Dynamic Measurement of Strain and Shape on a Rotating Helicopter Rotor Blade Using Optical Fibre Sensors

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Abstract

Fibre Bragg grating (FBG) and interferometric direct fibre-optic shape sensing (DFOSS) instrumentation were deployed on helicopter rotor blades during a full-speed ground run to provide insights into the blade dynamics. Data were streamed wirelessly from the rotor hub-mounted sensor interrogators. Changes in strain and vibration signatures in response to a series of pilot test inputs were successfully identified and high-resolution blade shape change data has been acquired.

Key words: optical fibre sensors, fibre Bragg gratings, shape sensing, modal analysis, interferometry.

Introduction

Helicopter rotor blades incorporate complex light-weight internal structures to facilitate their operation over a broad flight envelope. With the increasing use of numerical model-based design approaches, there is a need for the development of methodologies for the validation in real flight conditions of the complex aeroelastic models. Instrumentation used in ground vibration testing, including accelerometers and strain gauges, are inappropriate for in-flight use due to the added weight and potential influence of the sensors and the cabling on the blades' aerodynamics and structural dynamics. While imaging approaches have been trialed in wind tunnels and on whirl rigs [1], their in-flight use is hampered by the large observation angle and depth of field required to measure along the entire length of the blade, along with issues related to background light and to the fouling of the blade surface. Optical fibre based approaches have the potential to meet both the measurement requirements and the demands of the measurement environment, with recent reports of flight testing of blades instrumented with optical fibre Bragg gratings (FBGs) [2].

FBGs represent a relatively mature technology, and their use in the ground vibration testing of rotor blades was described in [3], where their sensitivity to the flapping and lagging vibration modes of the blade was a result of the local curvature induced strain and was shown to be dependent on the location of the optical fibre relative to the structure's neutral axis, requiring an appropriate distribution of the sensor elements over the surface of the rotor blade. Direct fibre optic shape sensing (DFOSS) [4], based on the fibre segment interferometry approach [5] deployed in the form of three optical fibres arranged around a thin, flexible plastic former and attached to the surface using adhesive tape, was shown to allow the full characterization of the rotor blade's structural dynamics using a single sensor rod aligned along the axis of the blade [3]. Successful characterization of vibration mode shapes has also recently been achieved. Here the two optical fibre based sensing approaches are deployed on two of the four, 5 m long, bearingless main rotor blades of an Airbus Helicopters H135, with the aim of monitoring blade dynamics and operational mode shapes during a series of full-speed ground runs.

The sensor interrogators were mounted in custom designed hub support cap assemblies, with battery-powered wireless telemetry to a ground station located away from the helicopter. The hub support cap assemblies also included a kill functionality that allowed the pilot, or other protection circuits, to rapidly shut down the system for safety reasons. In addition to monitoring during a track and balancing activity, the sensor performance was assessed as the pilot provided a number of control inputs to the blades with the aim of exciting blade dynamics. A schematic of the ground test arrangement is shown in Fig. 1.

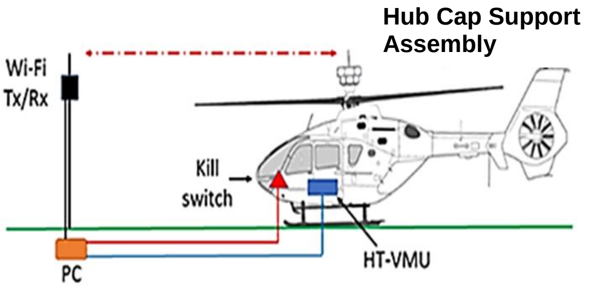


Fig. 1. Ground run configuration. The hub support cap assembly contained the sensor interrogator, battery, and local pc and Wi-Fi router. Data received by the ground station PC was streamed to the vehicle monitoring unit (HT-VMU) over an Ethernet cable

Sensors and Instrumentation

Four FBG sensor arrays, each containing 10 wavelength-division multiplexed FBGs, were fabricated in-house in hydrogen loaded SMF 28 optical fibre, with the sensors distributed along a 2.1 m length of the fibre. Arrays were bonded to the top and bottom surface of two rotor blades using cyanoacrylate adhesive, located 35 mm chordwise from the leading edge, with the final sensor in each array located at approximately 55% of the rotor length. The arrays were interrogated using a 4-channel SmartScan Aero mini interrogator mounted in the hub support cap assembly, running at a data rate of 2.5 kHz.

For DFOSS, arrays of 11 low reflectivity (~10 to 100 ppm) broad bandwidth (FWHM 5nm) FBGs, each of length 250 µm and with adjacent FBGs separated by 190mm, were in 4 optical fibres. These FBGs acted as the reflectors to form an array of low finesse Fabry-Perot cavities, which, together with the Fresnel reflection from the cleaved fibre end, formed the fibre segment interferometers in each fibre. The optical fibres were bonded into slots cut along the 1.2 m length of a D-shaped flexible PLA plastic rod using cyanoacrylate adhesive, with the fibres arranged in a rectangular lattice configuration on the rod. The locations of the reflectors in the fibres along the rod were matched to within 1 mm. The interferometers were interrogated and demodulated using the range resolved interferometry approach [6], which uses the wavelength modulated output from a sinusoidal injection current modulated telecoms DFB laser to produce a carrier signal characteristic of each reflector based on its range. This mechanically robust and simple approach offers high resolution measurement of strain (less than 1 nε/√Hz) over the 33 kHz interferometric bandwidth. The broad optical bandwidth of the low reflectivity FBG reflectors ensured that a reflection was achieved at the laser wavelength irrespective of the strain or temperature experienced by the FBG. Differential measurement of the strains experienced by the segment interferometers in diametrically opposite fibres allowed the sampling of changes in the angle of the rod at the locations of the reflectors, which, by interpolating between these measurement points and integrating along the path, allowed the shape of the rod, and thus the rotor blade, to be determined as described in more detail in [4]. The angular resolution of the measurement at each reflector location was of order 10 nrad/√Hz. In general, DFOSS does not require strain transfer from the object under test to the fibres, but, in this case, the rod was bonded to the surface of the blade using cyanoacrylate adhesive.

The DFOSS sensing rod was attached near the leading edge of the rotor blade, running parallel to the axis of the blade and parallel to the FBG arrays. The DFOSS rod and the FBGs were covered by blade protection tape, which is routinely used to protect the leading edge of the blade from rain droplet induced erosion. A bespoke DFOSS interrogator was constructed, comprising the DFB laser, a network of couplers to allow each array to be monitored by an individual detector, 4 A-D converters and an FPGA to provide the modulation signal and undertake processing of the phase of the returned signals from each interferometer.

Results

Results obtained from one array of FBG sensors mounted on the upper surface of one of the blades are presented in Fig. 2. The data is down-sampled to a rate of 1Hz to allow the effects of the pilot's input to be seen clearly. As the rotor began to rotate (after approximately 50 s), the fibres initially experienced a compressive load as the initially drooping blades rose up to the horizontal. As the rotation rate and centrifugal forces increased, the FBGs experienced tensile strain. The rotors were held at idling speed for approximately 100 s and then increased to full rotation rate. The pilot then manipulated the controls to induce different blade conditions and repeated these three times before returning to idling speed and then running down. The influence of pilot inputs, the stepped collective input, where the pitch angle of all four blades are changed, and the collective doublet input, are visible in the data, for example at 300s and 380s, respectively. Detailed interpretation of the data is beyond the scope of this paper and will be reported in subsequent publications.

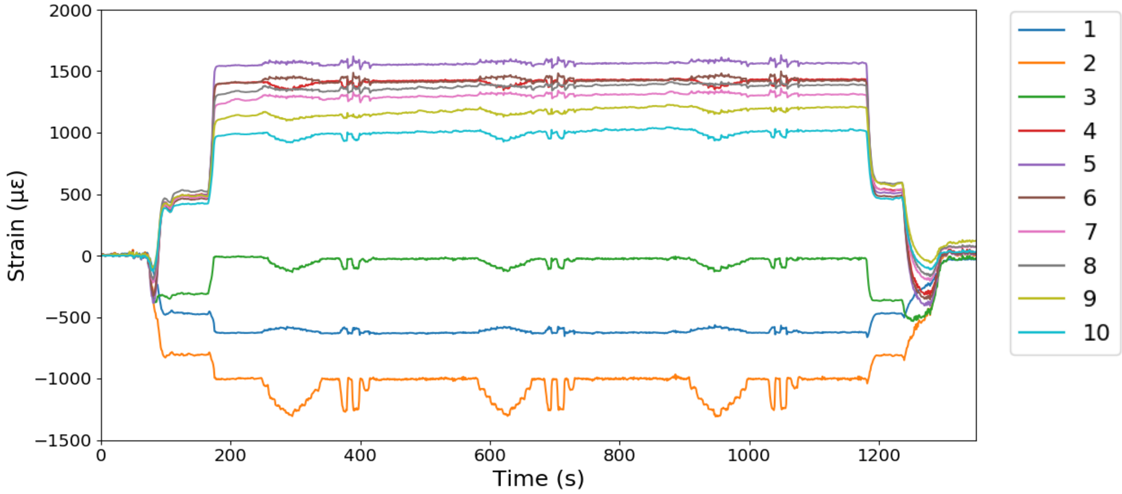


Fig 2. Time-averaged (1s) strain measured by an FBG array bonded to the upper surface of a rotor blade during a ground run on the helicopter. The numbers 1-10 denote the FBGs, with 1 closest to the rotor hub.

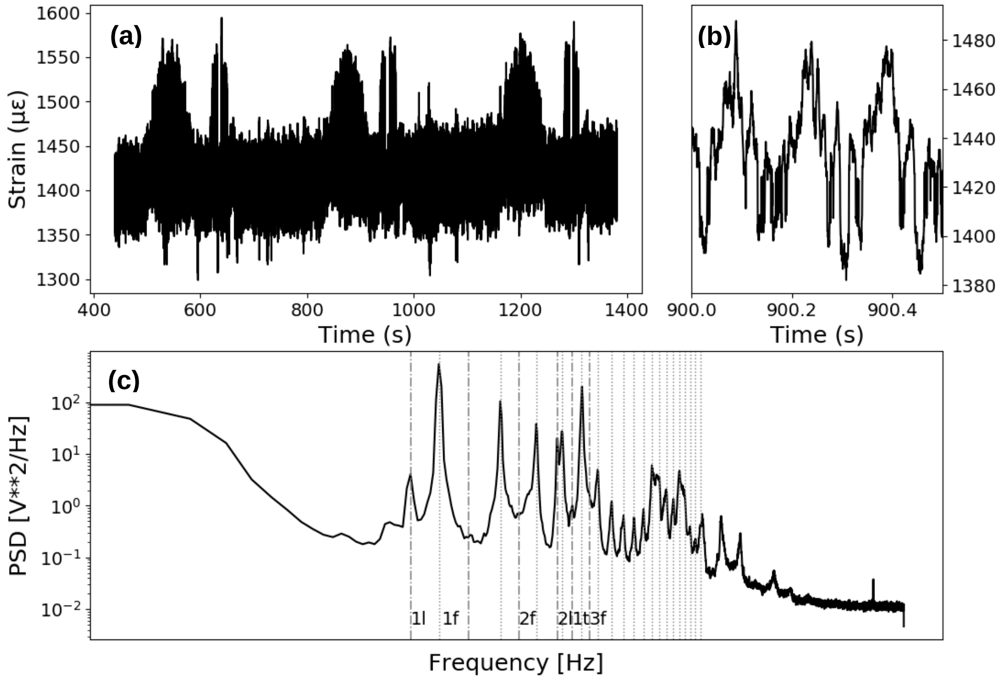
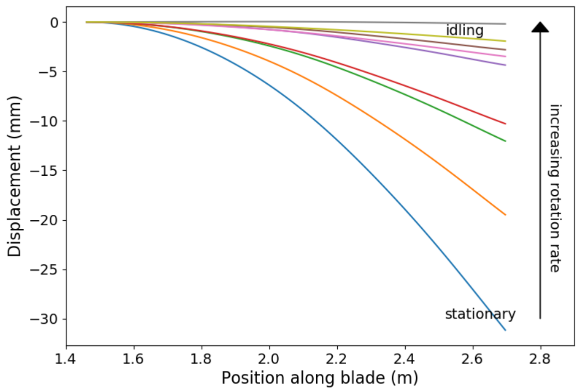


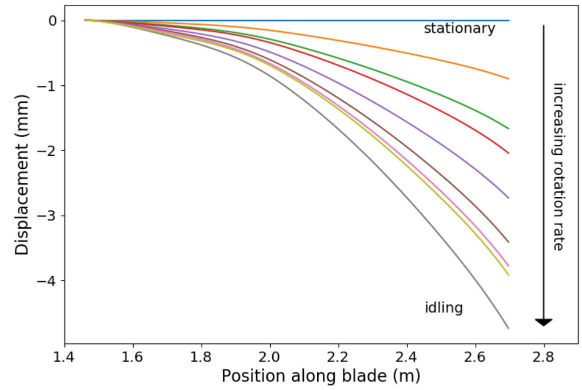
Fig. 3. (a) shows a section of the time series for data recorded from FBG 6, mounted on the upper surface of the blade at 1.76 m from the centre of rotation, while (b) shows a 0.5 s section of the data. (c) shows the power spectral density determined using Welch's method. The dotted lines indicate the rotor frequency harmonics. The dash-dot lines indicate the natural frequencies of the blade: 1l – 1st lagging mode, 1f – 1st flapping mode, 2f – 2nd flapping mode, 2l – 2nd lagging mode, 1t - 1st torsional mode, 3f – 3rd flapping mode.

To illustrate the dynamic information that can be determined, Fig. 3 shows a frequency spectrum calculated from the strain measured by the FBG located 1.76m from the centre of rotation, on the upper surface of the blade. The harmonics of the rotor frequency can be seen, as can the 1st, 2nd and 3rd flapping (out-of-plane) modes, the 1st and 2nd lagging (in-plane, perpendicular to the long axis of the rotor) modes and the 1st torsional mode.

For DFOSS, Figure 4, shows the shape changes determined by the DFOSS sensing system, in the flapping and lagging directions, as the rotor rate was increased from 0 to the idling rate of 5 Hz. For clarity, the shape changes in the vertical direction are referenced to that measured with the blade rotating at approximately 5 Hz. The raising of the blade with increasing rotor rate is clearly observed, the displacement of the blade at the outermost measurement point being 31 mm. Extrapolation



(a)



(b)

Fig.4. Shape changes measured using the DFOSS system in 2-second intervals as the rotor rate was increased from 0 (blue line) to the idling rate of 5 Hz (brown line). Each measurement presented is separated in time by 2 s. (a) Measurements in the flapping (vertical) direction and (b) measurements in the lagging (horizontal) directions. For ease of interpretation, the measurements in the flapping direction are referenced to the blade shape at the highest rotation rate, while those in the lagging direction are referenced to the shape measured with the blade stationary.

to the tip of the blade reveals a tip displacement of 200-300 mm, in line with expectations. Future work will seek to verify this independently in the rotating frame in addition to existing lab-based displacement verification experiments [5]. In the lagging direction, the bending of the blade away from the direction of rotation is clear, with a small kink in curvature data visible at ~1.9 m. The resolution of the measurement of the displacement along the interrogated 1.2 m long blade section is ~40 µm over the 33 kHz interferometric bandwidth.

Summary

Optical fibre sensing systems have been deployed on a helicopter to measure dynamically the strain and shape of the blade during a series of ground runs. Time averaged strain data allows the effect of pilot inputs to control systems to be observed, and the excitation of vibrational modes of the blade by these inputs is being investigated. For the first time, direct fibre-optic measurement of the shape of the blade in the rotating frame has been demonstrated, the analysis of which will allow the aerostatic interactions to be better understood, providing a new tool for the validation of blade designs and potentially for in-service blade condition monitoring.

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