Investigating experimental repeatability and feature consistency in vibration-based SHM using nominally-identical helicopter blades

T.A. Dardeno[1], L.A. Bull[2], R.S. Mills[1], N. Dervilis[1], K. Worden[1]

[1]Dynamics Research Group, Department of Mechanical Engineering,
University of Sheffield, Mappin Street, Sheffield S1 3JD, UK
[2]The Alan Turing Institute, The British Library, London NW1 2DB, UK

email: t.a.dardeno@sheffield.ac.uk

ABSTRACT:
Recent advances in structural health monitoring (SHM) research have improved the safety, reliability, and management of engineering structures; however, the practical implementation and generalisation of SHM technologies have been limited, because of several challenges. Fluctuations in operational and environmental conditions, repeatability issues, and changes in boundary conditions may cause inconsistencies in the captured features (e.g., frequency shifting). These inconsistencies can be problematic for SHM based on machine learning, as healthy states may be flagged as damaged, even when no damage is present, or damaged states may be incorrectly classified as normal variation. The aim of this work is to quantify this variability and evaluate the applicability of SHM when such deviations occur.

In this paper, an experimental campaign is discussed, in which vibration data were collected over a series of tests on a set of four healthy, nominally-identical, full-scale composite helicopter blades. The blades were tested in fixed-free and free-free configurations. For the fixed-free tests, additional variability was introduced by adjusting boundary conditions between each testing repetition. The frequency response functions of the blades are examined to identify changes in natural frequency.

KEY WORDS: repeatability; uncertainty; vibration testing

1 INTRODUCTION

Structural damage is often associated with reduced stiffness. Depending on the location and severity of the damage, and the complexity of the examined mode, this damage may present as a decrease in natural frequency. Increased ambient temperature, loosening of bolts at a support, or similar situations may also reduce stiffness and can mimic damage. These difficulties, related to differentiating between damaged states and normal variations, affect the practical implementation and generalisation of structural health monitoring (SHM) technologies, particularly if a given feature is sensitive to both damage and normal fluctuations [1–4]. Alampalli [2], performed impact modal testing on a small 6.76 x 5.26 metre bridge, before and after damaging the bridge with a saw cut made across the bottom flanges of both the main girders. They found that for temperatures above freezing, the stiffness reduction caused by damage was reflected as a downward shift in natural frequencies (-2% to -11%, depending on the mode), as expected. However, they also found that for temperatures below freezing, the measured frequencies increased significantly, primarily from freezing of accumulated moisture within the supports (+25% to +58%, depending on the mode), which masked the reduction caused by damage.

In addition to environmental/operational variability, difficulties arise when generalising between different but nominally-identical structures. Small discrepancies in the internal structure, material properties, and dimensions of such structures can present as differences in dynamics. Cawley [3], initiated a crack at the fixed end of a cantilever beam and evaluated the natural frequencies as the beam length varied. He found that the change in natural frequency resulting from a cut through 2% of the beam depth was 40 times smaller than that caused by a 2% increase in the beam length [3, 4].

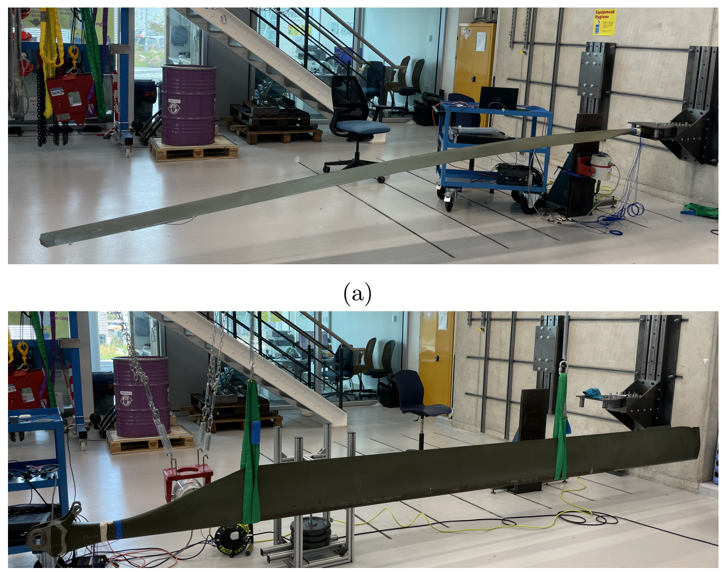
In this work, vibration data were collected over a series of tests on a set of four healthy, nominally-identical, full-scale composite helicopter blades. The blades were tested in fixed-free and free-free configurations. For the fixed-free tests, additional variability was introduced by adjusting the blades within the fixture mount between each testing repetition. This paper discusses how differences among the blades and from one testing repetition to another, present as changes in the frequency response functions (FRFs) of the blades, particularly with respect to the locations of the peaks.

2 EXPERIMENTS

Vibration data were collected at ambient temperature on four healthy, full-scale composite helicopter blades using Siemens PLM LMS software. The blades were nominally-identical (i.e., of the same make and model), and any discrepancies among the blades were the result of manufacturing differences, such as slight variations in material properties and/or geometry. Testing was performed five times on each blade in a fixed-free configuration and once in free-free. To approximate a fixed-free boundary condition, one end of the blade was placed in a substantiated strong-wall mount. Variability was introduced by adjusting the fixture between each testing repetition. The blade was returned to approximately the same position after each fixture adjustment, which consisted of loosening the bolts, adjusting the blade within the wall mount, and tightening the bolts. To approximate a free-free boundary condition, the blade was suspended from a gantry via springs and cables.

Ten uniaxial 100 mV/g accelerometers were placed along the length of the underside of each blade. Note that the same accelerometers were used on each blade, and care was taken to ensure that they were attached to approximately the same locations on each blade. For the fixed-free tests, an electrodynamic shaker with force gauge was mounted to a fixture bolted to the laboratory floor and attached to the blade 0.575 metres from the fixed end. The shaker was attached to the underside of the blade in the flapwise direction. A continuous random excitation was generated in LMS and applied to excite the blade up to 400 Hz. Approximately 7.4 minutes of throughput force and acceleration data were collected for each test, with a time step of 1.25e-03 seconds. The data were then divided into 20 blocks, each with a dimension of 16384. Some data at the start and end of the acquisition were discarded as these data corresponded to powering up and down of the shaker. A Hanning window was applied to each data block and FRFs were computed in LMS. The FRFs were then averaged in the frequency domain. For the free-free tests, the shaker was connected at the same location on the blade as the fixed-free tests, but was suspended from a gantry via springs. A continuous random excitation was generated in LMS and applied to excite the blade up to 512 Hz. Approximately 5.8 minutes of throughput force and acceleration data were collected for each test, with a time step of 9.77e-04 seconds. As with the fixed-free tests, the data were divided into 20 blocks, each with a dimension of 16384, and some data corresponding to powering up/powering down of the shaker were discarded. A Hanning window was applied to each data block and FRFs were computed for each measurement and then averaged in the frequency domain. The measured bandwidths for the fixed-free and free-free tests were selected to maximise the number and accuracy of the captured modes (there was a large dip in the input spectrum just after 400 Hz for the fixed-free tests and just after 512 Hz for the free-free tests). Data were collected over a relatively-long time period for each test and a large number of averages were used to improve the spectra at the lower modes near the limits of the operating range of the sensors. The experimental setup for the fixed-free and free-free tests are shown in Figures 1a and 1b, respectively. The sensor layout is shown in Figure 2. Acquisition parameters are listed in Table 1.

The coherence spectrum and drive-point FRF for Blade 3 in free-free and fixed-free (from the fourth testing repetition) are shown in Figures 3a and 3b, respectively. These spectra are representative of all measurements and show that coherence values were close to 1 at the resonances, with the exception of some difficulty with collecting the first two modes below 10 Hz. This difficulty in acquiring the first few modes resulted in part from the operating frequency range of the accelerometers and the extremely high flexibility of the blades, which limited the shaker placement.



(a)

(b)

Figure 1: Helicopter blade in (a) fixed-free and (b) free-free.

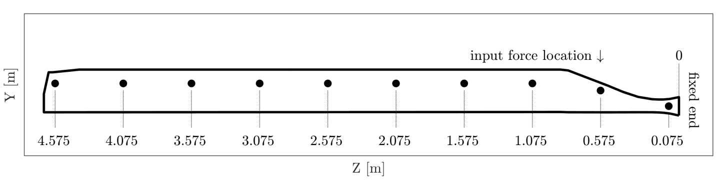


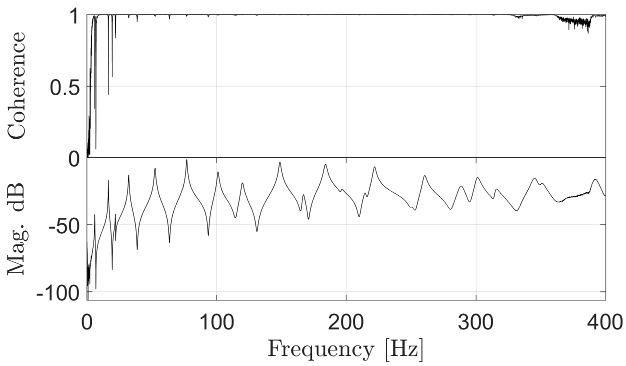
Figure 2: Sensor locations on helicopter blades.

3 RESULTS AND DISCUSSION

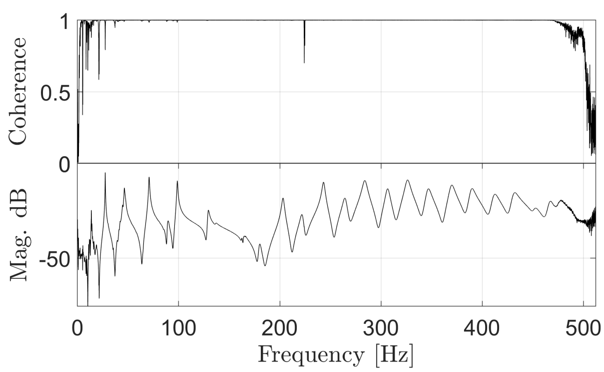
This work is concerned with demonstrating how differences among the nominally-identical blades and from one testing repetition to another, present as changes in the peak positions

Table 1: Acquisition parameters.

Acquisition Settings	Fixed-Free	Free-Free
Time step	1.25e-03 s	9.77e-04 s
Acquisition time	20.48 s	16.00 s
Bandwidth	400 Hz	512 Hz
Lines	8192	8192
Frequency step	4.88e-02 Hz	6.25e-02 Hz
Window	Hanning	Hanning



(a)

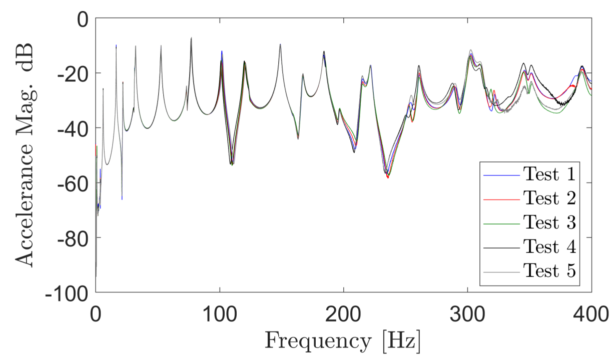


(b)

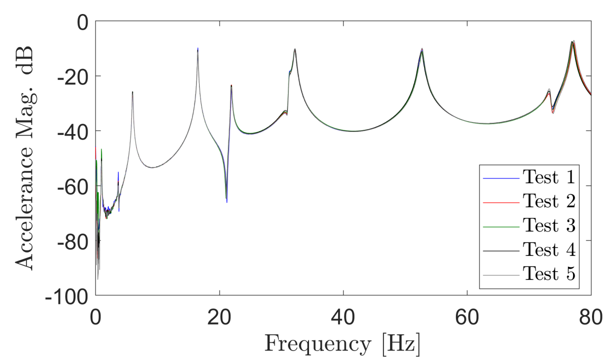
Figure 3: Representative drive-point coherence and FRF from Blade 3 in (a) fixed-free and (b) free-free.

as visible in the FRFs. Vibration testing was performed five times on each of the four blades in fixed-free and once in free-free. Data were collected from 10 accelerometers during each test, giving a total of 240 averaged FRFs. This discussion considers the results from the accelerometer near the blade tip, as the feature changes visible in these spectra are representative of all test points along the blade length.

For the fixed-free tests, variability was introduced via fixture adjustment between each testing repetition, which consisted of loosening the bolts, adjusting the blade within the wall mount, and then tightening the bolts. Care was taken to return the blade to approximately the same position after each fixture adjustment, to avoid discrepancy resulting from shaker misalignment. In addition, because of variation in material properties, dimensions, and internal structure, the helicopter blades were nominally-identical but distinct. These variations resulted in changes in the dynamic characteristics of the blades. The averaged FRF from each testing repetition for Blade 3 in fixed-free are shown in Figures 4a and 4b, with Figure 4a showing the full measured 400 Hz bandwidth and Figure 4b showing only modes below 80 Hz. The averaged FRFs from the fourth testing repetition for each blade in fixed-free are shown in Figures 5a and 5b. Figure 5a shows the full measured 400 Hz bandwidth and Figure 5b shows only modes below 80 Hz. The free-free tests focussed on the discrepancies between blades, rather than the effects of mounting/dismounting. The averaged FRF for each blade in free-free is shown in Figures 6a and 6b, where Figure 6a shows the full measured 512 Hz bandwidth and Figure 6b shows only modes below 80 Hz.



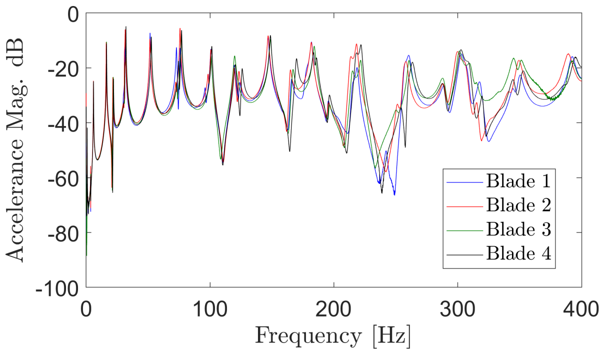
(a)



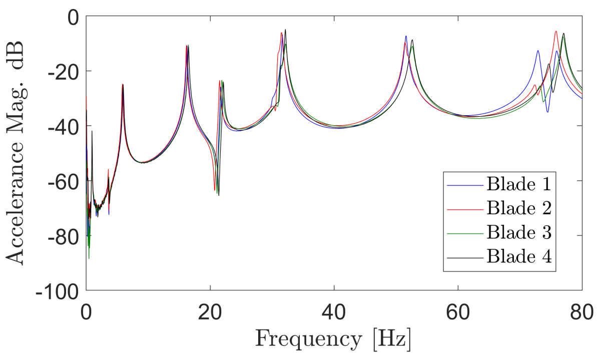
(b)

Figure 4: FRF magnitudes for all repetitions on Blade 3 in fixed-free (a) full bandwidth and (b) first 80 Hz.

Figures 4a and 4b show that the captured FRFs were very consistent between repetitions, with variability only noticeable starting around 80 Hz, and gradually increasing with frequency. These results are expected, as higher-frequency modes are more sensitive to small physical changes than

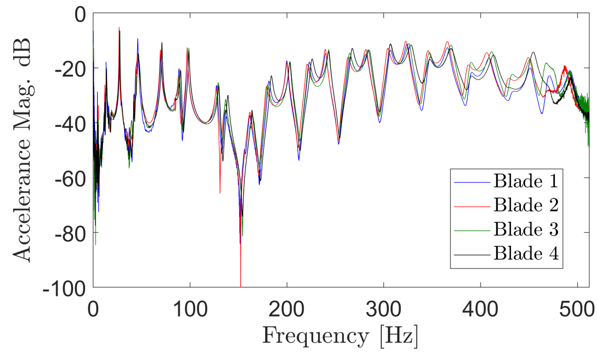


(a)

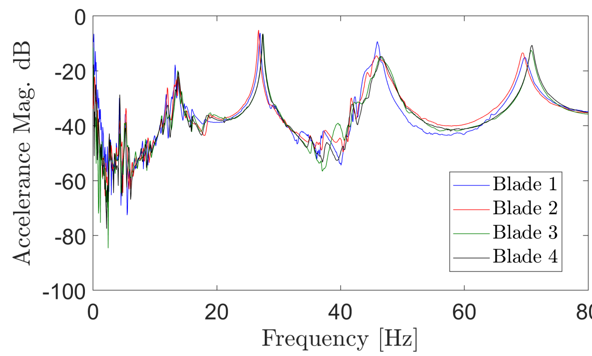


(b)

Figure 5: FRF magnitudes for the fourth repetition on all blades in fixed-free (a) full bandwidth and (b) first 80 Hz.



(a)



(b)

Figure 6: FRF magnitudes for all blades in free-free (a) full bandwidth and (b) first 80 Hz.

lower-frequency modes. For modes less than 80 Hz, the maximum frequency difference among the tests for each blade was less than 0.5 Hz, as obtained via peak-picking. For modes greater than 80 Hz, the maximum frequency difference among the tests for each blade was higher, at approximately 3.2 Hz - also obtained via peak-picking. Figures 5a and 5b also show increasing variability with respect to frequency, but show more discrepancy in the lower modes than resulting from fixture adjustment alone. For modes less than 80 Hz, the maximum frequency difference among the blades was approximately 2.5 Hz, while for modes greater than 80 Hz, the maximum frequency difference was approximately 6.3 Hz. Figures 6a and 6b show similar variation among the blades as the fixed-free tests shown in Figures 4a to 5b. For modes less than 80 Hz, the maximum frequency difference among the blades was approximately 1.6 Hz. For modes greater than 80 Hz, the maximum frequency difference among the blades was approximately 6.8 Hz.

These results demonstrate how the test setup, boundary stiffness, and differences among nominally-identical structures can present as changes in the natural frequencies obtained from vibration testing. These findings are quite relevant for SHM purposes, where a population-based approach to SHM (PBSHM) seeks to transfer valuable information across similar structures. If using these data to develop a normal condition for the blades, this variation could present some interesting problems. For example, if a new blade were added to the population and was slightly less stiff than Blade 2, the new blade may be flagged as damaged when compared to the normal condition developed using the original blades and test results. Figures 5a to 6b show that for many peaks, Blades 1 and 2 appear closely aligned in frequency while Blades 3 and 4 appear closely aligned. These results are particularly noticeable in Figure 5b, between 40 Hz and 60 Hz, and in Figure 6b, between 60 Hz and 80 Hz. Another potential issue would be if Blade 4 experienced some damage that reduced its natural frequency, such that it aligned with the same peak from Blade 1. In this case, the damage may be missed.

To differentiate between normal and damaged states, an important development in PBSHM will involve establishing a normal condition for a population of structures. In certain cases, the behaviour of the group can be represented using a general model, called a *form*, against which new data can be evaluated for novelty [5, 6]. This work has used Gaussian process (GP) regression to model the form for the FRFs of the helicopter blades, as shown in Figure 7. The current progress of this research is detailed in [7].

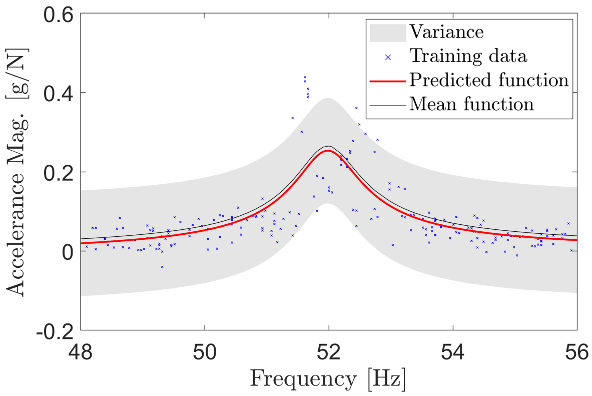


Figure 7: Gaussian process prediction.

4 CONCLUSIONS

In this work, vibration data were collected over a series of tests on a set of four healthy, full-scale composite helicopter blades to demonstrate how the test setup, boundary stiffness, and physical differences among nominally-identical structures can present as changes in natural frequency. Examination of FRFs showed that frequency differences as high as 6.8 Hz occurred among the various tests. These findings are important for the implementation and generalisation of SHM systems that may depend on monitoring the effects of damage-related stiffness reduction. Accounting for normal variations is especially important for PBSHM, which seeks to transfer valuable information, such as normal operating conditions and damage states, across similar structures.

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