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Characterisation of a cryostat using simultaneous, single-beam multiple-surface laser vibrometry

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Abstract. A novel range-resolved interferometric signal processing technique that uses sinusoidal optical frequency modulation is applied to multi-surface vibrometry, demonstrating simultaneous optical measurements of vibrations on two surfaces using a single, collimated laser beam, with a minimum permissible distance of 3.5 cm between surfaces. The current system, using a cost-effective laser diode and a fibre-coupled, downlead insensitive setup, allows an interferometric fringe rate of up to 180 kHz to be resolved with typical displacement noise levels of $8 \text{ pm} \cdot \text{Hz}^{-0.5}$. In this paper, the system is applied to vibrometry measurements of a table-top cryostat, with concurrent measurements of the optical window and the sample holder target inside. This allows the separation of common-mode vibrations of the whole cryostat from differential vibrations between the window and the target, allowing any resonances to be identified.

INTRODUCTION

Using a recently developed signal processing technique¹ we present the simultaneous optical measurements of vibration on two surfaces using a single, collimated laser beam. This is used to characterise the vibrations of a commercial table-top cryostat system² (OptistatDry) produced by Oxford Instruments Nanoscience. Here, the first signal is provided by the Fresnel reflection from the window of a vacuum chamber of the cryostat, while the second signal is reflected off the target inside the chamber. In this application, the piston-driven coldhead of the cryostat introduces vibrations and it is important to simultaneously characterise, along a single measurement axis, both the movements of the chamber itself and the additional vibrations of the target, distinguishing any common-mode and differential movements between the two. This information was of particular interest and great benefit during the development phases of the product, allowing the identification of the origin of vibrations and resonances.

The signal processing technique is based on optical frequency modulation by sinusoidal injection current modulation of a cost-effective, continuous-wave monolithic diode laser. Vibrometry using frequency modulated laser diodes has been presented before³ and offers stable, downlead-insensitive vibration measurements using a compact sensor head consisting solely of a simple fibre collimator. However, previous systems could only resolve the signal from a single surface and furthermore required precise control of the laser modulation amplitude to match the given stand-off distance. In contrast, the presented range-resolved approach allows return signals from multiple surfaces to be evaluated simultaneously, with ranges continuously variable, subject to a minimum spatial separation. In this demonstration, the minimum spatial distance between sources is approximately 3.5 cm, where the spatial resolution is a property of the optical frequency modulation characteristics of the laser diode and could be improved in the future using more widely tunable laser diodes. Also, as long as the minimum separation between sources is maintained there is no need to control the modulation amplitude when geometrical parameters change, making the system considerably more flexible in practical use.

The multi-surface measurement capability of the system allows it to perform differential vibration measurements. In commercial differential vibrometers^{4,5} light from two spatially offset beams interferes in a

heterodyne system. Applications for differential vibrometers include the measurement of small differential vibrations in the presence of large common-mode vibrations. However, disadvantages of commercial systems are that they can yield only differential vibration data, whilst the common-mode vibration information is lost and that the measurements must be taken at spatially offset locations. In contrast, in the self-referencing multi-surface vibrometry system that is presented here, a single delivery beam is employed and range-resolved interferometric signal processing is used to separate the return signals based on their range. The presence of multiple surface reflections in the return beam permits the individual measurement of the movement of each surface, which allows both differential and common-mode vibration signals to be calculated. However, range-resolved techniques can have advantages even when only a single surface is to be interrogated, as the influence of undesired signals, such as window reflections⁶, can be suppressed. In addition to the approach proposed here, range-resolved vibrometry⁷ has also recently been demonstrated using an optical frequency comb technique. However, this demonstration uses very complex optical equipment and only allows the selection of the range of a single location along the optical beam at any point in time. Thus, unlike the technique presented here; it is not capable of simultaneous multi-surface vibrometry.

SETUP

Figure 1 shows the experimental setup, consisting of a laser diode, circulator and photo detector connected using regular single-mode fibre. The laser diode is a cost-effective continuous-wave DFB-type laser operating at a wavelength of $\lambda=1551$ nm. The injection current of the laser is modulated sinusoidally at frequency, f_m , yielding a corresponding optical frequency modulation. As described previously in detail^{1,8}, for interferometers of non-zero optical path difference (OPD) this results in a characteristic interference signal that can be evaluated using a smooth, Gaussian window function and a time-variant carrier that resembles the complex version of the photo detector signal expected for the desired range. Furthermore, in this technique, the laser intensity modulation normally associated with injection current tuning as well as non-linearities in the sinusoidal frequency modulation can be corrected straightforwardly. The signal processing exploits low-cost field programmable gate array (FPGA)-based processing (Altera Cyclone IV) and all modulation and demodulation is carried out synchronously at a digital sample rate of 150 MHz. As seen in Fig. 1, in this approach the interferometric reference is taken from the fibre tip Fresnel reflection, providing an extremely simple, self-referencing configuration with complete down-lead insensitivity, and allowing a very compact measurement head comprising only of a packaged fibre collimator.

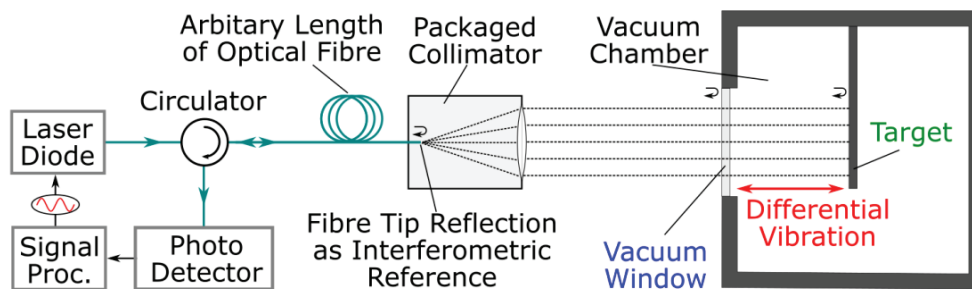


FIGURE 1. Illustration of the setup and a typical measurement configuration, where sinusoidally frequency modulated light from a laser diode is guided by a single-mode optical fibre lead that can be of arbitrary length to a packaged collimator, which then collects light reflected from the vacuum window and the reflective target surface. This light, along with the interferometric reference provided by the fibre tip, reaches the photo detector and the resulting interference signals are demodulated.

A picture of the cryostat is shown in Fig. 2(a), while a typical physical measurement arrangement is shown in Fig. 2(b), illustrating a measurement in the X-direction. For the measurement in the Z-direction, the kinematic mount was lowered close to the surface of the optical table and a 45° prism was inserted under the cryostat to direct the light upwards through the bottom window of the cryostat. In all measurements, the first measurement surface is the vacuum window, while the second measurement surface is the sample holder target inside the cryostat. The measurements shown later were obtained using reflective tape attached to the target, but successful measurements have also been obtained from the unpolished copper surface of the sample holder. In general, in a collimated measurement configuration, return signal powers are lower than for a focused configuration. Also, a collimated

beam will result in a higher angular sensitivity than a focused beam. Therefore all measurement surfaces in the setup need to be parallel to each other and the optical axis needs to be aligned using a kinematic mount to achieve perpendicularity to the measurement surfaces. In general, however, the optical configuration is of no relevance to the signal processing, as long as sufficient return power is received. For possible future applications in vibrometry of single surfaces, a focused configuration, commonly used in other vibrometry approaches, offering higher angular tolerances and providing stronger returned signals, could equally be used.

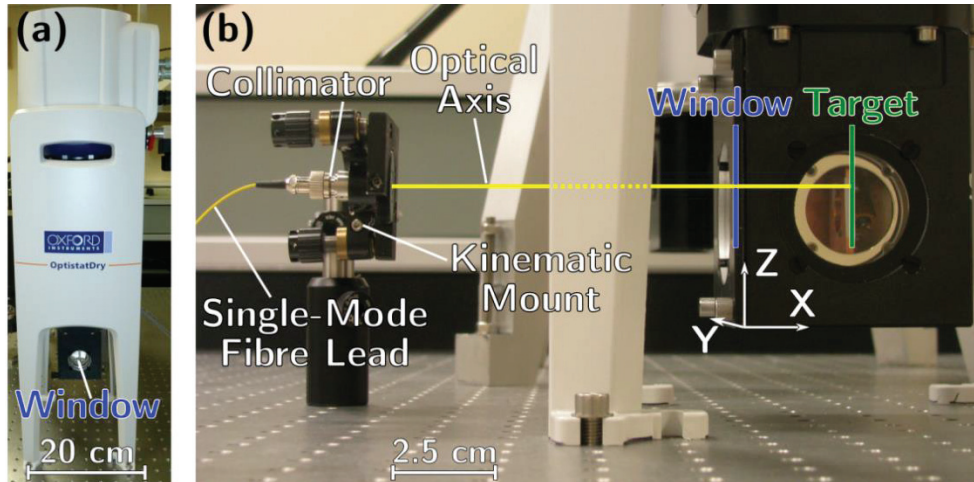


FIGURE 2. A picture of the whole cryostat is shown in (a), while (b) shows an annotated picture of a typical physical measurement arrangement in the X-direction. In (b), light leaving the single-mode fibre lead and packaged collimator is directed to the vacuum chamber window and the sample holder target inside the cryostat, with perpendicular alignment to the measurement surfaces achieved using the kinematic mount.

In the current implementation, the sinusoidal modulation frequency is $f_m = 391$ kHz, allowing an unambiguous interferometric fringe rate of 180 kHz, which is slightly lower than the theoretical value of $0.5f_m$ due to the necessary low-pass filtering in the FPGA. This corresponds to a maximum resolvable velocity of 0.14 ms^{-1} . This could be improved through the use of a higher modulation frequency f_m in future implementations. A typical photo detector signal over one modulation period resulting from this arrangement, which also displays some of the undesired influences, such as intensity modulation, is plotted in Fig. 3(a). After demodulation in the prescribed way^{1,8}, the range dependence of the return signals can be calculated, with the corresponding range dependence shown in Fig. 3(b). Here, the two peaks that originate from the vacuum window and the target can be identified clearly.

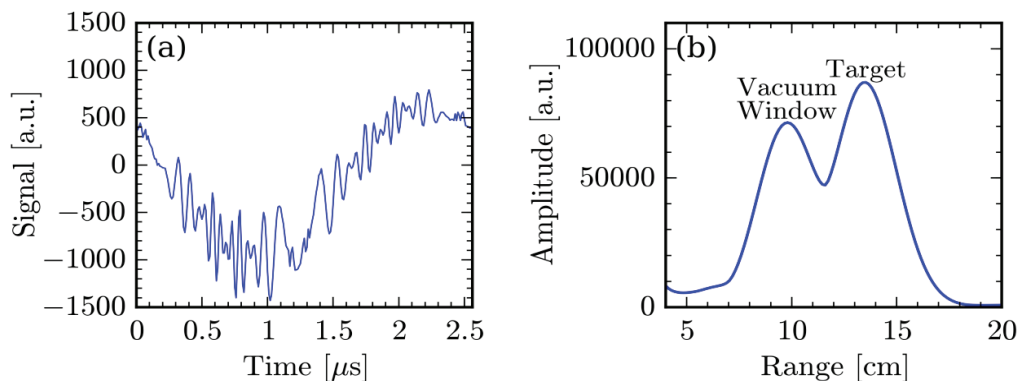


FIGURE 3. (a) shows a captured photo detector signal over one modulation period, while (b) plots the return signals after demodulation as a function of range, with the peaks labelled according to the originating signal source.

With the current parameters of the implementation, the full-width half maximum (FWHM) width of the peaks in Fig. 3(b) is 3.5 cm. Therefore, the minimally permissible distance between signal sources where no significant crosstalk will be present, as well as the initial stand-off distance from the fibre-tip, is also approximately 3.5 cm. This property is inversely proportional to the peak frequency excursion of the laser. In this work, the thickness of the window of the vacuum chamber is much smaller than the minimum resolvable spatial separation between sources. Therefore the phasor sum of the Fresnel reflections of both window surfaces is effectively measured and taken as the window signal, which does not pose any problems as long as the window thickness remains constant.

RESULTS

Figure 4 shows example measurements plotting the directly measured signals from the vacuum window and the target together with the numerically computed differential vibration signal, where Fig. 4(a) shows measurements in the X-direction and Fig. 4(b) shows measurements in the Z-direction. In the example measurement in the X-direction in Fig. 4(a), one period of a low-frequency vibration of 6 Hz that is common to both window and target, and therefore does not show up in the differential signal, can be observed. This indicates that for this frequency the whole vacuum chamber, including the target, moves as a rigid unit. In contrast, the window and the target vibrate in anti-phase for the 95 Hz high-frequency signal visible, and the differential signal amplitude is larger than both individual components for this frequency. This indicates a resonant behaviour, where the resonance can be seen to increase and then decrease over the 0.2 s interval plotted in Fig. 4(a). This clearly contrasts with the measurements in Z-direction, where the difference signal in Fig. 4(b) reveals a complete absence of any high-frequency resonances, even in the presence of large common-mode vibrations of approximate 16 Hz. Therefore it appears that for high-frequency excitations the system is very stiff in the Z-direction. However, it can be observed in Fig. 4(b) that there are slow changes in the difference signal at both ends of the 0.2 s interval. It can then be seen in Fig. 5, where the Z-direction signal is plotted over an extended period of 6 s, that the difference signal carries a contribution at 1 Hz with an amplitude of $\approx 8 \mu\text{m}$, which can be traced to the coldhead piston movement occurring at that frequency.

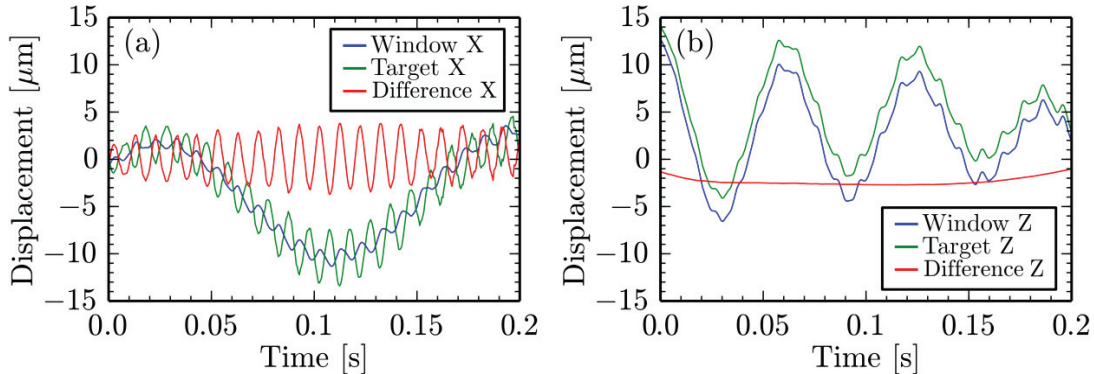


FIGURE 4. Typical signals over 0.2s are shown in (a) for the X-direction and in (b) for the Z-direction. Here, the directly measured signals of the window and target are plotted together with the numerically computed difference signals.

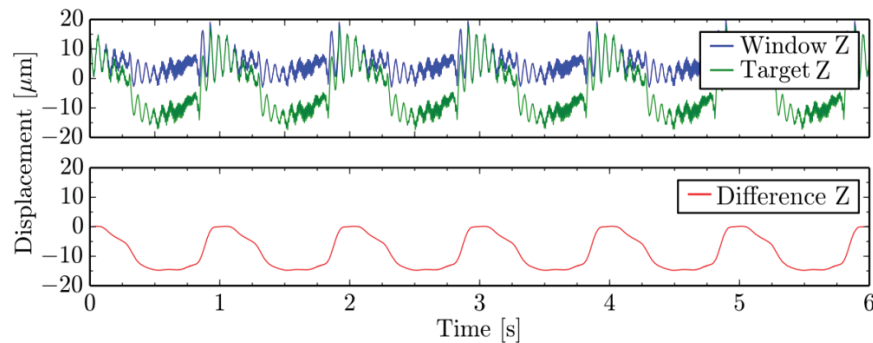


FIGURE 5. Typical signals over 6s in the Z-direction. The upper traces show the directly measured window and target signals, while the lower trace plots the numerically computed difference signal.

DISCUSSION

The results shown in Figs. 4 and 5 demonstrate clearly the novel capabilities that the technique offers, with multiple surfaces measured simultaneously using a single optical beam. This provides valuable insight into the origin of vibrations, allowing, for example, the identification of mechanical resonances within systems.

This implementation achieved noise levels of $\approx 8 \text{ pm} \cdot \text{Hz}^{-0.5}$ over a typical stand-off distance of 10 cm, where noise in this technique is mainly limited by laser phase noise that is proportional to the OPD. This is significantly higher than noise levels in typical commercial vibrometers⁹, of $0.05 \text{ pm} \cdot \text{Hz}^{-0.5}$, using low-noise helium-neon lasers and allowing operation in an OPD-balanced setups. However, it is thought that there are many applications where the instrumental displacement noise is not the limiting factor. Instead, the possibility of suppressing environmental noise¹⁰ by local referencing of the measurement could be a much more important practical advantage. The ability of this approach to perform common-mode vibration suppression was demonstrated by the measurements presented in this paper, where common-mode movements of the cryostat are suppressed to a high degree in the differential signal, as particularly evident in Fig. 4(b).

In addition to offering these novel measurement capabilities, the low complexity and high stability of the system are compelling advantages that could make this approach interesting for permanently installed vibration sensors, even if only a single surface is evaluated, and may also make it a suitable candidate for further miniaturization in integrated photonic circuits. It is thought that the demonstrated interferometric fringe rate of 180 kHz, which could also be improved through faster modulation, should be sufficient for many applications of permanently installed vibration sensors.

CONCLUSION

In this paper, a recently developed range-resolved interferometric signal processing technique based on sinusoidal optical frequency modulation has been applied to single-beam, multi-surface vibrometry. Using a simple fibre-coupled optical setup and measurement head with complete down-lead insensitivity, simultaneous measurements of the vacuum window and the sample holder target inside an industrial table-top cryostat have been obtained. Vibration measurements with typical displacement noise levels of $8 \text{ pm} \cdot \text{Hz}^{-0.5}$ have been demonstrated, with an interferometric quadrature bandwidth of 180 kHz. These results highlight the ability of the approach to separate common-mode vibrations of the whole cryostat from differential vibrations between the target and the window, highlighting its benefits in identifying mechanical resonances. Further applications are envisaged in areas where the cost-effectiveness and robustness of the setup would allow permanently installed vibration or displacement sensors to be used, possibly within integrated photonics circuits, or where local referencing, using a window close to the target, would improve suppression of environmental noise.

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