Multiplexing of long-gauge length fibre optic dynamic strain sensors using range-resolved interferometry

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Abstract. A recently developed range-resolved interferometric signal processing technique is employed to multiplex segments of optical fibre that each act as a long-gauge length dynamic strain sensor, in an approach termed fibre segment interferometry, which is aimed at condition and structural health monitoring. The instrument employs cost-effective diode lasers, off-the-shelf digital signal processing hardware and a very simple optical setup. In this implementation, six concatenated fibre segment sensors of individual length 12.5 cm are formed between seven partial in-fibre reflectors formed by optical fibre Bragg gratings. The interferometric phase signals of the fibre segments are interrogated at a data rate of 98 kHz and, in an experimental demonstration of the ability of the technique to measure dynamic events, the speed of sound in a suspended metal rod is determined, where the acoustic signal is induced by a hammer strike.

Introduction

In fibre segment interferometry (FSI), consecutive segments of an optical fibre are separated by in-fibre partial reflectors that act as interferometric signal sources. The phase signals from two neighbouring reflectors can be subtracted, resulting in a measurement of the optical path difference (OPD) integrated over the length of the fibre segment between the reflectors. The fibre segments can be thought of as long-gauge length fibre sensors that respond to any physical effect that changes the OPD, such as strain and temperature. In general, interferometric techniques allow only phase evaluation relative to an unknown starting point and are therefore best suited to dynamic measurements. The multiplexing of long-gauge length fibre optic interferometric sensors spanning the sections of fibre separating an array of in-fibre partial reflectors was developed originally for fibre optic hydrophone applications [1, 2]. Past implementations have been based mainly on time-division multiplexing [1,2], optical frequency modulation of the laser source [3,4] or code-division multiplexing [5]. In this work, the FSI sensing fibre is interrogated using a novel range-resolved optical interferometric signal processing technique [6] that is based on sinusoidal optical frequency modulation of a continuous-wave laser diode. When applied to FSI, this approach simplifies considerably the optical setup of the interrogation unit and allows large improvements in the minimum fibre segment length that can be resolved, reducing this from many metres, as reported in prior work [1,2,5], to tens of centimetres as presented here. Additionally, when compared to other optical frequency multiplexing techniques [3,4], the susceptibility to crosstalk from parasitic signal sources is reduced because the new technique does not require integer optical path length difference ratios to be maintained between the multiplexed interferometers. Furthermore, in this work, the use of low-reflectivity broadband fibre Bragg gratings (FBGs) that are all inscribed at the same wavelengths to act as partial in-fibre reflectors eliminates the use of couplers within the sensing fibre [2], also allowing mass-produced draw tower gratings to be employed [7].

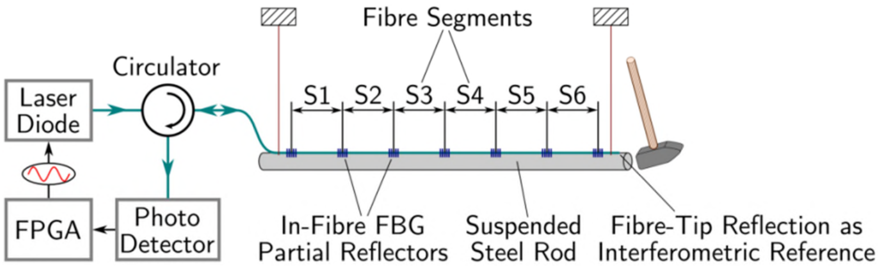

Figure 1 Illustration of the optical setup and measurement configuration.

Experiment

Fig. 1 shows the setup used for the experimental demonstration. Here the FSI sensing fibre, consisting of six fibre segments (S1 to S6) of individual length 12.5 cm, is attached to a freely suspended stainless steel rod of 78 cm length. The interferometric reference is taken from the fibre tip reflection, providing an extremely simple, self-referencing configuration with complete down-lead insensitivity. The optical setup consists of a laser diode, a circulator and a photo detector connected using regular single-mode fibre. The laser diode is a cost-effective DFB-type laser, originating from telecom industry applications, operating at a wavelength of λ=1550 nm and all modulation and demodulation is carried out using low-cost field programmable gate array (FPGA)-based processing at a digital sample rate of 150 MHz. The FBG partial reflectors used, manufactured in-house, were broadband (>5nm), designed so that the FBGs would return a signal under all practical strain and temperature conditions. The reflectivity was low (<0.01%), but the return signals were sufficiently strong for the measurement to remain in laser phase noise limited operation. The data rate of 98 kHz of the current implementation allows an unambiguous interferometric fringe rate of 45 kHz, corresponding to a maximum strain change rate over the whole array of six segments of approximately $40\ \mathrm{m\epsilon \cdot s^{-1}}$. This could be improved through faster modulation. In this technique, the minimum fibre segment length that can be resolved is a property of the modulation characteristics of the laser diode only and could be enhanced further by using more widely tuneable laser diodes.

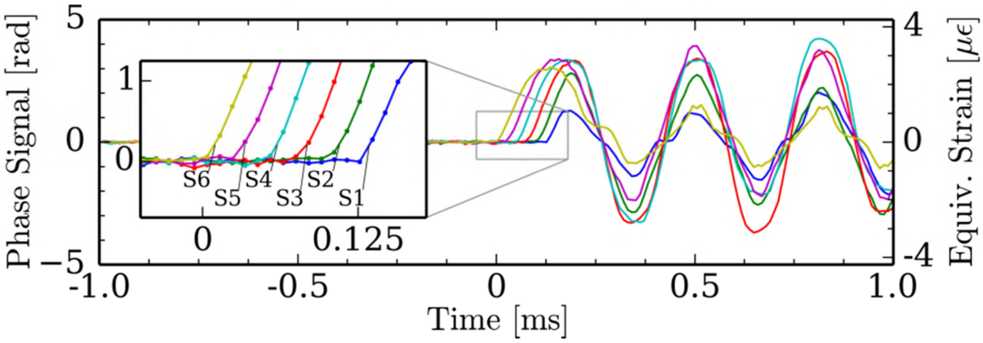

Figure 2 Measurements of the segment signals S1 to S6 at the time of the hammer impact, with the inset showing the delayed onset of the initial signal rises and the secondary y-axis on the main plot in equivalent strain units [3] for a 12.5 cm fibre segment.

Results & Discussion

Example measurements using the described setup are shown in Fig. 2. Here the propagation of the acoustic signal through the rod due to the hammer impact can be observed. By evaluating this delay for the middle segments S2 to S5 over 10 repeats of this experiment, the speed of sound in the stainless steel rod was determined as $4.97\ \pm 0.36\ \mathrm{km \cdot s^{-1}}$, which is within the error limits of the expected value of $4.91\ \mathrm{km \cdot s^{-1}}$ for a longitudinal acoustic wave in a thin stainless steel (Type 316) rod calculated using [8]. Noise levels in the segment data were typically $0.2\ \mathrm{mrad \cdot Hz^{-0.5}}$, equating to a dynamic strain sensitivities [5] of $0.2\ \mathrm{n\varepsilon \cdot Hz^{-0.5}}$. When compared to widely used FBG strain sensing techniques that have typical dynamic sensitivities of several $\mathrm{n\varepsilon \cdot Hz^{-0.5}}$ [9] at best, the dynamic sensitivities that can be achieved with this FSI technique compare very well. This could be advantageous in control applications, where high data quality, especially of the input signal derivatives, is very important. Additionally, the inherently high data rate in this technique would be of great benefit when low data latency is required. It is also worth noting that, in FSI, strain data is integrated over the whole gauge length of the sensor, reducing the impact of localised disturbances [10] and leaving no sensing gaps, advantageous in damage detection applications, such as vibration based condition monitoring [11]. Furthermore, there are no moving parts or spectrometers that require precise alignment in the setup, promising very robust interrogation units that could also be easily integrated into moving frames of reference.

Conclusion

A novel range-resolved interferometric signal processing technique has been applied to the multiplexing of dynamic fibre optic long gauge length sensors in an approach termed fibre segment interferometry. Very low dynamic strain sensitivities of $0.2\ \mathrm{n\varepsilon \cdot Hz^{-0.5}}$ at a data rate of 98 kHz for six fibre sensors and with equipment cost in this prototype totalling less than £5k have been demonstrated.

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