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The use of ranged-resolved interferometry for multi-parameter sensing in a wind tunnel

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ABSTRACT

The work presented demonstrates that key parameters in aerodynamic structural characterisation of pressure, strain, and structural dynamics, can be all measured via optical fibre sensors interrogated using the principles of range-resolved interferometry (RRI). When used to interrogate sensors simultaneously deployed on a high lift wind in a wind tunnel, the approach yielded resolutions of 31 μPa/$\sqrt{Hz}$ and 1 nϵ/$\sqrt{Hz}$ at a bandwidth of 1526 Hz for pressure and strain, respectively, demonstrating the accuracy and versatility of the RRI signal processing technique.

Keywords: Range-resolved interferometry, Wind tunnel, Optical fibre sensors, Strain, Pressure

1. INTRODUCTION

The knowledge of pressure, strain, and structural frequencies of a wing element during a wind tunnel trial are of vital importance for its characterisation.[1] These parameters would typically be assessed through the installation of electronic pressure transducers, resistive foil strain gauges, and accelerometers on the test structure.[1,2] Although these approaches yield accurate data, the number of sensors that can be utilised is restricted by the necessity for numerous wire looms running through the wing. Non-contact methods such as pressure sensitive paint, digital image correlation and laser vibrometry avoid this issue, however, each measurement campaign requires its own interrogation instrumentation, adding further complexity and cost.

Optical fibre sensors offer a solution to the problem of bulky wiring looms, since it is possible to multiplex strain sensors on a single optical fibre. In addition, optical fibres can facilitate the deployment of extrinsic approaches to the measurement of vibration and pressure. Typically, the sensors for these parameters would be interrogated using different approaches. Range-resolved interferometry (RRI) is a technique that can derive phase information from multiplexed optical fibre interferometers, based on their effective optical path length at kHz data rates, while maintaining high linearity.[3,4] Since this signal processing technique can identify individual interferometers from an interferogram of multiple optical cavities, it can therefore be used for interrogating different interferometer designs that are adapted for measuring specific physical parameters.[4,5] Recent work[6] has shown that this processing technique is a reliable, robust approach and would be suited for use in a wind tunnel environment. In this paper, we show that the key parameters of pressure, strain, and vibrational frequency can all be measured on a high-lift wing during a wind tunnel trial, via optical fibre-based sensors, using only the signal processing technique of RRI.

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2. EXPERIMENTAL METHODS

2.1 Signal processing

Interrogation was performed using a DFB laser diode, subject to a sinusoidal injection current modulation at a frequency of 24.4 kHz, producing a wavelength modulation amplitude of ±300 pm around a centre wavelength of 1521 nm. The returning interferometric signal was acquired with an InGaAs photodiode, converted to a digital signal with a 12-bit A-D converter. The RRI signal processing was accomplished via use of a FPGA, yielding a relative phase measurement, downsampled to a data rate of 1526 Hz.[3] Due to the limited number of input channels on the available interrogators, each measured parameter (pressure, strain, vibration) was assessed with separate units but using the same underlying signal processing technique as previously described. In principle however, since the modulation parameters are comparable, these could be combined into one unit with sufficient input channels, using only a single laser source.

2.2 Wing model and wind tunnel trial

The optical sensors were installed in a 2-dimensional, 3-part high-lift wing configuration. This comprised of a carbon-fibre slotted leading edge slat (1.4 m x 0.13 m), a wooden main element (1.4 m x 0.6 m), and a single slotted carbon-fibre trailing flap (1.4 m x 0.18 m). The model was installed vertically, at an angle of attack of 16°, between two end-plates in the working section of the 2.4 x 1.8 m wind tunnel facility at Cranfield University, where flow velocities between 5 – 50 m/s are achievable.

The wind tunnel trial consisted of a single ramp-up in wind speed from 0 – 40 m/s, with the speed held at 40 m/s for approximately 30 s before being ramped down to 0 m/s, with a single run taking a total of 300 s to complete. All interrogation equipment was located in the wind tunnel control room, directly adjacent to the wind tunnel's working section. Optical and electrical leads were passed out of the wind tunnel through the strut that held the wing model and fed into the control room.

2.3 Optical pressure, strain, and vibration sensors

The optical pressure sensor was based on an external Fabry-Perot cavity that was constructed using a D-shaped castellated cylindrical ceramic ferrule, with the optical fibre glued inside and a reference pressure tap attached

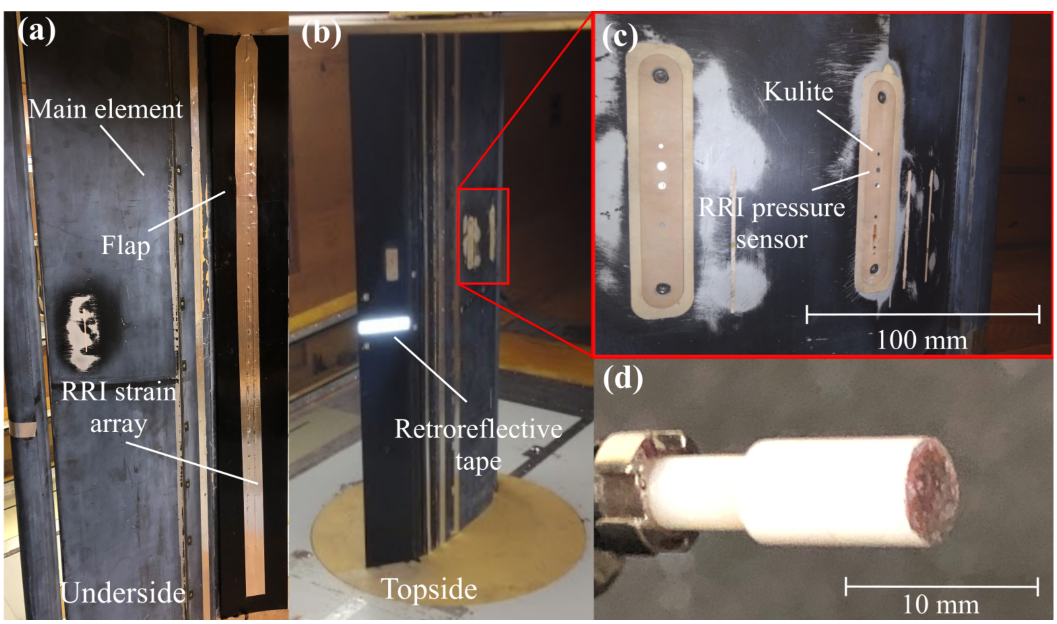

Figure 1. Images of the high-lift wing installed in Cranfield University's 2.4 x 1.8 m wind tunnel highlighting the fibre strain array on the underside of the flap (a), the location of the retroreflective tape and pressure sensors on the topside (b), a more detailed view of the embedded pressure sensors (c), and an image of the RRI interrogated Fabry-Perot pressure sensor (d)

to the flat of the ferrule. This was fitted inside a ceramic sleeve that had an aluminium diaphragm of 30 µm thickness attached creating a gap of approximately 500 μm between the ferrule and diaphragm (Figure 1d). The optical cavity interrogated was formed by using a low-reflectivity, broadband, fibre Bragg grating (LRFBG) as a reflector (length 250 μm, reflectivity 0.01%, bandwidth 5 nm), which was inscribed in the downlead of the optical fibre, 10.5 mm from the diaphragm. Following calibration, the sensor was found to have a sensitivity factor of 1.755×10^{-3} rad/Pa. A Kulite pressure transducer was installed in the main element, adjacent to the optical pressure sensor, to provide a 'gold-standard' comparison with the optical pressure sensor (Figure 1c). The Kulite had a linear sensitivity of 1.343x10-4 V/Pa and was interrogated using an external high speed DAQ card (National Instruments) using an in-house Python script at a data rate of 10 kHz that was downsampled to 1526 Hz to match the RRI approach. The optical pressure sensor and Kulite were installed in a Necuron block, located in a recess of the main element 100 mm from the leading edge and 560 mm spanwise from the top-endplate.

To form the strain sensing array, 11 reflectors, with an 80 mm separation, were created by fabricating LRFBGs in hydrogen-loaded SMF28, forming 10 interferometric segments. The distal end of the fibre was cleaved 40 mm from the final LRFBG, providing a reference reflector to generate a unique optical path length for each segment. Strain, ϵ, was derived from the relative phase change of each segment using a sensitivity factor of 1.34 $\mu\epsilon$/rad, determined by the interrogation wavelength and segment length as described in.[5] The sensor was attached to the underside of the carbon-fibre flap using cyanoacrylate, 95 mm chordwise from the leading edge, where the first and last segments were both 300 mm from the span-wise edges. Aluminium tape (3M) was used to protect the optical fibre (Figure 1a). Both the RRI pressure sensor and the strain sensor were not temperature compensated.

To monitor the vibrations of the wing model, the output from an interrogation unit was fibre coupled to a collimating/focussing lens which was housed in a post structure attached to a stable, small optical breadboard in the control room. The collimated beam illuminated a piece of retroreflective tape positioned, spanwise, in the centre of the flap (Figure 1b). The Fresnel reflection from the collimating lens provided the reference reflection for the measurement.

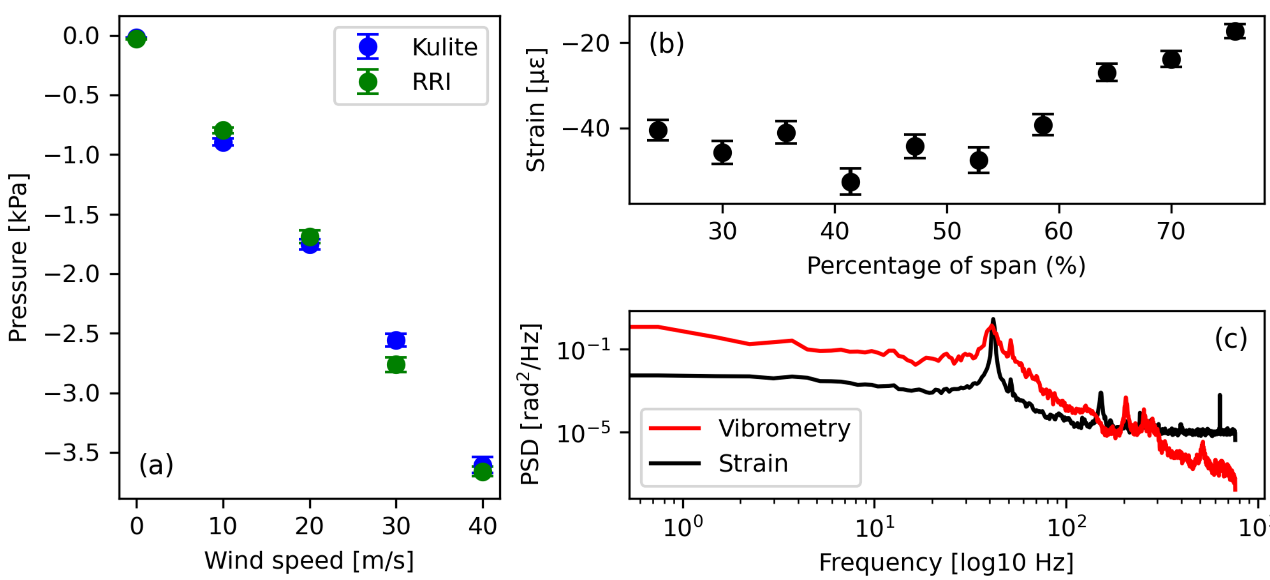

Figure 2. Plots from the ramped wind tunnel test for the measured parameters where (a) shows a comparison between the RRI interrogated optical pressure sensor and Kulite at set wind speeds, (b) the strain distribution for the centre of each segment on the flap at a wind speed of 40 m/s (b), and (c) the frequency analysis from strain and vibrometry data on the flap at 48% span for a wind speed of 40 m/s. All error bars are one standard deviation

3. RESULTS AND DISCUSSION

Figure 2a compares the responses of the RRI interrogated pressure sensor and the electrical sensor, revealing a good agreement between the two devices, where the difference in recorded mean pressures is to within 2% of full scale. The results in Figure 2a also illustrate the expected reduction in pressure with increasing wind tunnel speed on the suction side of the aerofoil. Additionally, the standard deviation of both devices also increases with correspondingly greater wind speeds. This effect is consistent with increases in turbulent flow adjacent to the sensors. The resolution of the RRI pressure sensor was calculated to be 31 μPa/$\sqrt{Hz}$.

The strain distribution measured by the optical strain sensors can be seen in Figure 2b, where the greatest strain, as expected, is located around the centre of the flap. The standard deviation of the strain recorded when there was no flow velocity in the working section was 0.1 $\mu\epsilon$ (data not shown), significantly lower than the values indicated by the error bars in Figure 2b. This variance derives from the oscillation of the flap caused by the turbulent flow shed by the main element. The error from a flow velocity of 0 m/s yields a resolution of 1 n$\epsilon/\sqrt{Hz}$. Additionally, Figure 2b shows that there is a clear asymmetry in the strain distribution, most likely due to the differences in torque applied to the bolts in the end-plates.

A comparison of the spectral frequency content of the phase data obtained from the strain sensor at 48% span and from the vibrometer is plotted in Figure 2c. The flap's structural frequency at 42 Hz can be clearly seen in both the strain sensor and the vibrometry analysis. Although there is a good correlation between the two spectral analysis, the differences are suspected to arise from off-axis deflections.

4. CONCLUSION

We have shown that the signal processing technique of RRI can demodulate relative phase measurements from optical fibre-based pressure, strain, vibrometery sensing approaches. This approach yields pressure and strain resolutions of 31 μPa/$\sqrt{Hz}$ and 1 n$\epsilon/\sqrt{Hz}$, respectively, with mean pressures within 2% of full-scale to that of the Kulite. Additionally, key frequency information related to the flap was also identified using RRI.

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