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Cost-effective vibration and displacement measurement using range-resolved interferometry

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Abstract. A recently developed range-resolved optical interferometric signal processing technique is applied to vibration and displacement sensing with fibre-based beam delivery. The technique is demonstrated to allow the simultaneous acquisition of high-quality, high resolution *relative* displacement measurements $(\sigma = 3\,\mathrm{nm})$ based on interferometric phase evaluation along with coarser $(\sigma = 0.05\,\mathrm{mm})$ *absolute* displacement measurements. The interferometric relative displacement data can be used for vibrometry measurement and to yield high-quality derivative velocity and acceleration data suitable for position control applications. The absolute data can serve as an additional proximity sensor. The sensing approach employs cost-effective diode lasers, off-the-shelf digital processing hardware and a very simple optical setup, and can, due to the use of a collimated beam, operate over a wide range of working distances.

Introduction

In this work, a novel range-resolved optical interferometric signal processing technique [1] that is based on sinusoidal optical frequency modulation through injection current modulation of a continuous-wave laser diode, is applied to vibration and displacement sensing, promising a cost-effective approach to obtain interferometric quality data. Because the technique is based on optical frequency modulation, it can be used in a stable, self-referencing setup with fibre-based beam delivery that is completely down-lead insensitive due to the use of the fibre-end reflection as an interferometric reference. In contrast to widely-used interferometric techniques [2], this approach is range-resolved, thus allowing the selection of the range at which the interferometric data is evaluated, which provides isolation against spurious out-of-range signals, such as reflections from windows. Additionally, the range information also yields absolute displacement data that can, after calibration, serve as a proximity sensor. This is useful, because, in general, interferometric techniques allow phase evaluation relative to an *unknown* starting point, and here, the coarser absolute displacement data can serve as a plausibility check on the interferometric measurements. There are several range-resolved interferometric techniques in the prior art that are all based on optical frequency modulation of a laser diode and that could also be used in self-referencing configurations. These include the well-known pseudoheterodyne technique [3], based on linear frequency modulation, which previously has also been used in a self-referencing vibrometry setup [4]. Sinusoidal techniques, such as the phase generated carrier approach [5] or gated techniques [6] have also been employed for interferometric signal processing. However, when applied to displacement sensing with variable working distances, all of these techniques [3-6] require the adjustment of the modulation parameters for changes in the working distance, which would require an active control loop during operation. Additionally, some techniques, such as J1…J4 processing [7], have been proposed to allow correction for changes in working distance in post-processing. However, these still only work over a limited range of working distances and lack out-of-range signal suppression. In contrast, the presented technique allows continuously variable working distances, subject to a minimum stand-off distance, and is capable of out-of-range signal suppression, therefore greatly increasing the practicality and flexibility of the sensing approach.

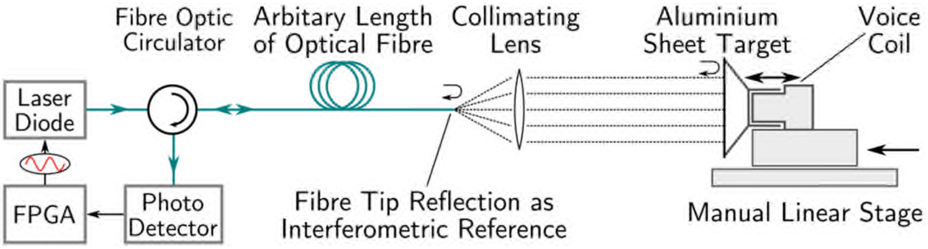

Figure 1 Illustration of the optical setup and experimental configuration, with a vibrometry test signal induced by a voice coil and with a long-travel movement introduced using the manual linear stage.

Experiment

Fig. 1 shows the optical setup, consisting of a laser diode, circulator and photo detector connected using regular single-mode fibre. The laser diode is a cost-effective DFB-type laser 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 digital data conversion sample rates of 150 MHz. In this technique, the interferometric reference is taken from the reflection from the fibre tip, allowing a compact measurement head consisting only of a standard fibre collimator. The sinusoidal modulation frequency is 98 kHz in the current implementation. This allows an unambiguous interferometric fringe rate of 45 kHz, limiting the maximum velocity that can be resolved to $\pm 35\,\mathrm{mm} \cdot \mathrm{s}^{-1}$. This could be improved in future implementations through faster optical frequency modulation. With the modulation characteristics of the laser diode employed, the minimum stand-off distance is 5 cm, but this could be enhanced using more widely-tunable lasers.

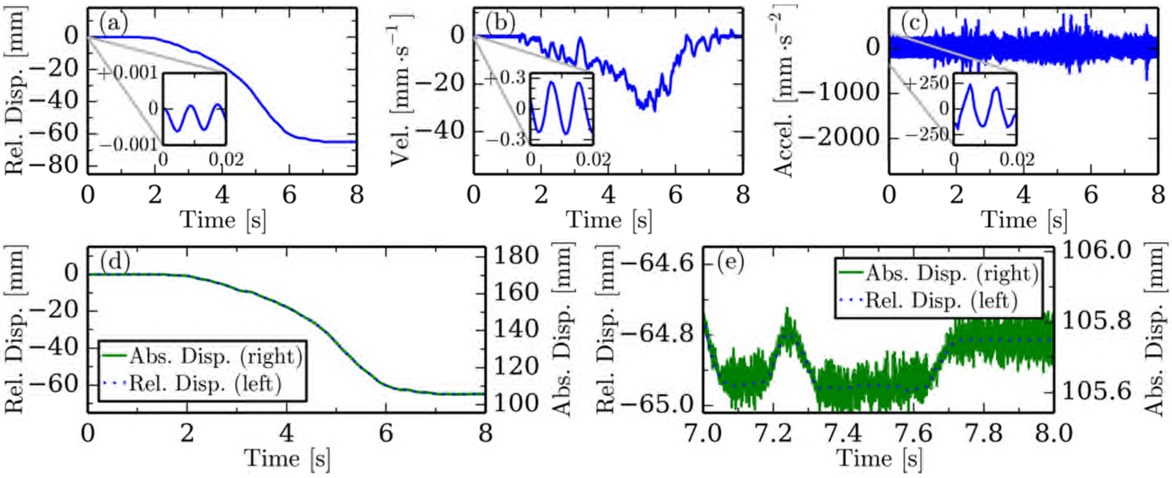

Figure 2 Measurements using interferometric phase data in (a), (b) and (c), showing relative displacement, velocity and acceleration, respectively. (d) Illustrates the overlap between absolute displacement data, with units indicated on the secondary y-axis, and the relative data of (a), with a zoomed version of this in (e).

Results & Discussion

The results for a test measurement are shown in Fig. 2, where a long-travel movement of 65 mm and a vibration test signal of peak-to-peak amplitude 0.7 $\mu\mathrm{m}$ at 120 Hz are present simultaneously. Here, Fig. 2(a) plots directly the displacement signal obtained by interferometric phase evaluation, downsampled to a data rate of 1.53 kHz, while (b) and (c) plot the first and second derivative of this data, the velocity and acceleration, respectively. In all three plots the vibration signal induced by the voice coil can be observed in the insets, with the acceleration data in Fig. 2(c), even after being twice differentiated, still being dominated by the 120 Hz signal and not by noise. The noise standard deviation of the interferometric displacement signal has been determined as 3 nm. Fig.2(d) then compares the relative displacement data obtained by interferometric phase evaluation with the absolute displacement data, with the latter plotted on the secondary y-axis. It can be seen in Fig.2(d) that complete overlap is maintained over a range of 65 mm. Fig.2(e) shows a zoomed version of the same data, from which a value for the standard deviation of the instantaneous noise in the absolute displacement data of typically 0.05 mm can be extracted. In general, the onset of laser speckle from rough surfaces and any variation in perpendicularity of the sensor alignment can lead to signal loss. This could be compensated by additional beam focussing optics, which may reduce the working distance range. Nevertheless, the results shown in Fig. 2 were obtained using a collimated beam incident on an untreated aluminium sheet and demonstrate the measurement quality and robustness of the sensing approach, highlighting its potential in displacement, sensing, position control and vibrometry applications.

Conclusion

A novel range-resolved interferometric signal processing technique has been applied to vibration and displacement sensing. High-quality interferometric relative displacement and vibration data with noise standard deviations of 3 nm along with additional absolute displacement data with noise standard deviations of 0.05 mm has been obtained at a data rate of 1.53 kHz and over a working range of 65 mm on an untreated aluminium sheet surface using equipment totalling less than £5k in this prototype implementation.

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References

[1] T. Kissinger, T. O. H. Charrett, and R. P. Tatam, "Range-resolved optical interferometric signal processing using sinusoidal optical frequency modulation," UK Patent Application 1416037.8 (2014).
[2] N. Bobroff, "Recent advances in displacement measuring interferometry," Meas. Sci. Technol. **4**, 907-926 (1993).
[3]: D. A. Jackson, A. D. Kersey, M. Corke, and J. D. C. Jones, "Pseudoheterodyne detection scheme for optical interferometers," Electron. Lett. **18**(25), 1081–1083 (1982).
[4]: A. C. Lewin, F. Ritter, and G. Siegmund, "Laser diode based pseudo-heterodyne interferometer for online process control of wire bonders," Proc. SPIE **4072**, 8-18 (2000).
[5]: A. Dandridge, A. B. Tveten, and T. G. Giallorenzi, "Homodyne demodulation scheme for fiber optic sensors using phase generated carrier," IEEE J. Quantum Electron. **18**(10), 1647–1653 (1982).
[6]: I. Sakai, R. Youngquist, and G. Parry, "Multiplexing of optical fiber sensors using a frequency-modulated source and gated output," J. Lightwave Technol. **5**(7), 932–940 (1987).
[7]: V.S. Sudarshanam, and K. Srinivasan, "Linear readout of dynamic phase change in a fiber-optic homodyne interferometer," Opt. Lett. **14**(2), 140–142 (1989).

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