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Lessons learned from wind tunnel testing of a droop-nose morphing wingtip

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ABSTRACT

This work presents the lessons learned from wind tunnel tests of a droop-nose morphing wingtip as part of the EU project NOVEMOR. The design followed a sequential chain and was largely driven through optimization tools, including a glass-fiber composite skin optimization tool and a topology optimization tool for the design of internal superelastic and aluminium compliant mechanisms. The device was tested in the low speed tunnel at the University of Bristol to determine the structural response under aerodynamic loading. Measurements of strain from strain gauges show that the structure is capable of handling the aerodynamic loads though also show an imbalance of strain between the components. Measurements of surface pressures show a small variation of c_p with the 2° droop morphing variation as per the target. The wind tunnel testing showed that further developments to the design chain are necessary, in particular the need for a concurrent as opposed to sequential chain for the design of the various components. Considerations of other problem formulations, the inclusion of nonlinear finite element analysis, and ways to interpret the structural boundary of the topology optimization results with more confidence are required. The utilization of superelastic materials in morphing structures may also prove to be highly beneficial for their performance.

Keywords: Morphing, compliant mechanism, droop-nose, topology optimization

1. INTRODUCTION

A high level of integration of the components which comprise a morphing system is crucial for its overall success, and if designed appropriately, morphing structures have the potential to save fuel and reduce harmful emissions in aircraft applications^{1,2}. A droop-nose morphing wingtip of a regional jetliner (Fig. 1) featuring a flexible composite skin and internal superelastic compliant mechanisms was designed, manufactured and wind tunnel tested as part of the EU project NOVEMOR³. It was anticipated that the drooping device (target deflection 2°) could save fuel by reducing drag and improving aeroelastic characteristics of the aircraft. The design followed a chain which incorporates aerodynamic, structural, manufacturing and assembly design and sought to integrate the various components such as the skin, substructure and actuators, thus leading to a functional morphing device. Wind tunnel testing of the morphing droop-nose device was performed to put the design chain into effect, to investigate the structural response under the wind tunnel loads, and to acquire knowledge on how the design chain can be improved. This paper highlights the lessons learned for improving the design and design tools for future morphing structures. A short summary of the design chain and constituent tools is first presented. The wind tunnel test regime is then described, the results are discussed through a listing of these lessons learned, and the conclusions stated.

2. STRUCTURAL DESIGN CHAIN AND OPTIMIZATION TOOLS

A sequential design chain based on that of Kintscher *et al.*⁴ and Rudenko *et al.*⁵ was further developed in this work which begins with aerodynamic optimization and load data calculation (performed by project partners) before continuing into the structural design. The structural design chain starts with the skin design and the results at the end of this stage

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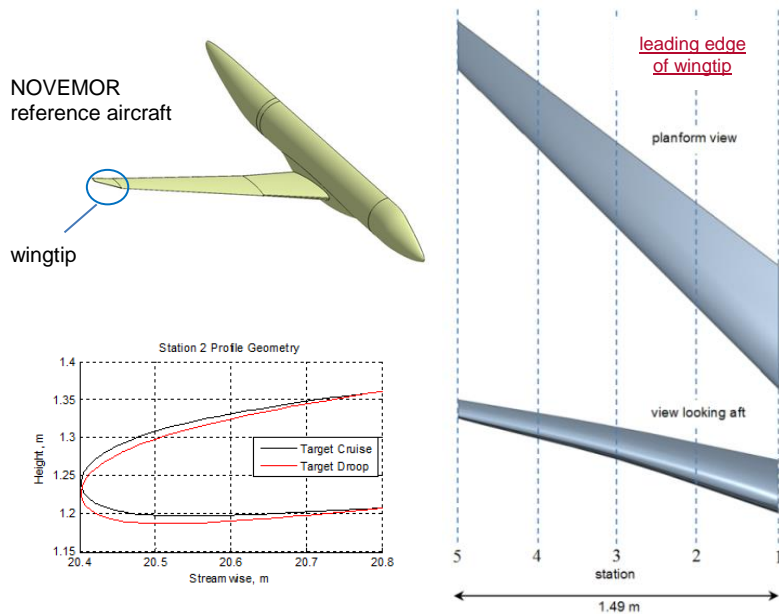


Figure 1. Geometry of wingtip.

are transferred to the design domains of the compliant mechanisms which are designed via gradient-based topology optimization. The processes are briefly explained here and the reader is referred to Vasista *et al.*⁶ for more details.

2.1 Skin Design

The fiberglass skin was designed through an optimization tool based on Kintscher *et al.*⁴ though redeveloped for 3D structures in this work. The 3D thickness distribution, stringer position (load introduction from compliant mechanisms onto skin) and transmission force at these connection points were optimized such that the displaced shapes match the targets with the least error. The optimization tool is based on a Nelder-Mead Simplex algorithm with multiple calls to the finite element analysis subroutine for different load cases to account for stiffness and flexibility requirements. The result featured a highly complex though manufacturable 3D thickness distribution.

2.2 Compliant Mechanism Design

Continuum gradient-based topology optimization⁷ was developed and used for the design of the compliant mechanisms. The problem was formulated to maximize the stiffness in the clean configuration subject to the shape control displacement constraints of the droop case. The results were topologies which featured no artificial one-node hinges and with bending distributed through the linkages of the compliant mechanisms. However, given the tight space in the outboard region, modifications to the compliant mechanism were required as the strains were exceeding safe limits. A pin joint was added at the stringer-mechanism connection region to alleviate this problem. The results were post-processed and dimensions further tweaked to obtain the best possible performance.

2.3 Manufacture

The skin was manufactured through the use of HexPly[®] 913 prepreg plies cut into the optimized shapes, laid up in the correct sequences of orientation angles, and vacuum-bagged and cured. The process was conducted in two stages by first curing half of the leading edge (up to the stringer) and then laying up and curing the second half, resulting in a single piece finished part. The inboard compliant mechanism was made from nickel titanium superelastic material to exploit its high strain capability. A stock sheet of 5 mm thickness was cut into shape using the wire EDM method. The outboard compliant mechanism was manufactured from aluminium 7075 and was laser cut into the optimized and modified shape. The leading edge device was mounted to the wingbox structure via an auxiliary spar. The wingbox region was constructed from steel tubing and milled plastic skins to form the aerodynamic surface. The conceptual sketch, finite element results and a photo of the internal installation is shown in Fig. 2.

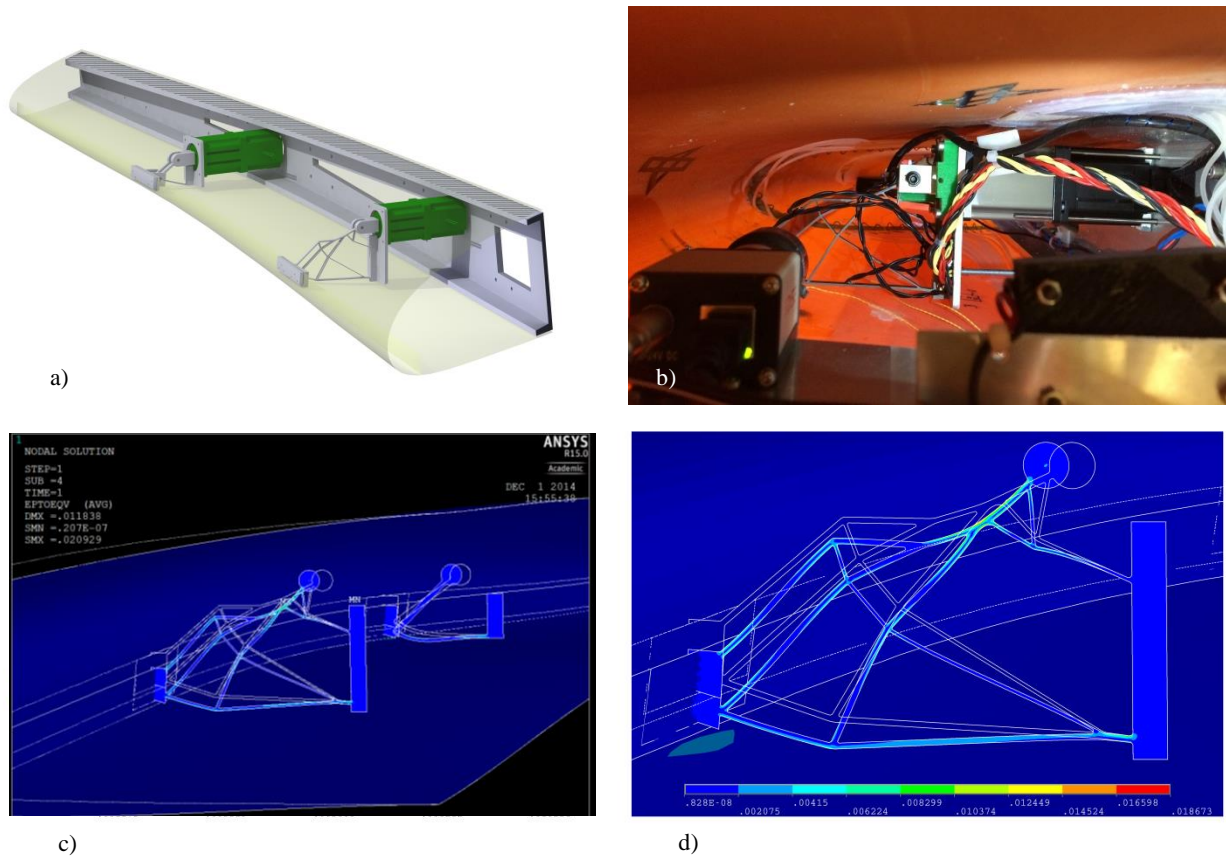


Figure 2. a) Conceptual model of droop nose device; b) photo of installed inboard compliant mechanism and internal camera; c) von Mises strain field of the inboard and outboard compliant mechanisms; d) zoomed in result of von Mises strain field of the actuated inboard compliant mechanism;

3. WIND TUNNEL TESTING

Wind tunnel testing was performed at the University of Bristol's 7' x 5' low speed subsonic wind tunnel (Fig. 3). The mounting was in a vertical orientation and could be rotated on the mount to change the loading condition through a range of angles of attack. The testing was not intended to quantify the aerodynamic or flight benefits of the device, rather to evaluate the morphing structure's ability to hold shape under loads and to assess the design chain under which it was produced. Measurements of strain were taken from strain gauges placed at 14 locations: 6 on the skin, 6 on the inboard compliant mechanism and 2 on the outboard compliant mechanism. Surface pressure measurements were taken from pressure tappings placed at one station along the span and were used for comparison with CFD data as well as for measuring the variation in pressure coefficient due to the morphing action. The wind tunnel balance was also used to determine total wingtip loads and internal cameras monitored the movement of the mechanisms.

The wind tunnel test matrix involved taking steady-state measurements at a range of speeds up to 55 m/s at 5 m/s increments. An angle of attack range of -10° to $+10^\circ$ was used. Transient measurements were also taken i.e. measuring the response under the actions of drooping and undrooping under aerodynamic loads. The results from the wind tunnel tests were compared with the finite element and computational fluid dynamics models for validation purposes. The reader is referred to Cheung *et al.*⁸ for further information on the wind tunnel set up.

The results of the wind tunnel tests form the basis for discussion on the lessons learned as explained in the next section.



Figure 3. Assembly process of the wingtip in the wind tunnel (left) and assembled model at -10° angle of attack (right).

4. DISCUSSION – LESSONS LEARNED

A number of lessons were obtained for improving the design of future morphing structures. These are listed in this section and are based on the experimental results and the inferences made.

4.1 Concurrent Optimization Chain

An optimization chain which generates optimum skin and compliant mechanism designs and actuator positions and orientations concurrently rather than sequentially is required. The strain results of the positions BL, IB1 and OB7 in Figs. 4-6 show a large difference in maximum strain between the skin (0.1% strain), inboard compliant mechanism (2.23% strain), and outboard compliant mechanism (0.6%). Furthermore, it was shown by Riemenschneider *et al.*⁹ that there was a mismatch between the target and actuated shapes during 3D scans of the device outside the wind tunnel. Isolating the components and transferring the results to the next stage (e.g. from the skin optimization to the compliant mechanism design) as used in this work leads to a restriction of the design space with subsequent steps. This led to the strains being localized to the inboard compliant mechanism and the accumulation of shape error over the steps leading to the measured discrepancies. It should also be noted that the number, position and orientation of compliant mechanisms were decided prior to the design chain. There is scope to obtain better designs by including these as design variables in a concurrent optimization chain. Given the high interdependence of all components, the full design space needs to be explored to obtain the best possible performance in terms of stress concentrations, stiffness, required input energy and weight.

A large computational effort will be required to achieve such a concurrent design chain. A combination of heuristic schemes as used by Lu and Kota¹⁰ and De Gaspari and Ricci¹¹ and gradient-based topology optimization methods may lead to a tool which generates suitable results within a reasonable computational effort. Further investigations into achieving concurrently-optimized components are required.

4.2 Compliant Substructure Architecture

The overall performance of the morphing device may be better with a 3D substructure supporting and driving the skin, as opposed to 2D planar morphing ribs. It can be deduced from beam equations that the maximum stress per deflection is cubically dependent on the in-plane heights of the structure's geometric features and is independent on the out-of-plane thickness. In this work, the in-plane thickness were in the range from 1-3 mm whilst the out-of-plane thickness was larger at a uniform 5 mm. The skin will likely be better served by a compliant substructure which also bends in the same manner as a shell. Furthermore, with complex 3D wing geometries a 3D compliant substructure may yield better results and the 3D design will need to be accounted for by the concurrent optimization chain in §4.1 and the topology optimization development in §4.3.

4.3 Topology Optimization Developments

Further developments to the gradient-based topology optimization routine are required. From the strain results in Figs. 4-6, it is clear that the structure is capable of handling the aerodynamic loads at the tested wind tunnel conditions (example

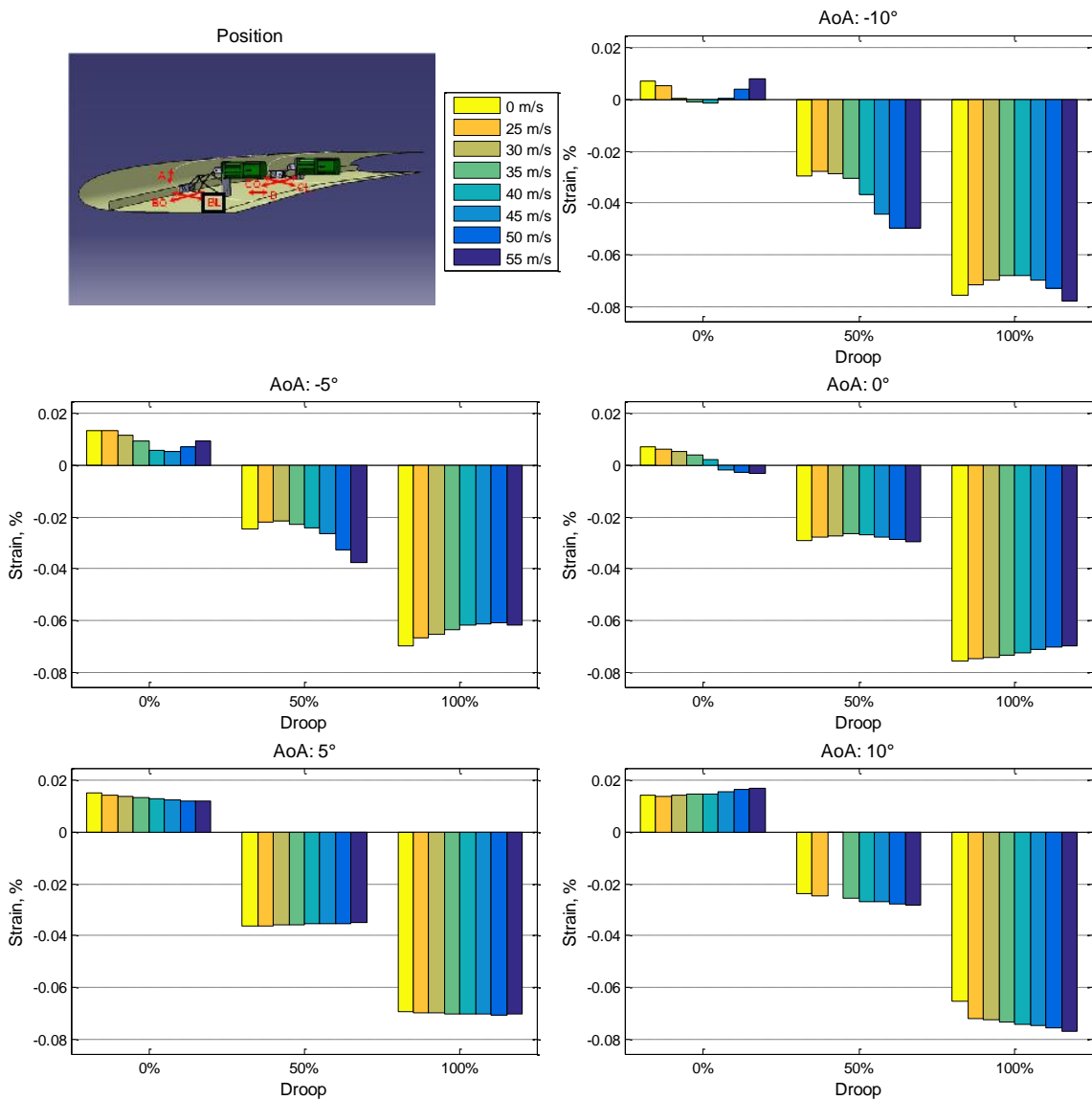


Figure 4. Strain gauge position BL strain results at different droop settings, angles of attack and wind tunnel speeds.

c_p distribution and effect of morphing shown in Fig. 7) and the majority of strain arises from the action of drooping, rather than from external aerodynamic loads. This suggests that there is an ‘imbalance’ of the stiffness-flexibility tradeoff. It is true that given the wind tunnel tests were at low speeds, the design flight loads should be significantly higher. However, finite element analysis results of the structure under design flight loads (to be reported at a later stage) showed that the strains due to flight-aerodynamic loads still remained low. The reason for this imbalance may be attributed to the topology optimization problem formulation, which as presented in Vasista *et al.*⁶ was to maximize stiffness in the clean configuration subject to the shape control displacement constraints of the droop configuration. A problem formulation based on strain energy may lead to a better stiffness-flexibility balance.

Nonlinear finite element subroutines in the topology optimization methods are necessary for the accurate design of large-displacement structures. The issue of low density elements and the resultant excessive distortions and finite element non-convergence remain a challenge and much effort has already been made in literature to address these¹²⁻¹⁴. In this

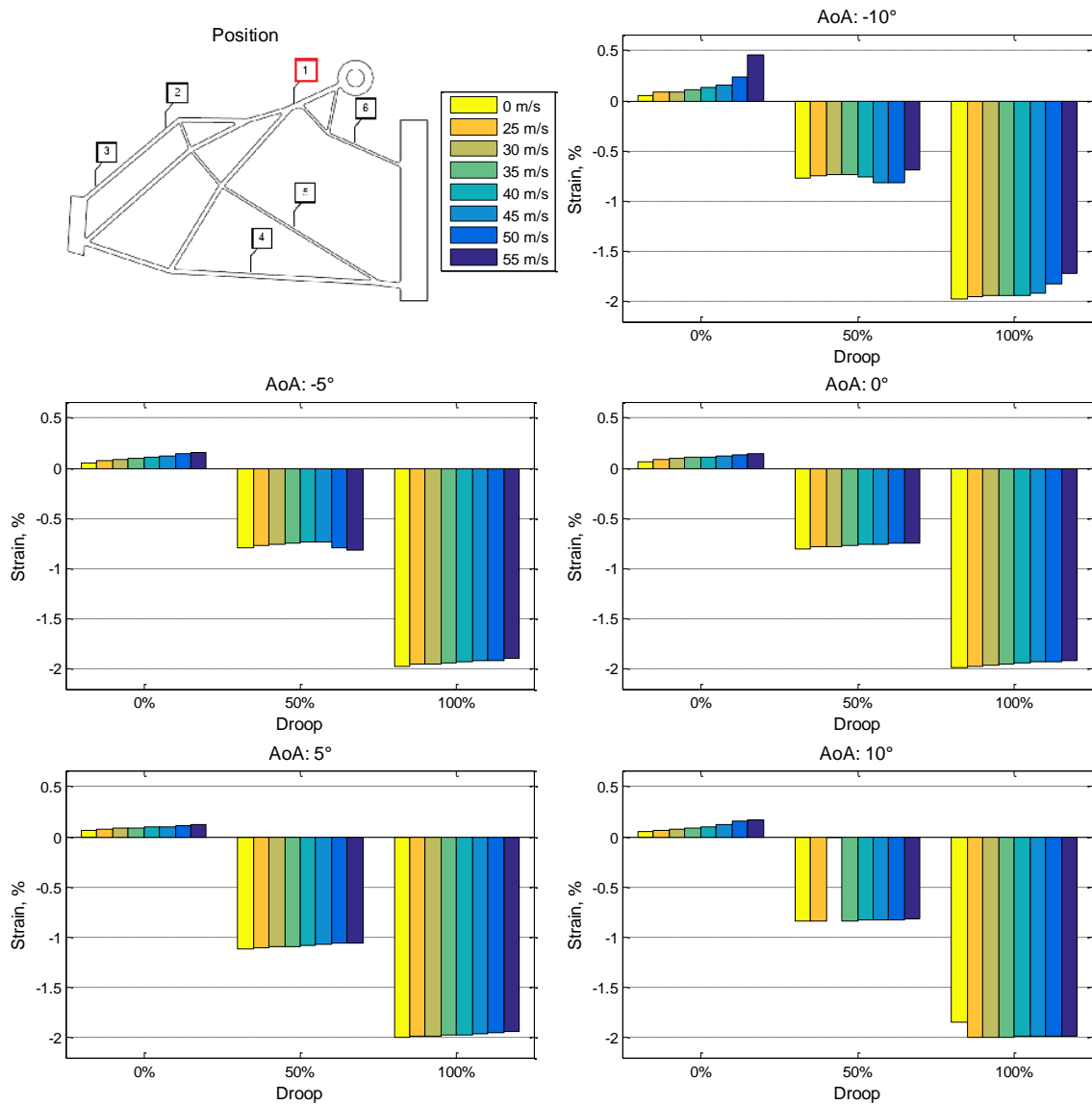


Figure 5. Strain gauge position IB1 strain results at different droop settings, angles of attack and wind tunnel speeds.

work, linear finite element analysis was used in the topology optimization process given the target deflection was small at 2° .

It was experienced in this work that the interpretation of intermediate or ‘grey’ densities in the topology optimization result was highly sensitive to the displacement and stress fields of the compliant mechanisms. More work to address this issue is also required.

4.4 Superelastic Materials

The nickel titanium superelastic material used for the inboard compliant mechanism has high potential for use in morphing structures. The high measured values of strain (2.23% strain at 100% droop and up to 4.1% strain at 250% droop as shown visually in Fig. 8) show that the material has high displacement capability whilst supporting the stiffness of the skin and external loads.

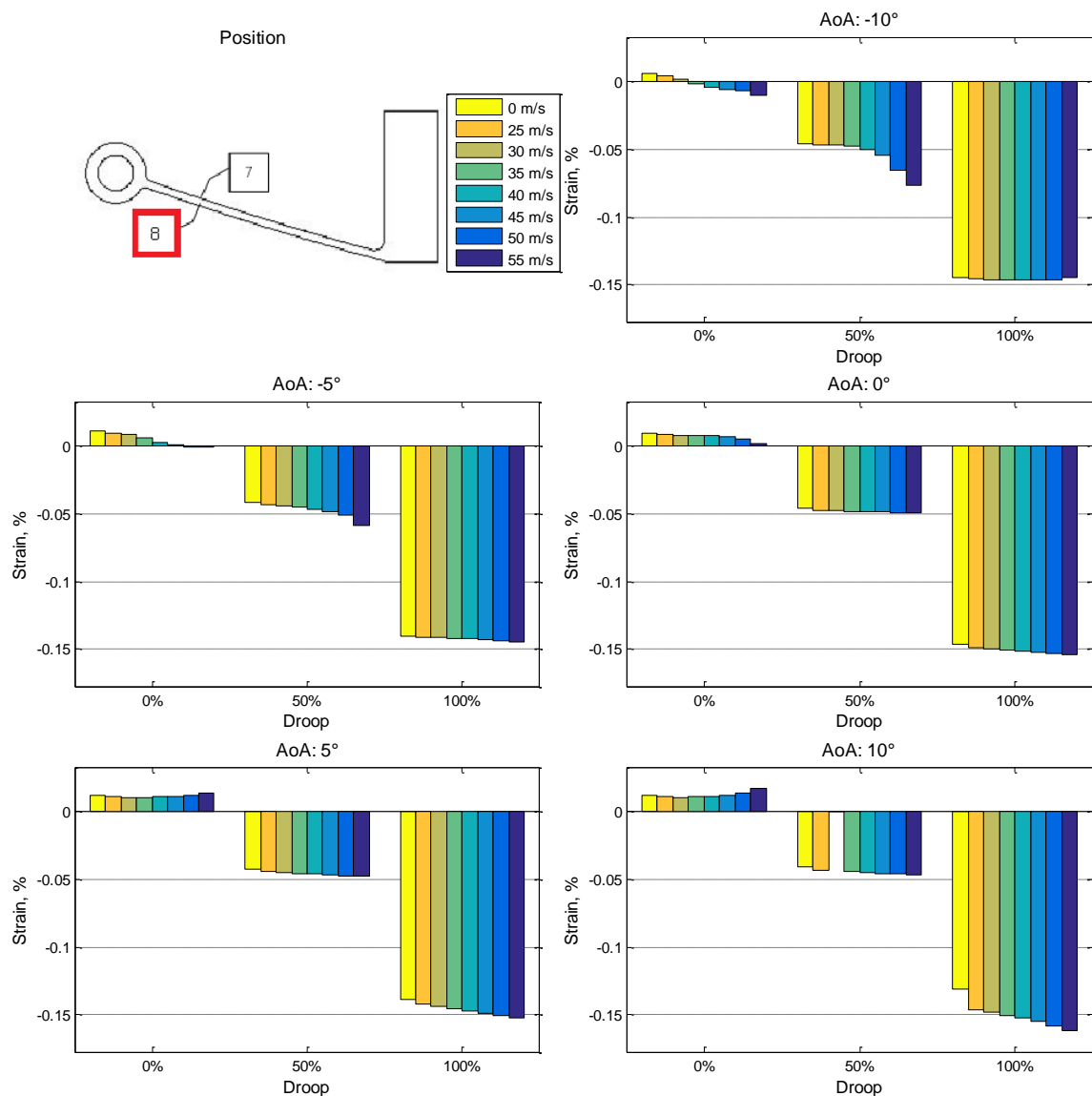


Figure 6. Strain gauge position OB8 strain results at different droop settings, angles of attack and wind tunnel speeds.

More comprehensive modelling of the material properties is required, capturing accurately the change in stiffness between the martensite and austenite phases. It is also difficult to machine and difficult to obtain in forms other than standard wire and low-thickness plate forms. Consideration of the future manufacture of parts from the material is required, such as through additive layer manufacturing as investigated by Haberland *et al.*¹⁵. The consideration of aircraft operating temperatures is also required given the dependence of material phase on temperature and may be appropriately designed through correct alloying with other substances¹⁶.

5. CONCLUSION

A droop-nose morphing wingtip was successfully designed, manufactured, and wind tunnel tested as per the aims of the NOVEMOR project. The wind tunnel test results have provided many insights into how to design morphing structures

for the future, including the need for the concurrent design of components in the morphing device, efficient optimization tools to fully explore the design space, and the further development of manufacturing technologies for superelastic smart material-based structures.

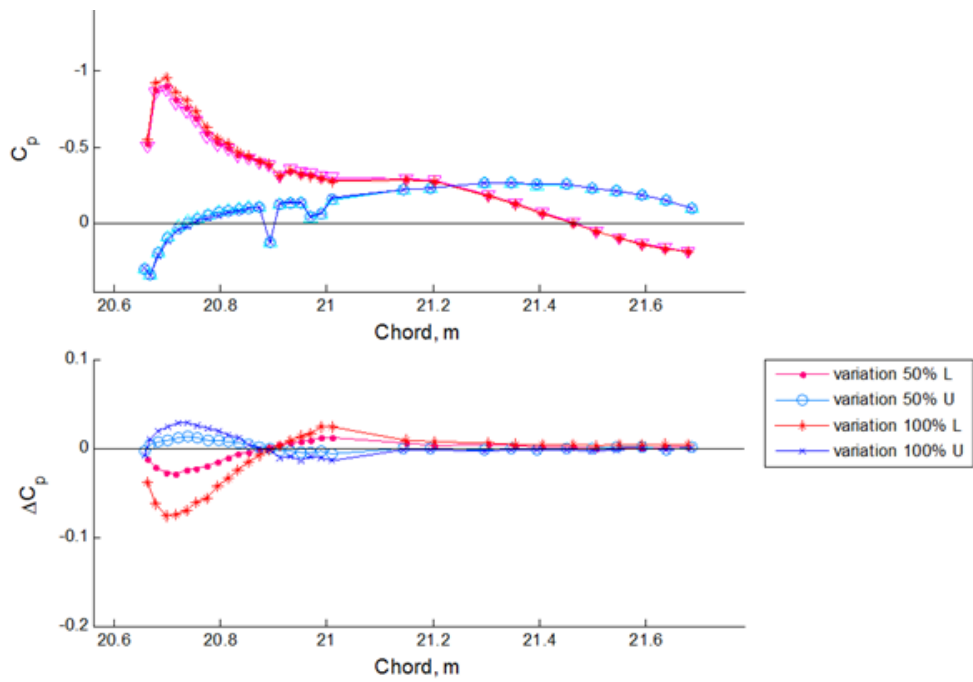


Figure 7. Surface pressure measurements at different droop settings. Bottom plot shows variation in c_p due to morphing.

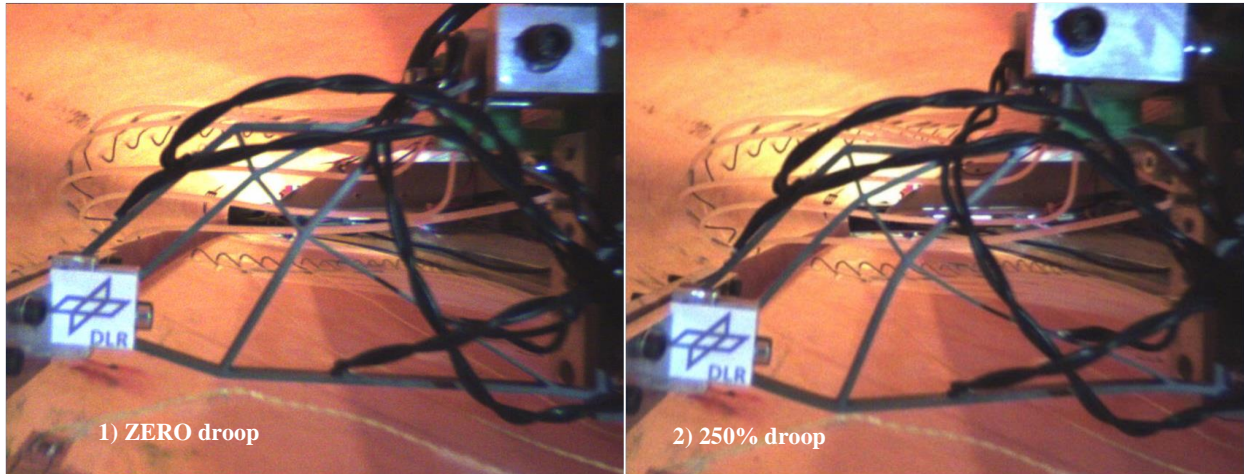


Figure 8. Photos of the inboard compliant mechanism without aerodynamic loading and cycling up to 250% actuator stroke. The extreme deformation is noticeable in the connection region with the actuator in the top right of the figures.

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