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Highly linear, compact and cost-effective sensor probes for displacement measurements using range-resolved interferometry

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Abstract
We demonstrate a novel approach for interferometric displacement and vibration sensing using range-resolved interferometry (RRI). The concept exploits the ability of RRI to reject the signal contributions due to multiple reflections that would otherwise lead to high levels of periodic non-linearity errors, allowing the use of very compact and cost-effective sensor heads based on gradient index (GRIN) lenses, with the presented approach thought to be widely applicable across many precision engineering applications.

Keywords: Interferometry, Instrumentation, Metrology, Vibration measurement

1. Introduction

Optical interferometry can provide non-contact displacement and vibration measurements with nanometre-level resolutions, in many cases exceeding the performance and accuracy of competing sensing approaches [1]. However, the application of traditional optical interferometry for more mass-market displacement and vibration sensors is hindered by the cost and complexity of the technology, for example often requiring the use of polarisation-sensitive components and complex alignment procedures. In recent years, the emergence of interferometric techniques based on laser wavelength modulation, coupled with the availability of high-performance diode lasers and fibre-optic components, has simplified the design of sensor heads and interrogation units [2,3], for example removing the need for polarisation-sensitive components and also offering the benefit of fibre-coupled sensor heads with down-lead insensitivity. Several systems of compact fibre-coupled sensor systems based on this approach using Michelson [2] or Fabry-Perot sensor head configurations [3] are now commercially available. In general, a major problem for the design of these sensor heads is the avoidance of multiple reflections that can lead to periodic non-linearities. Here, sensor designs based on the Michelson configuration limit the contribution of multiple reflections through optical means, at the price of more complex and less compact heads, for example involving beam splitters integrated into the sensor head, while sensing approaches using a Fabry-Perot configuration require careful alignment to ensure that either the direct or dual-bounce reflection exclusively enters the sensor head [3], with typical magnitudes of periodic non-linearities of commercial systems, at, or sometimes well above, nanometre levels [2,3].

Therefore, a laser wavelength modulation interferometric technique that can provide linear measurements even in the presence of multiple reflections is highly desirable as it allows the use of very compact, cost-effective and alignment-insensitive sensor heads. In this paper, we propose the use of our range-resolved interferometry (RRI) [4] approach in conjunction with sensor probes employing very compact and cost-effective gradient-index (GRIN) lenses. RRI is an interferometric interrogation technique based on sinusoidal wavelength modulation of diode lasers. Through its inherent ability to resolve signal contributions from different ranges, RRI can cope with the presence of multiple reflections by simply ignoring their contributions, leading to very low linearity errors below <0.2 nm as demonstrated in this paper. The high linearity performance achieved is thought to be especially relevant for the measurement of small displacements or vibrations (<~1um) where periodic non-linearities are typically the dominant cause of measurement uncertainties. The proposed sensors are universally applicable, with applications including precision motion control, surface probe microscopy, grating-based encoders or non-contact vibration sensors.

2. Principle and Setup

2.1. Range-Resolved Interferometry

Range-resolved interferometry (RRI) [4] is a signal demodulation technique that uses sinusoidal wavelength modulation resulting from sinusoidal injection current modulation of a diode laser. Using appropriate range dependent demodulation carrier waveforms and a window function to select the appropriate parts of the wavelength sweep, the phase of one, or several interferometers that differ in optical path difference (OPD), can be demodulated simultaneously. Fig. 1(a) shows a typical interferogram and window function. Signal contributions from interferometers that do not correspond to the desired range are suppressed provided their OPDs differs sufficiently from the target interferometer, where any overlap

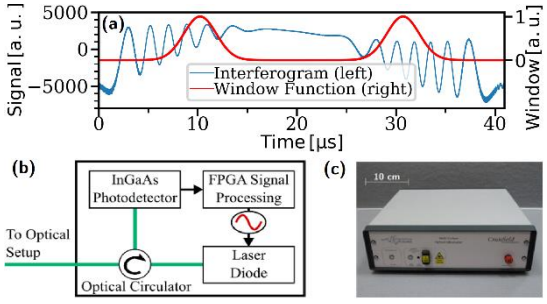

Figure 1. (a) shows a typical interferogram over one modulation period as well as the window function used. (b) illustrates the optical setup, with a picture of the fully enclosed interrogation unit shown in (c).

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would result in periodic non-linearities. In the present RRI implementation, a single discrete-mode laser diode (λ ≈ 1520.5 nm) is sinusoidally modulated at a frequency of 24.4 kHz, with a resultant wavelength modulation amplitude of ± 0.3 nm. The laser emission is passed via a fibre-optic circulator to the sensor head. The returning light is guided to the InGaAs photodetector and the resulting interferograms are demodulated in real-time by field programmable gate array (FPGA)-based signal processing hardware. A schematic of the interrogation hardware is shown in Fig. 1(b) along with the interrogation unit in Fig. 1(c).

2.2. GRIN lens sensor probes

The general setup for the compact and cost-effective GRIN lens sensor heads is shown in Fig. 2(a). Here, a fibre pigtail within a flat-polished ferrule provides the reference reflection and an anti-reflection coated GRIN lens forms a collimated beam. In Fig. 2 the interferometric standoff is defined as the effective distance (in air equivalent) including the GRIN lens to the minimum target position, while the physical standoff is the distance from the front of the GRIN lens to the minimum target position. The GRIN lens used has a length of 4.8 mm (air equivalent path length of 7.7 mm), therefore the interferometric standoff is 7.7 mm larger than the physical standoff. As shown in an illustration of the range view of the return signal in Fig. 2(b), in this approach the RRI system is set to evaluate the return signal at a range centred between the minimum and maximum target positions. Here, the target signal can be demodulated over the entire travel range, while contributions from dual-bounce interferometers are suppressed, as the chosen stand-off distance ensures multiple reflections occupy ranges that lie well beyond the evaluation location.

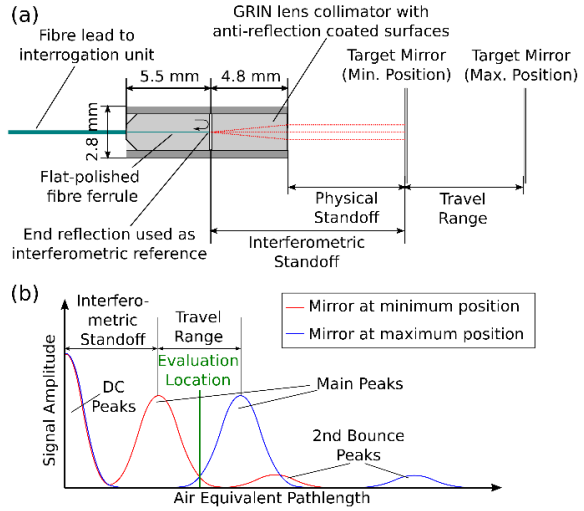

Figure 2. (a) shows an illustration of the sensor head configuration used in this paper, with (b) detailing the range dependencies of the return signal with the target mirror at minimum/maximum positions.

3. Results & Discussion

Fig. 3(a) shows an example displacement measurement where the target stage was set to travel linearly at a velocity of 0.1 mm/s over a distance of 5 mm, on top of a 5 mm standoff distance from the GRIN lens collimator. The insets enlarge the measurement traces at the start and end of the movement, showing that the end point differs from the expected value of 5 mm by ~8 µm, with the most likely causes for errors due to alignment mismatch between the stage and sensor axis or insufficient accuracy on the stage encoder resolution. The noise standard deviation (1σ) observed in this measurement stays below 1.5 nm (over a 10 kHz bandwidth). Fig. 3(b) shows the corresponding signal. During the stage movement, the fluctuations of signal amplitude visible in the insets give an indication of the magnitude of the periodic non-linearities. Fig. 4 further investigates this and plots the normalised Lissajous figures, where the high linearity achievable in this concept is evident from the high circularity exhibited even in the magnified

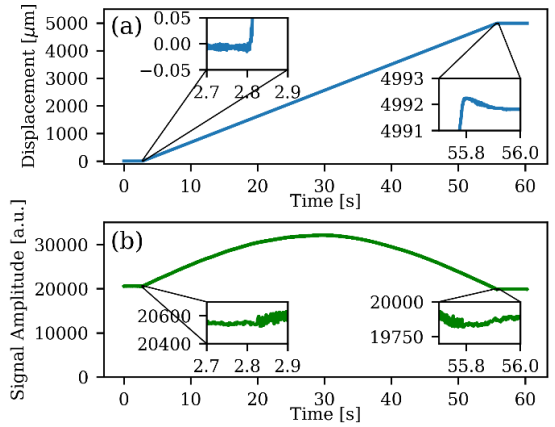

Figure 3. (a) shows a displacement measurement over a 5 mm travel range at a 5 mm stand-off distance, while (b) shows the corresponding signal amplitude registered at the evaluation location.

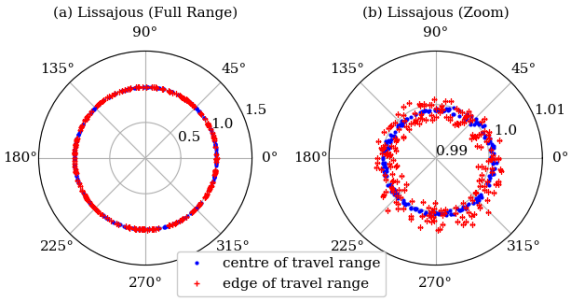

Figure 4. The normalised Lissajous figures is drawn in (a) using two datasets located at the centre and at the edge of the travel range. (b) then shows a magnification for normalised amplitudes from 0.99 to 1.01.

Lissajous plot of Fig. 4(b). More detailed investigations show that periodic non-linearities amplitudes in this measurement vary between 0.1 and 0.2 nm between the centre and the edges of the travel range. This level of periodic errors is already on a par with highly sophisticated interferometric techniques [5], while the use of a Heydemann correction [6] could be explored in the future to further reduce the periodic non-linearities.

4. Conclusions

In this paper we have outlined the benefits of using RRI for interferometric displacement sensors, permitting the use of cost-effective and compact sensor heads even in the presence of multiple reflections. We have demonstrated a sensor capable of 5 mm travel range at 5 mm stand-off distance. In particular the good linearity performance, with periodic non-linearities below <0.2 nm, are a hallmark of the sensing approach and it is thought that the concept could be universally applicable across many high-precision engineering applications.

References

[1] Fleming A J 2013 Sensors Actuators, A: Phys. 190 106–126
[2] Thurner K, Quacqarelli F P, Braun P-F, Dal Savio C and Karrai K 2015 *Appl. Opt.* **54** 3051-3063
[3] Šiaudinytė L, Molnar G, Köning R and Flügge J 2018 *Meas. Sci. Technol.* **29** 054007
[4] Kissinger T, Charrett T O and Tatam R P 2015 *Opt. Exp.* **23** 9415-9431
[5] McRae, T G, Hsu, M T, Freund, C H, Shaddock, D A, Herrmann, J and Gray, M B 2012 *Opt. Lett.* **37**, 2448-2450
[6] Heydemann P L M 1981 *Appl. Opt.* **20** 3382–3384

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