INVESTIGATION OF FATIGUE DAMAGE INITIATION AND GROWTH FOR COMPOSITE WIND TUNNEL MODEL PROPELLER BLADES

B.R. Nahuis[1], T.M. Panis[1], M. Hetebrij[1], R.A. Grijpma[1]
[1] Royal Netherlands Aerospace Centre
Anthony Fokkerweg 2 Amsterdam, NL-1059CM
Keywords: Composites, Wind tunnel testing, propeller blades, High Cycle Fatigue testing, Damage initiation, Damage growth

ABSTRACT

In order to understand the results from a high cycle fatigue test of a composite wind tunnel blade, a test campaign was performed with simplified test elements, representative for a typical composite blade. Next to monitoring the frequency drop for a fixed number of cycles as done in traditional high cycle fatigue testing, an alternative approach with a focus on phase response instead of frequency response was also studied. Multiple test elements were tested at different amplitudes, for at least several million cycles. Test elements were inspected after each test with in-house penetrant and ultrasonic C-scan inspection techniques. It can be concluded that using a 3% drop in eigenfrequency as a determination for fatigue initiation is questionable. It is clear that before a 3% drop in eigenfrequency is found, damage is already present in the elements. It was shown that changes in phase can be measured, before a significant change in eigenfrequency can be found.

INTRODUCTION

European Green Deal

As committed to in the European Green Deal, the ambition is to reach net-zero greenhouse gas emissions and enable a climate-neutral aviation system in Europe by 2050. To be able to reduce these emissions, the aircraft fuel efficiency needs to be improved by further optimizing the aircraft aerodynamic efficiency and reducing the aircraft weight. Also the propulsive efficiency has a big impact on the overall aircraft fuel efficiency, explaining why since the early jet age the engine bypass ratios are continuously increasing. Considering a propeller as an ultra-high bypass ratio propulsive system, the propeller manages to secure a position for future aircraft concepts. EU-Clean Aviation research program HEROPS focuses on Flying Fuel Cell (FFC) technology, which is a novel fuel-cell based propulsion system aiming at climate-neutral aviation, that drives a propeller.

Wind tunnel model propeller blades

As a propeller will experience a non-uniform inflow during flight, produced by an angle of attack of the propeller or by interference with other aircraft parts like the fuselage or wings, there will be unsteady aerodynamic forces applied on the blade. In combination with the high rotational speed – certainly for model scale testing – blades potentially can fail under fatigue. For a model scale of 7 as often used for wind tunnel testing at NLR/DNW wind tunnels in the Netherlands, a common propeller speed of 7000 rpm will lead to a very high number of cycles (>> millions) in one test campaign easily. NLR wind tunnel model propeller blades are typically made from solid carbon fibre reinforced composites; for which an example is shown installed on a model in Figure 1.

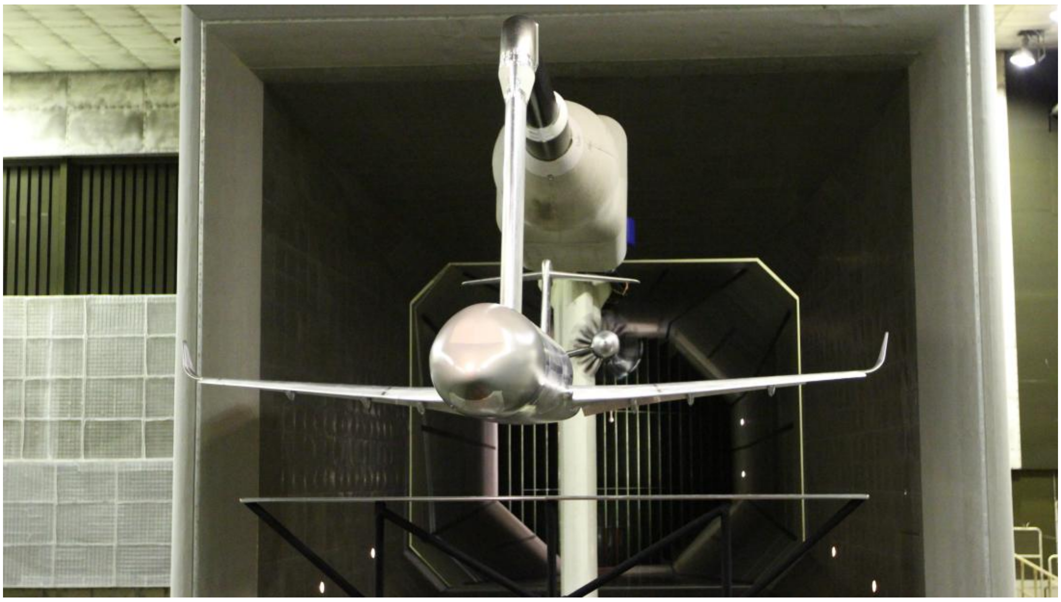


Figure 1: NLR model propeller blades for a test in DNW large low speed (LLF) wind tunnel

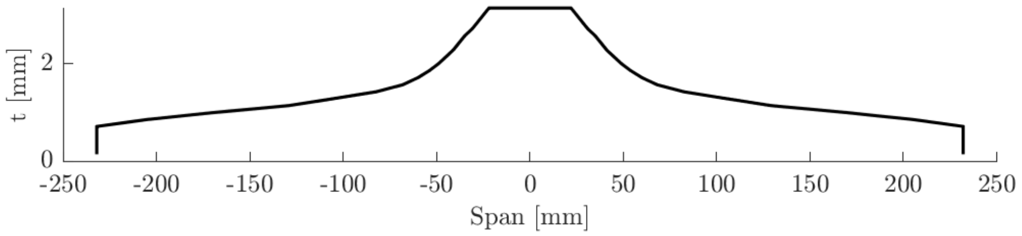
Current state-of-the-art HCF testing

Traditional High Cycle Fatigue (HCF) testing implies monitoring the frequency drop for a fixed number of cycles at a constant amplitude related to the strain level as expected for the wind tunnel test. A total frequency drop up to 3 % is currently accepted, after which the blade will be CT-inspected – either outsourced or at the client premises – and checked for any damage. In HEROPS this approach will be applied to test elements, where in addition also an alternative approach with a focus on phase response instead of frequency response is studied [1]. The goal is to understand if damage can be detected with in-house penetrant and ultrasonic C-scan inspection techniques and to understand where this damage actually occurs, to potentially account for it in future wind tunnel propeller blade designs. Finally, the currently set acceptable frequency drop will be brought up for discussion.

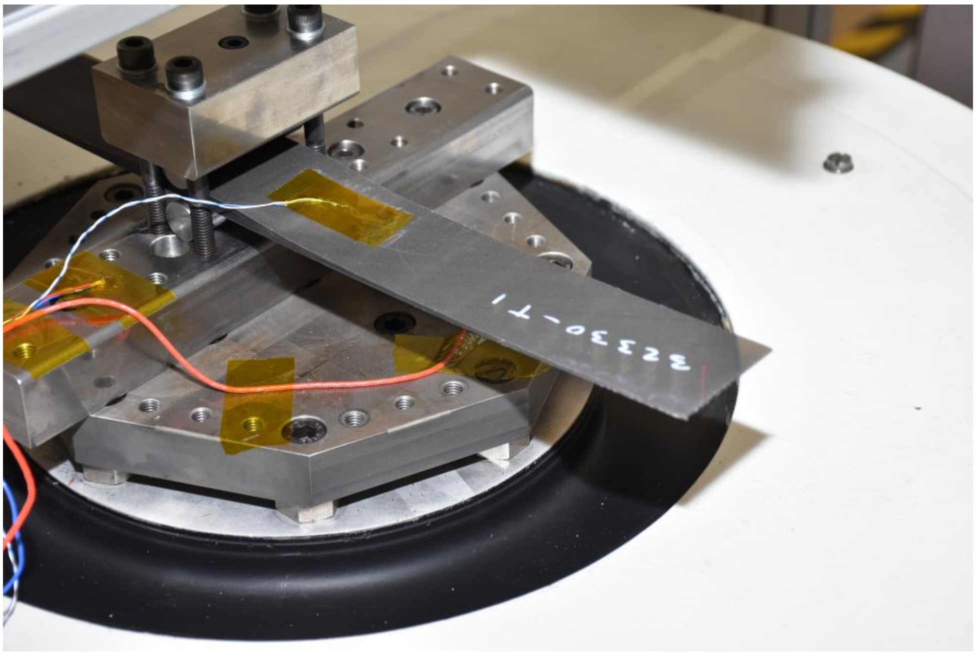
RESEARCH TESTS & EXPERIMENTS

2.1 Design and manufacturing test elements

Within the HEROPS program, composite test elements are designed and manufactured and subjected to high cycle fatigue loading on a shaker table. All elements are manufactured from carbon fibre reinforced plastic Unidirectional (UD) plies using Toray 2510/T700 and oven-cured under vacuum. The ply-layup as used for the 2.5D test elements is reflecting a typical layup for wind tunnel model propeller blades such that acceptable blade eigenfrequencies, stresses and deformations are found, both for on-design as well as for off-design load cases. Since there is no need for impact resistance in wind tunnel testing, the typical layup consists for the majority of 0 degree plies providing bending stiffness and some +/- 45 degree plies providing torsional stiffness. The test element is symmetric around the line where it will be clamped on the shaker, at which both sides of the element are representing the aerofoil of a blade. This spanwise thickness distribution, as shown in Figure 2, leads to ply drop-offs in the 2.5D test elements. Other than natural existing potential crack initiation points, for example ply drop-offs or voids, there is no crack already introduced in the laminate. The elements are machined from a panel to a size of 460 mm long and 50 mm wide.



a) Thickness/span distribution test element



b) Test element installed on the shaker

Figure 2: Test element geometry

2.2 Set-up of the experiment

The HCF tests were conducted using an electro-magnetically driven shaker, equipped with a laser displacement sensor on both tips of the test element to measure displacement, similar to test described in [1, 3]. A piezoelectric accelerometer was mounted on the fixture to capture the response between the applied force and frequency, as well as the displacement measured by the laser distance sensor. The temperature of the fixture and the test element was measured with use of type T thermocouples. An overview of the equipment as used can be found in Table 1.

To determine the eigenfrequency a low-level up and down Resonance Sweep (RS) were performed at a constant acceleration level of 0.15 g over a frequency range of 20-200 Hz. The eigenfrequency was identified at the maximum acceleration amplitude, with the average of the up and down sweep. The speed of the test is maximized to keep the hysteresis of up and down sweep below 1 Hz. The eigenfrequency is used as the constant dwell frequency for the following HCF test. Prior to the high cycle fatigue tests, low-level dwells were performed at amplitudes of 40 %, 60 % and 80 % of 32.0 mm (0-Pk) to prevent control issues – such as the laser point falling off the test element, a too large input voltage required or running into limitations of the shaker (force, displacement or speed) – and to prevent unwanted resonance of the laser mounting construction. These dwells also served to verify that the test level was sufficient for the test element.

Table 1: Equipment list

Item	Manufacturer	Type/model	Serial
Shaker	LDS	LDS V-810-240	S1422-001
Power Amplifier	LDS	LDS SPAK 32-34 k	654-010
NLR02642W (Computer)	Dell	5400	-
Test.Lab (Software)	Siemens	Environmental	-
Vibration Control System	Siemens	Scadas Mobile	52124208
Accelerometer	Endevco Corporation	7703A50	15213
Displacement laser	Micro-Epsilon	NCDT 1700-200	1309116
Displacement laser	Micro-Epsilon	NCDT 1700-200	1309180
Torque Wrench	Torqueleader	1 – 6 Nm	6E101011
Counter	Agilent	53220A	MY62239240
cDaq-9188	National Instruments	cDaq-188	187E8E6
Analog Output module	National Instruments	NI 9269	018F3704
Thermocouple Module	National Instruments	NI 9211	012E9F1D

2.3 Testing and inspection test elements

The test element was suspended between two cylinders – forcing a line contact – and clamped down with four bolts torqued with 6 Nm to a fixture that is installed on the shaker. This setup was chosen to avoid sharp edges, which could lead to high stress concentrations and potential unwanted damage due to high centred pressure on the test element. Notably, no damage growth was observed at the clamping points during these tests. To monitor crack initiation and growth, the tests are interrupted at predetermined intervals, specifically after 10 million cycles or when a phase shift ($\Delta\Phi$) of 10° is detected. Upon interruption, the natural frequency is determined and the test element undergoes a penetrant inspection and an ultrasonic C-scan inspection. After inspections the natural frequency is re-determined and used for the next constant frequency dwell.

The high cycle fatigue tests were conducted at tip displacements of 32.0 mm and 38.4 mm (0-Pk) – which are representative for similar size wind tunnel model blades, with advanced phase measurement techniques employed to monitor the phase (Φ) between the output signal of the controller and the response of the laser. The dwell frequency was maintained constant throughout each test. The control system provides the constant dwell frequency and maintains a constant tip displacement during testing. A separate system, utilizing a counter, measures the phase and aborts the test if the average phase shift exceeds 10°. The excitation frequency used is set equal to the natural frequency of the test element. Both the frequency drop and the phase shift of the test element deformation response are being studied.

In total, six similar test elements were manufactured and available for testing, labelled T1/T2/.. etcetera. T3 and T4 were outsourced for CT-scan inspection before any HCF testing was performed. Apart from a few low-cycle runs for T4, no work has been performed yet with these elements. For follow-up research, it is planned to CT-scan these two elements after testing as well.

3. Results and discussion

The results for the tested elements T2, T5 and T6 are shown in Figure 3 for which the cumulative phase shift can be found on the left vertical axis, the frequency on the right vertical axis and the number of cycles on the horizontal axis. The point before and after a 10° dwell, i.e. a run with constant excitation frequency that is stopped after 10 million cycles or when a phase shift ($\Delta\Phi$) of 10° is detected, is marked in the graph with a cross. For T2 and T5 the 32.0 mm amplitude is used, while for T6 a 1.2 times higher amplitude of 38.4 mm is used.

For this higher amplitude, a lower order of magnitude cycles (10^6 for T6 vs. 10^7 for T2/T5) is needed to get to the same total phase shift. Figure 3 for T6 shows, next to the cumulative phase shift, the individual phase-data per run as a dashed line as well. To be able to plot the cumulative phase shift for each test element, shown as a solid line in each plot, the phase shift for each run is added to the previous ones. For all the elements, notable damage is found after just a few 10° dwells. The damage initiates at the same location for all elements and the overall picture is also the same. Please find Figure 4 and Figure 5 for the Non-Destructive-Inspection (NDI) results as obtained – both penetrant and ultrasonic C-scan – for test element T2 and T6 respectively before testing, after the first 10° dwell, after the second 10° dwell and at the end of testing. The same machine setting like gain and scale for damping as shown in the colour bar in the figure, is used for each inspection. Because of the limited resolution of the C-scan and the size of the damage in the beginning of testing being close to that resolution, it is not straightforward to identify the exact moment of damage initiation. Although the inspection results after the first 10° dwell are already showing some small deviations with the picture before testing, especially after the second 10° dwell, the damage starts to become visible at the edge on both sides of the clamping as indicated. Although the penetrant inspection result is only shown for the upper side of the specimen, the lower side of the specimen is giving a similar picture.

In Figure 3 a linear fit for the frequency measurements of the initial low-level runs and the first 10° dwells is shown. Please note: the zoomed in plot is in a linear-linear scale, while the global plot is in a log-log scale. It can be seen from the plot that the frequency measurements at the start or end of each dwell (cross and an open dot respectively), typically do not follow that trendline anymore at the end of testing.

After the initial low-level dwells and the first 10° dwell, it can be seen in Figure 3 for T6 that the phase jumps suddenly once a new dwell is started. The same phenomenon was found for the other test elements, but is per definition filtered out for the cumulative delta phase plot. The change in damping of the system, causing the change in phase, could potentially be caused by a temperature change of the shaker and/or element. Another hypothesis is that a change in damping could potentially also be caused by re-clamping of the element after the element is removed to perform NDI's. Finally, these jumps could potentially be caused by the adjustment of the testing frequency for each dwell.

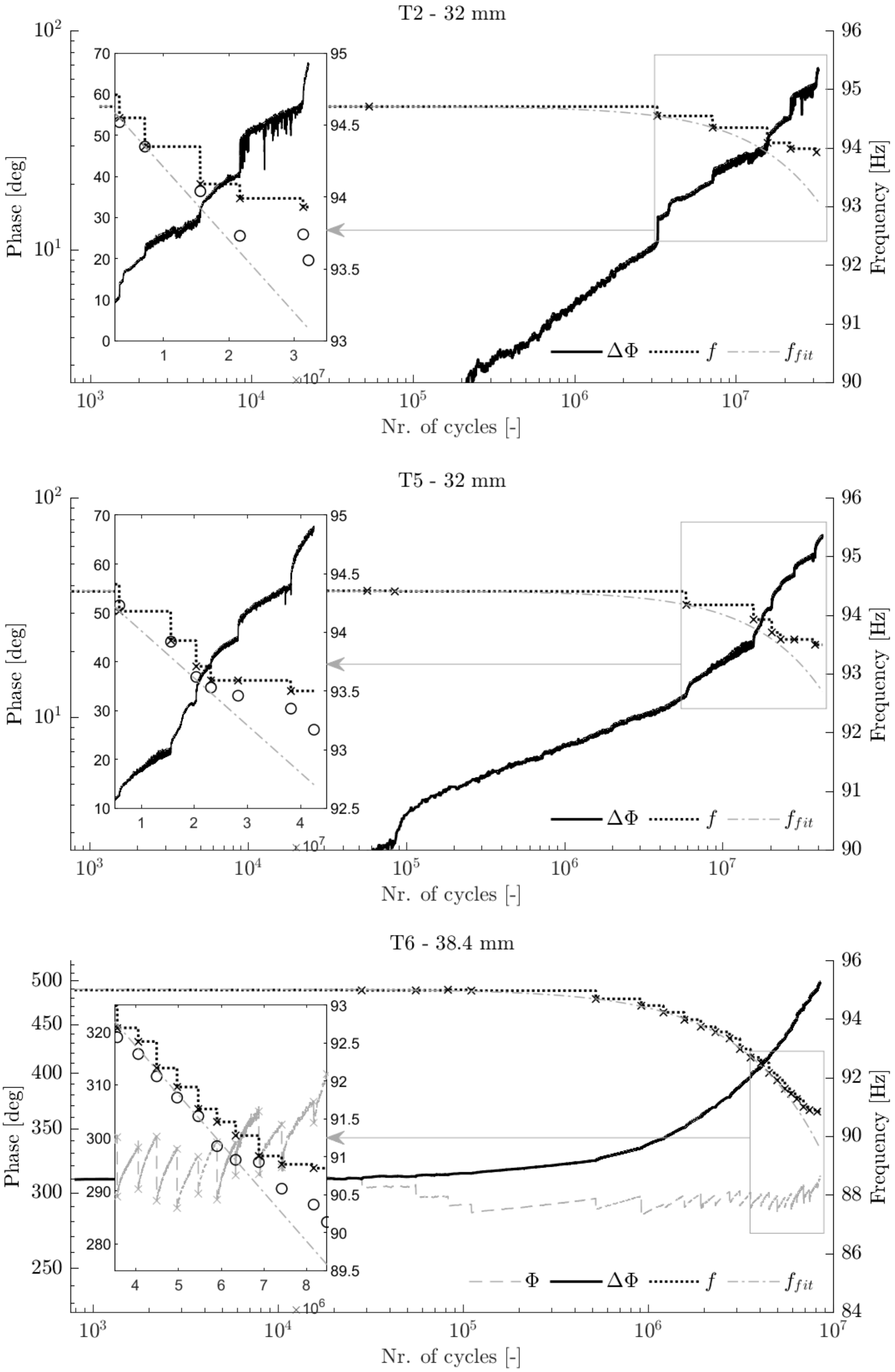


Figure 3: Test results for T2, T5 and T6

Run	Inspection result
No load N = 0 cycles Δf = 0 Hz ΔΦ = 0°	
Dwell #1 N = 3.2e+06 Δf = 0.19 Hz ΔΦ = 11°	
Dwell #2 N = 7.1e+06 Δf = 0.36 Hz ΔΦ = 21°	
Dwell #6 (end) N = 3.2e+07 Δf = 1.15 Hz ΔΦ = 68°	

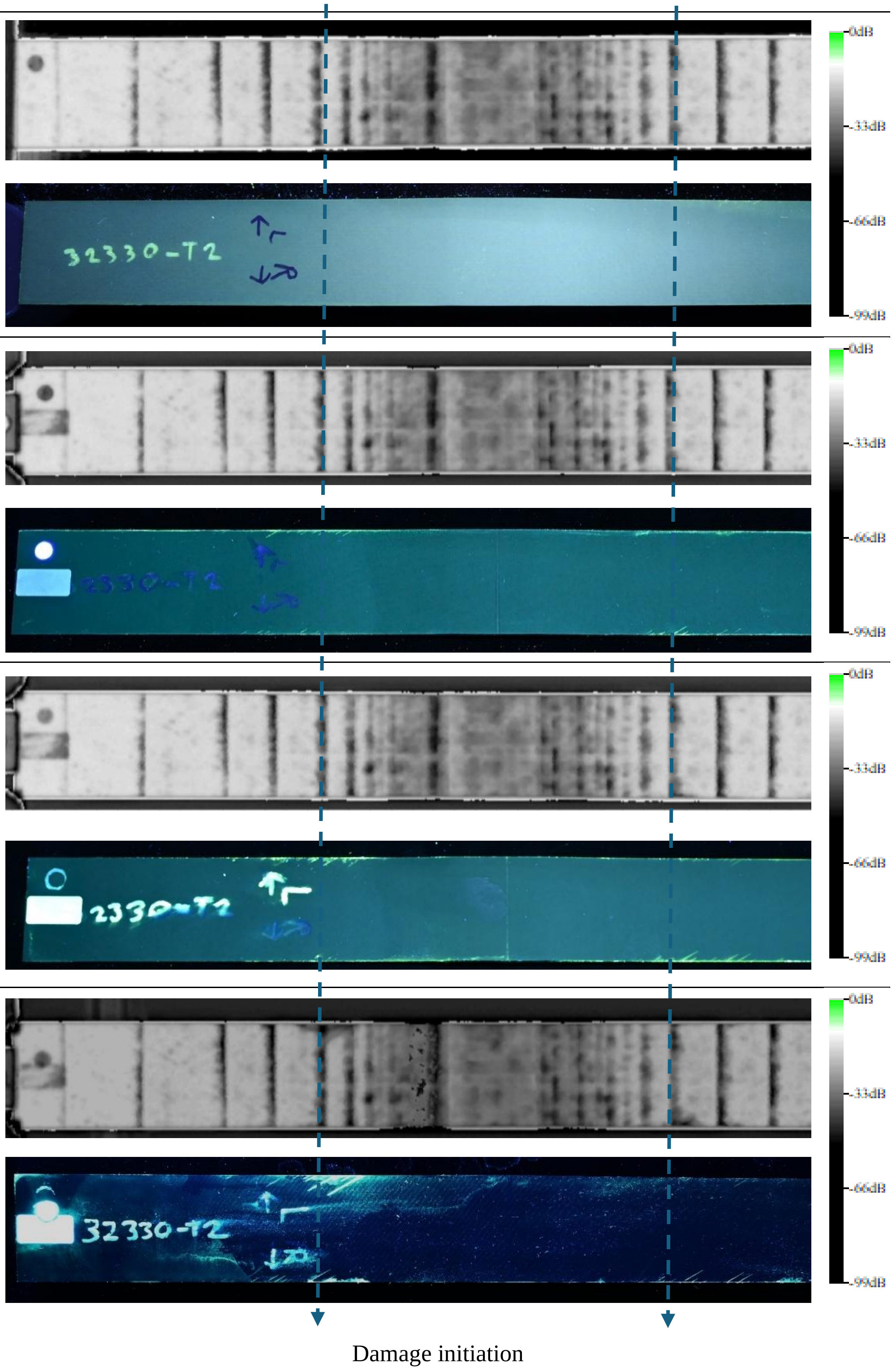


Figure 4: Penetrant and C-scan inspection results for T2 (top = C-scan, bottom = penetrant)

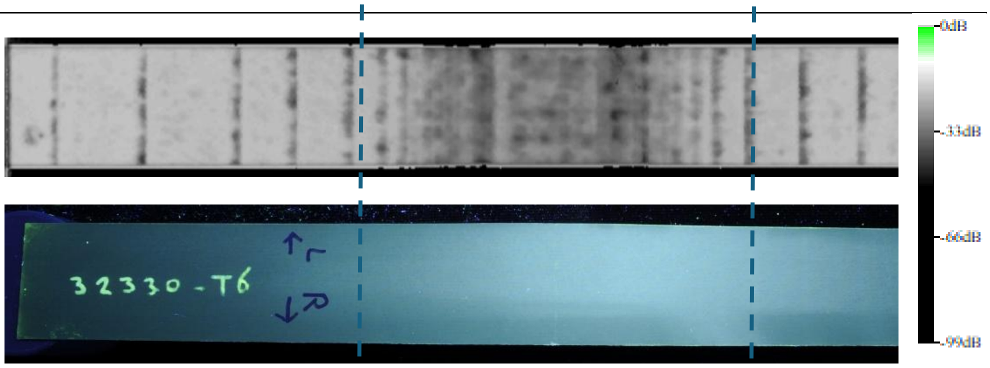
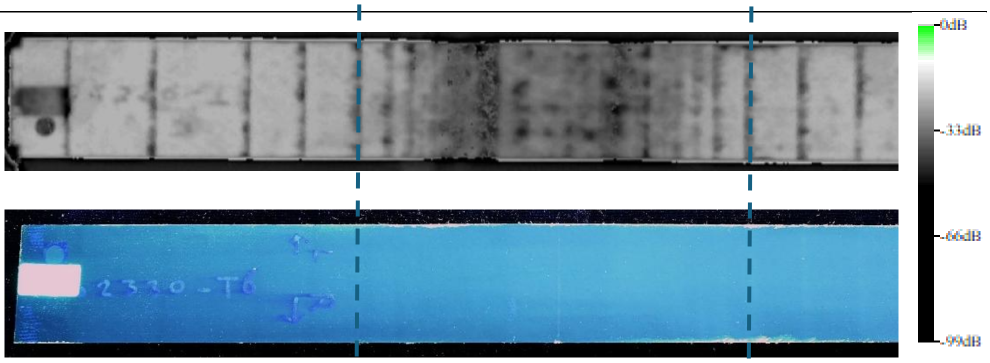
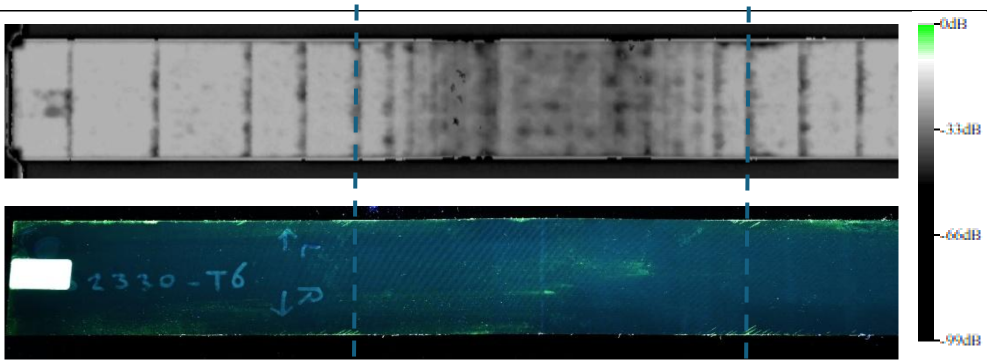
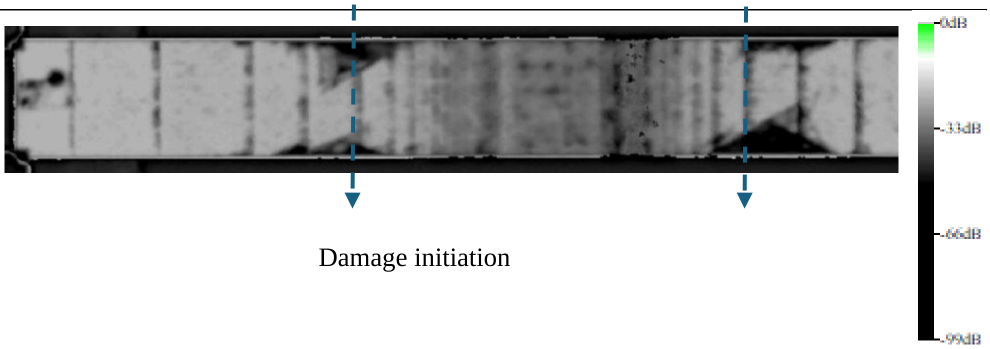
Run	Inspection result
No load N = 0 cycles Δf = 0 Hz ΔΦ = 0°	
Dwell #1 N = 5.2e+05 Δf = 0.30 Hz ΔΦ = 10°	
Dwell #2 N = 9.1e+05 Δf = 0.53 Hz ΔΦ = 20°	
Dwell #19 (end) N = 8.5e+06 Δf = 4.85 Hz ΔΦ = 189°	

Figure 5: Penetrant and C-scan inspection results for T6 (top = C-scan, bottom = penetrant). For T6 there is no penetrant data available after the last dwell (#19).

Before the test, the eigenfrequency of the element is measured and this is used as the excitation frequency for the following dwell. At the end of the dwell, due to the change in eigenfrequency of the element, the test frequency is no longer exactly at the eigenfrequency causing a jump in the phase line. Tests were performed for T4 to study this effect further. In Figure 6 the test results for T4 can be found. Dwells were performed at 32 mm amplitude for $1x10^3$ cycles. A new test was started directly after the last one was finished, without doing an RS and without changing the eigenfrequency. No jump in the phase was detected. After finishing two dwells, a resonance sweep was performed and a new sequence of two dwells was started without removing the element from the shaker. The measured eigenfrequency dropped from 95.26 to 95.25 Hz. For these two dwells no adjustment of the excitation frequency was made. After these dwells (so after four dwells in total), the excitation frequency was adjusted to the last measured eigenfrequency, which resulted in a jump in the phase and therefore confirms that changing the excitation frequency will cause a phase jump. A temperature change of the shaker and/or element can still be an additional reason for the jump. Temperature was only measured during the test on the outside of the clamping block. Unfortunately the thermocouples on the element itself kept breaking during the test. Although no large temperature differences were found on the thermocouple on the clamping block, this effect needs to be studied further. The effect of temperature can be found in [2]. It should be noted that for T4 no (large) delaminations are present and heating from damages are not present in this sample. It can also be seen that the jumps are always downward. Also no difference can be found between the jumps when a NDI was performed and when the element was not removed. It cannot be ruled out that the removal of the element had some effect, but the effect is assumed to be negligible since no measurable difference in phase or frequency can be found between removed and non-removed elements.

What can be seen from all phase plots (Figure 3 and Figure 6) as well, is that the phase shift per cycle slows down during a single test. Once a new test is started at an adjusted frequency, the phase shift per cycle speeds up again and then becomes slower over time. This is what can be expected by looking at the phase Bode plot. At the eigenfrequency the phase change is the steepest and thus the phase changes relatively fast when the eigenfrequency starts to change. Once the eigenfrequency is further away from the test frequency the line is less steep, and thus the change per cycle is expected to be slower, assuming a constant eigenfrequency change per cycle during a single test interval. This effect can be easily explained, but it raises an issue. The phase plot from Figure 3 is a direct consequence of the test protocol; if one would use shorter test intervals – thus remain closer to the eigenfrequency – the delta phase line will be considerable steeper than when using larger intervals and therefore testing at a frequency further away from the eigenfrequency. This also raises the need for a clear test protocol, removing the dependency of the size of the test-interval as a variable. Furthermore one could argue if it is better to use a fixed number of cycles per test-segment or a fixed phase change. For the latter, one would preferably need to take the steepness of the phase Bode plot at the eigenfrequency in consideration, i.e. taking into account the damping of the test specimen.

It can be observed that a change in phase angle can be found before any change in eigenfrequency can be measured. It is more useful to look for the more sensitive phase shift than to look for a very small frequency drop. For example, for test element T2 the frequency drop where damage initiation occurs – assuming after the second 10° dwell looking at the NDI results from Figure 4 – is at a different order of magnitude than the phase shift (0.36 Hz and 20° respectively).

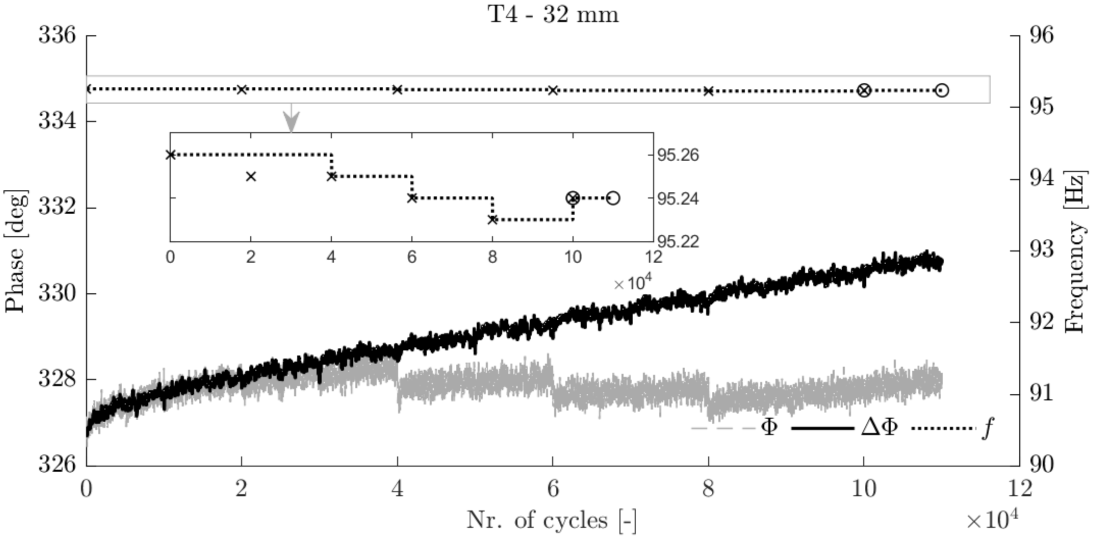


Figure 6: Test results for T4

Placing the fatigue study in a broader perspective, one should also think about the actual wind tunnel test. During wind tunnel tests eigenfrequency measurements are used to identify possible fatigue issues in the blades. Considering the accuracy of these measurements during wind tunnel tests – depending on the system and peak detection algorithm used, an accuracy of 0.50 Hz might be achievable – there should be considerable damage in the blade to find a definitive and detectable eigenfrequency drop. This raises the question if another non-invasive measurement might be more successful for early detection of fatigue initiation during wind tunnel testing.

A notable observation can also be made about the difference between the eigenfrequency RS directly after a dwell and directly before the new dwell. Initially no difference can be found between these measurements, as shown by the markers in the phase plots (open dot is a measurement after test, a cross is a measurement before new test). This can also be seen in the plot in Figure 7, where the cumulative frequency drop is plotted against the cumulative phase shift for both type of measurements. After several 10° dwells, a clear difference becomes visible between the measurements. This difference is not caused by additional damage, since no damage was introduced between these two measurements. Several hypothesis exist to explain the difference. One is a temperature effect, caused by rubbing of the delamination during vibration. When the damage is larger, this effect becomes larger and might become visible as a change in eigenfrequency. Another hypothesis is that water ingress in the delaminated area caused by the C-scan might change the eigenfrequency, however if mass in terms of water is added to the specimen one would expect the eigenfrequency to be lowered. Instead the eigenfrequency is increased. For this reason this hypothesis is unlikely. If the change is indeed caused by the temperature increase, one might consider using the after testing RS as the test frequency, since after several cycles the element will heat up and the eigenfrequency is lowered due to heating of the element. Furthermore it should be noted that testing the element further away from the eigenfrequency due to the potential heating of the element lowers the sensitivity of the phase angle. Again, this raises the need for a clear test protocol, here in order to remove the dependency on specimen heating as a variable for the phase angle measurement.

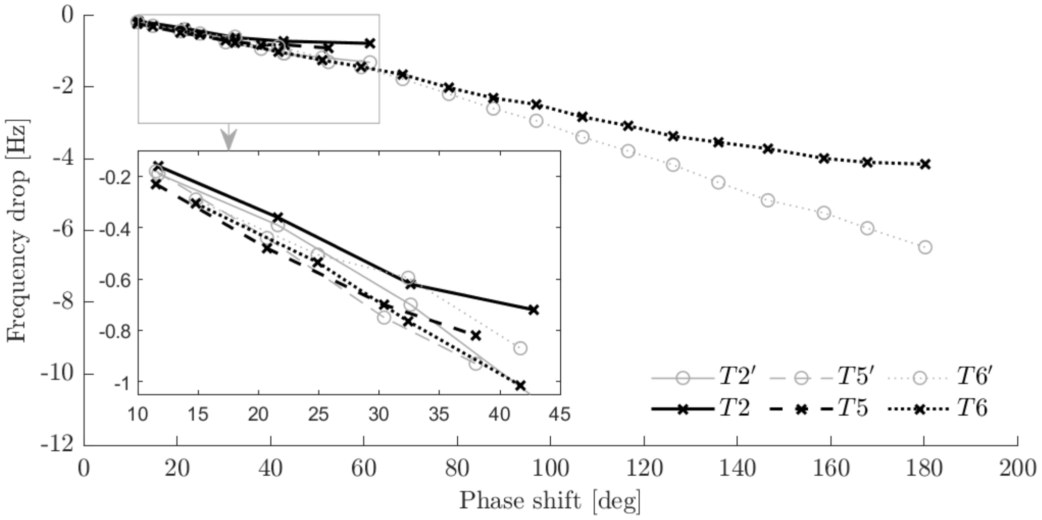


Figure 7: Frequency drop as a function of cumulative phase shift

One observation which is especially important for real wind tunnel blade HCF tests, is the results from what is called the pre-test. These are short tests at ascending amplitude to test if the laser dot is tracking the blade correctly. Due to the non-linear bending of the blade, the laser does not track along the blade in a straight line. Some tests are needed, at high amplitude, to ensure the laser is tracking along the blade correctly. During the element testing these tests were replicated, despite the fact that for simple flat specimen a pre-test is not necessary. It was always assumed that, because there is no measurable difference in the eigenfrequency, these tests did not have a significant effect. However, looking at the phase angle change, a significant change can be found already during these pre-tests. This once again raises the need for a test protocol, where the pre-test is not insignificant and should be evaluated since it might be a substantial part of the fatigue initiation life. Another observation during the pre-test is that there is a clear relation between the amplitude and the phase angle. If the amplitude is increased, the phase is lowered. This might be caused by the increased amount of air that is moved with an higher amplitude. This increases the damping and thus lowers the phase. It can be seen in the C-scan results that the damage appears to grow from the edges of the specimen inwards. It should be noted that this open edge is not actually present in wind tunnel propeller blades. In a wind tunnel blade plies are gradually dropped towards leading edge and trailing edge forming the aerofoil shape, where in the test-elements all plies run towards the end and are dropped together to form the edge of the specimen. Therefore the fatigue initiation life and damage cannot be directly copied to actual wind tunnel propeller blade.

4. Upcoming research towards Beyond state-of-the-art HCF testing

Recent research suggests that it is important to monitor the phase shift to find the point of damage initiation and growth. The benefit of measuring the phase shift, is that the phase shift at the eigenfrequency is very sensitive and can measure small changes in the test. It became clear during the current research that a lot of factors influence the phase shift. If the goal of the phase shift measurement is to identify the moment of damage initiation and somehow track damage growth, further research is necessary to identify the factors involved and to quantify their effect. After that, the effects on phase shift from other sources can be removed either by correcting the phase shift data or eliminating them as a source through a rigid testing plan. Furthermore, a comparison should be made between different measurements during a HCF test to identify damage initiation and damage growth. One can think of measuring the eigenfrequency, phase angle, temperature dissipation of the element, mode shape of the element, strain in the element and damping of the system. In order to have an accurate identification of damage initiation and/or growth, it might be necessary to combine different measurements. Furthermore, it should be noted that the identification of damage initiation requires a different measurement than damage growth.

5. Conclusions

In order to understand the results from a high cycle fatigue test of a composite wind tunnel blade, a HCF test campaign was performed with simplified test elements, representative for a typical composite blade. It can be concluded that using a 3% drop in eigenfrequency as a determination for fatigue initiation is questionable. It is clear that before a 3% drop in eigenfrequency is found, damage is already present in the elements. Damage is visible in both the penetrant as well as the C-scan inspection results.

Noticing how small the eigenfrequency changes are at fatigue initiation, one should also think about the actual wind tunnel test. During wind tunnel tests eigenfrequency measurements are used to identify possible fatigue issues in the blades. Considering the typical accuracy of these measurements during the wind tunnel test, there should be considerable damage in the blade to find a definitive and detectable eigenfrequency drop. This raises the question if another non-invasive measurement might be more successful for early detection of fatigue initiation during wind tunnel testing. It was shown that changes in phase can be measured, before a significant change in eigenfrequency can be found. A relation was shown between eigenfrequency drop and the phase shift, however it should be noted that this relation is dependent on the length of the test intervals in the test.

Correlating the phase shift to damage initiation was not possible in the current research. For damage initiation, the resolution of the C-scan does not have the accuracy necessary to exactly pinpoint the moment of damage initiation. Furthermore it should be noted that the damping increases with increased test amplitude. This implies that the magnitude of the phase shift at damage initiation depends on the amplitude which is used for testing. It was found that there are several other factors that influence the phase shift. More research and a better understanding and quantification of these factors are necessary to use the phase measurement as an identification for damage initiation. The results should be used to get to a test protocol, where the phase shift caused by damage initiation can be isolated from other effects. It is not unthinkable that this is not possible because of the complexity, especially when one would want to consider a fatigue spectrum with different amplitudes.

Correlating the phase shift to damage growth was not possible in the current research. For damage growth, it is presumed that the damping of the system would change due to the damage. How much the damping changes needs to be studied in more detail. If the change in damping due to damage changes significantly, the relation between phase change and damage growth will vary with changing damage/damping. Furthermore it should be noted that the damping also increases with increased test amplitude. This also implies that the magnitude of the phase shift for damage growth depends on the amplitude that it is being tested at.

6. References

1. M. Lasen, D. Di Maio, D. De Bono, M. Peluzzo, An investigation of fatigue damage growth in composites materials using the vibration response phase decay, to be published in the International Journal of Fatigue 2024, https://doi.org/10.48550/arXiv.2404.14834
2. G. Voudouris, D. Di Maio, I. A. Sever, Experimental fatigue behaviour of CFRP composites under vibration and thermal loading, International Journal of Fatigue 140 (2020), 105791
3. F. Magi, D. Di Maio, I. A. Sever, Damage initiation and structural degradation through resonance vibration: Application to composite laminates in fatigue. Composites Science and Technology, 132, 46-57 (2016), https://doi.org/10.1016/j.compscitech.2016.06.013

This research has been performed in the frame of the HEROPS project (Hydrogen-Electric Zero Emission Propulsion System), which is funded by the European Union. The project started on 1 January 2024 and is supported by the Clean Aviation Joint Undertaking and its members, under Grant Agreement No 101140499. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be hold responsible for them.

HEROPS
A Clean Aviation Project

CLEAN AVIATION

Co-funded by
the European Union