

Simultaneous optical interrogation of multiple tuning fork resonators using range-resolved interferometry

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Abstract— In a proof-of-principle experiment, the vibrations of a set of three tuning fork resonators are simultaneously interrogated along a single optical beam using range-resolved interferometry. Measurements with noise standard deviations in the nm levels over bandwidths of many kHz are possible. In addition, a high degree of environmental noise rejection is inherently achievable because only differential measurements between the vibrating tuning fork prong pairs are evaluated. Employing only highly coherent, robust and cost-effective diode lasers, this approach could be useful for a wide range of mechanical sensor interrogation tasks.

Keywords— *Optical interferometry, Optical sensors, Mechanical sensors, Sensor systems and applications*

I. INTRODUCTION

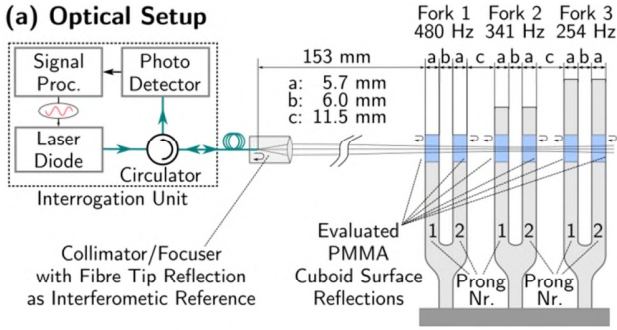
Mechanically resonating sensors, and in particular tuning fork resonators, are widely used across a large number of sensing applications, including photoacoustic spectroscopy [1], scanning probe microscopy [2], atomic force microscopy [3, 4], tip-enhanced Raman spectroscopy [5], fluid viscosity measurements [6, 7] and gyroscopes [8]. In some applications, only the frequency or the Q-factor of the resonance is of interest, while in others the vibration amplitudes are also evaluated. While optical interferometry has been used previously to calibrate [9] and interrogate [10] tuning fork resonators and allows direct non-contact measurement of the vibration frequencies and amplitudes, in most cases the interrogation of tuning fork resonators is performed electrically, using the piezoelectric effect of quartz-based resonators [1-7, 9] or using external capacitive sensors [8]. Here, capacitive sensors require close proximity to the sensor, while piezo-electric interrogation limits the choice of resonator material. In both cases, even if interrogation is electrical, there can still be an additional need for interferometric calibration if vibration amplitudes are to be evaluated.

In this paper, we demonstrate remote optical interrogation of tuning fork resonators along a single optical beam using range-resolved interferometry (RRI) [11] as a new route to optical tuning fork interrogation. RRI uses sinusoidal laser wavelength modulation to allow interferometric phase measurements at multiple spatial locations. This could be used for calibration of otherwise electrically interrogated resonators, or can be used directly for calibration-free remote measurements. We have previously used RRI for multi-surface vibration measurements in optical table-top cryostats [12] and have interrogated chains of fibre segment sensors [13] using this principle. A key advantage of the use of RRI for tuning

fork interrogation is that the differential movements of the prongs can be evaluated directly and, in contrast to interrogation of single prongs, differential measurements are very robust to common-mode vibrations of the whole tuning fork, such as those introduced by environmental noise. Additionally, we demonstrate that RRI can be used to multiplex resonators, allowing direct comparison between several resonators with theoretically lower uncertainties than using multiple individual interrogation systems. It is also worth noting that in RRI, stray signals in the beam path, which could originate from vacuum windows or liquid surfaces, do not affect the measurements if they are out-of-range from the desired signals, simplifying measurement configurations in vacuum or liquid environments. In this work, we implement RRI using highly-coherent (linewidth ~ 1 MHz) yet cost-effective DFB-type laser diodes that are commonly used in the telecoms and gas sensing industries. We typically achieve ~ 50 GHz frequency tuning via injection current modulation with these lasers, leading to minimally detectable range separations on the order of 5 mm in glass. Future implementation of this approach could take advantage of recent developments in highly coherent vertical cavity surface emitting lasers (VCSELs) technology [14], which have demonstrated sub-MHz linewidths, but allow much wider frequency tuning, which would make minimum range separations well below 1 mm feasible using the RRI approach. This would allow interrogation of more widely used tuning forks that have smaller dimensions [1].

II. EXPERIMENT

The optical setup used for this proof-of-principle experiment is illustrated in Fig. 1(a), while Fig. 1(b) shows a photograph of the interrogation unit and the tuning fork assembly. As seen in Fig. 1(a), the interrogation unit consists of an InGaAs photo detector, a fibre optic circulator and an Eblana EP1521-0-DM-B01-FM diode laser emitting at a centre wavelength of ~ 1520 nm. The laser is injection current modulated with a sinusoidal waveform at a frequency of 49 kHz, leading to a maximum resolvable interferometric signal bandwidth of 21 kHz. The RRI signal processing is implemented on an Altera Cyclone-IV field programmable gate array (FPGA), which controls and synchronizes both the laser modulation and the demodulation of the photo detector signals. Light leaving the interrogation unit is guided to an adjustable fibre collimator/focuser. Here the Fresnel reflection at the fibre tip serves as an interferometric reference for the measurement and the collimator/focuser imparts weak



(b) Picture of Interrogation Unit and Setup



Fig. 1. The optical setup is sketched in (a), with the light leaving the interrogation unit guided by a fibre collimator/focuser to and from an arrangement of three different tuning forks that have small PMMA cuboids attached to their prongs, where the PMMA surface reflections that are evaluated are labelled. (b) shows a photograph of the fully-enclosed interrogation unit and the tuning fork arrangement.

focusing on the optical beam to improve resilience against misalignments. As illustrated in Fig. 1(a), the weakly focused beam passes an arrangement of three metal tuning forks, where small transparent Polymethylmethacrylate (PMMA) cuboids of length 5.7 mm along the optical axis are attached to the tuning fork prongs at optical beam height. For each tuning fork, the two outermost Fresnel surface reflection signals are evaluated, as marked in Fig. 1(a). If in future implementations optically transparent materials are used for the tuning forks themselves, then the fork prongs themselves could be interrogated without the need for additional PMMA cuboids.

The range view in Fig. 2, which plots the return signal as a function of the demodulation phase carrier amplitude A_d [11], where A_d is approximately proportional to the optical pathlength from the fibre tip in Fig. 1(a). Fig. 2 shows that the six peaks corresponding to each desired surface reflection can be resolved and labels the values of A_d where interferometric phase evaluation is subsequently carried out. Note that the optical paths in the PMMA cuboids are longer than the geometrical path lengths because of the refractive index of ~ 1.48 . Because the PMMA cuboids were difficult to mutually align during the manual process of the tuning fork assembly, signal levels vary considerably between the individual return signals, as seen in Fig. 2, and overall return signals level are low because the alignment is a compromise between all of the desired reflection signals. In future implementations, with better control of the alignment, signals strengths are expected to be significantly increased.

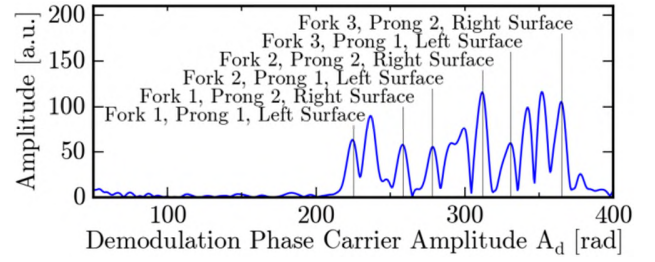


Fig. 2. Plot of the return signal as as function of the demodulation phase carrier amplitude A_d , where A_d is approximately proportional to the range. Those signal peaks that are evaluated in the experiments are marked.

III. RESULTS AND DISCUSSION

Results from the manual excitation of the tuning forks are plotted in Fig. 3, where Fig. 3(a) plots the simultaneously measured interferometric displacement signals from the six evaluated surfaces directly over a period of 20 ms at a data rate of 49 kHz. On close inspection, it can be seen that the two signals corresponding to each fork vibrate in antiphase, with different frequencies and amplitudes for each fork. Fig 3(c) plots the resulting differential vibration signals between the two prongs of each tuning fork, where it can be seen that the three vibration signals from the three forks can be resolved simultaneously with high signal quality and resonance frequencies of 447.7 Hz, 330.7 Hz and 249.6 Hz can be extracted for tuning forks 1, 2 and 3, respectively. These frequency values are below the nominal values stated in Fig. 1(a) because the additional mass of the PMMA cuboids lowers the resonance frequency. Furthermore, noise measurements have been carried out, revealing typical noise standard deviations, over the whole 21 kHz interferometric bandwidth, of 4.7, 4.2 and 5.9 nm in the differential signals of tuning forks 1, 2 and 3 respectively. The current implementation with a laser modulation frequency/data rate of 49 kHz and an interferometric bandwidth of 21 kHz, where the interferometric bandwidth is approximately equal to the maximum interferometric fringe rate that can be, would allow target velocities up to ~ 16 mm/s. For an example tuning fork of 500 Hz resonance frequency, this would equate to permitted vibration amplitudes of up to $5 \mu\text{m}$. Therefore, if larger vibration amplitudes need to be resolved, a higher modulation frequency would be required. We have previously demonstrated modulation frequencies up to 391 kHz [12], leading to maximum target velocities of ~ 140 mm/s.

Figs. 3(b) and (d) illustrate the immunity of the measurements to common-mode environmental disturbances. Here, over an elongated time scale of 0.5 s of the same measurement shown in Figs. 3(a) and (c), Fig. 3(b) again plots the displacement signals from the six evaluated signal sources directly. The disturbance caused by a manual tap of the post that holds the fibre collimator/focuser after 0.07 s introduces a common-mode signal that is visible in Fig. 3(b). Fig. 3(d) subsequently plots the corresponding differential signals, where there is virtually no evidence of the strike signal in the differential vibration signals. This clearly illustrates the high level of immunity to environmental noise that can be achieved for tuning fork resonators through the direct evaluation of the differential prong vibrations.

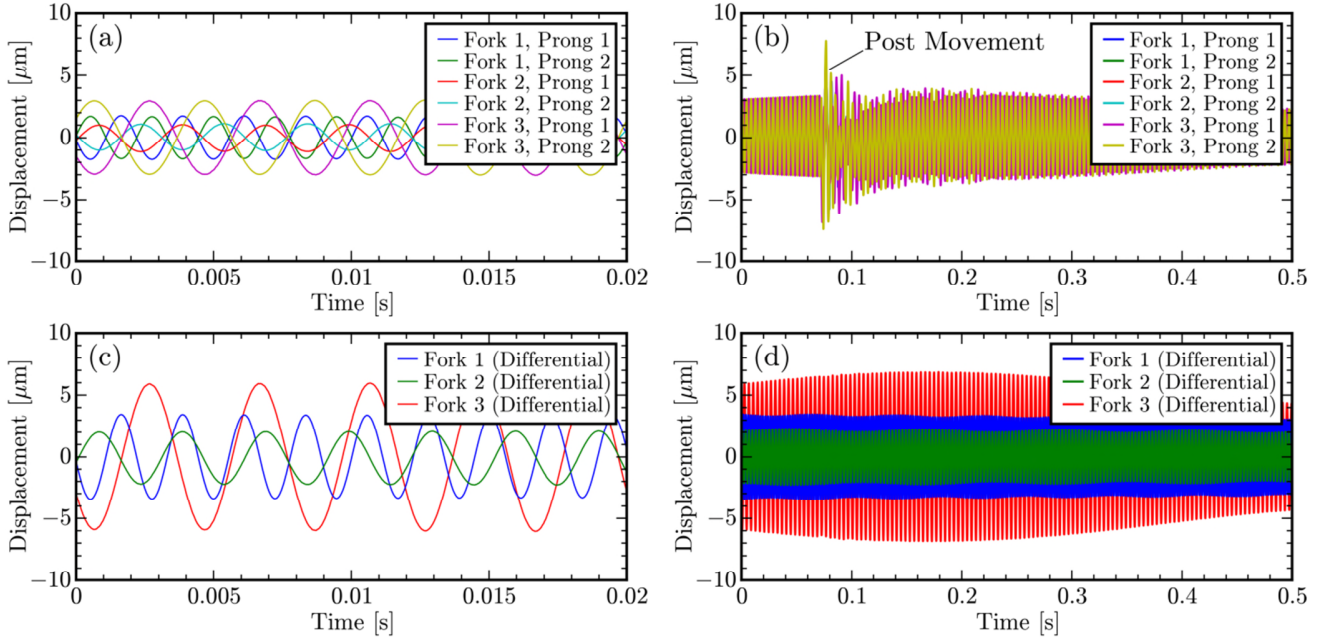


Fig. 3. Plots of tuning fork vibration measurements, where (a) shows the six prong signals that are directly measured, while (c) then plots the resulting differential signals for the three forks. (b) plots the same six signals as (a), over an extended time period of 0.5 s, where the fibre collimator post was tapped at the marked instant, introducing common-mode signals that can be seen to be nearly completely absent in the differential signals shown in (d).

IV. CONCLUSIONS

A novel optical interferometric method to interrogate one or multiple tuning fork resonators simultaneously was demonstrated in a proof-of-principle experiment, where the desired differential vibrations between the tuning forks prong pairs were evaluated directly. Measurements over an interferometric bandwidth of 21 kHz clearly show that the differential vibrations of the three tuning forks could be simultaneously acquired with instantaneous noise standard deviations below 6 nm. Furthermore, it was demonstrated that the evaluation of differential vibrations leads to a high degree of immunity to environmental common-mode vibrations.

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