstrated that, using this demodulation algorithm, the strain values can be more accurately determined. In comparison with the basic FT method, our demodulation algorithm improved the strain resolution by a factor of >50000 and the accuracy by a factor of >6. The algorithm can be implemented in real-time SHM.

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