THE HIPERTILT PROJECT: DEVELOPING NEW AERODYNAMICS METHODS ADAPTED FOR TILT ROTOR AIRCRAFT

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ABSTRACT

The HiPerTilt project was launched by Leonardo Helicopters, in partnership with the Universities of Bristol and Glasgow and Innovate UK to address new requirements for CFD to support the analysis of existing, and the design and development of new, tilt rotor aircraft. The project was split in five work packages, focusing on both the airframe and rotor aerodynamics. The current helicopter design tools were assessed and validated for tilt rotor aircraft, and new optimisation techniques were developed and tested. The new methods were developed by the Universities in collaboration with the industry, and allowed research results to be implemented in the procedures of Leonardo Helicopters for the design and optimisation of both helicopters and tilt rotor aircraft.

1. INTRODUCTION[1]

Following the development of tilt rotor aircraft, a need for new, adapted, Computational Fluid Dynamics (CFD) methods in Leonardo Helicopters arose. Due to the lowering cost of computing power, and the progress of CFD methods, it is now possible to perform more complex simulations in shorter times. This advancement brought forward a need to understand which additional capabilities would be required from CFD, to increase its use, not only for tilt rotors, but also for standard helicopters.

The increased interest in tilt rotor aerodynamics research is not limited to Leonardo Helicopters: during the last few years, there has been a series of European research programmes focusing on this particular problem, with NICETRIP [1] being the lastest. While this project provided a thorough database on the aerodynamics of a tilt rotor in all flight conditions, additional work is still to allow for newly developed software to be used in the industry on a regular basis, and further work was needed to couple CFD methods with optimisation techniques to improve current aircraft and develop new ones. Due to the cost of CFD simulations, and the number of conditions to be tested, to represent all flight conditions tilt rotor aircraft may undergo, specific optimisation techniques, based on a limited number of simulations, have to be explored.

To solve this particular issue, Leonardo Helicopters decided to team up with the Universities of Bristol and the University of

Glasgow. Both Universities have a long-standing relation with Leonardo Helicopters, such as the rotorcraft DARP [2] [3], REACT [4] [5] and RTVP [6]. Furthermore, the HMB CFD code [7], developed by the University of Glasgow, has been used in Leonardo Helicopter for more than 10 years.

This paper describes the way the project was divided into work packages, and then look at the actual achievements, before highlighting the exploitation of the obtained results and drawing some conclusions for future collaborative projects.

2. WORK BREAKDOWN

HiPerTilt, a 4-year long project, started in April 2013, and was supported by Innovate UK. The work planned for the partnering universities was completed by end of March 2016, by which time all their main goals were reached. The main project aim was to develop and implement new design and optimisation tools specifically adapted for tilt rotor aircraft.

It was decided to split the work in the project into five work packages, as shown in Figure 1. The first three work packages aimed at improving the understanding, prediction and optimisation of the aerodynamics of the airframe, while the last two work packages focused on the rotor aerodynamics.

Work package 1, performed in Leonardo Helicopters, aimed firstly at validating the CFD methods for the simulation of a tilt rotor airframe. The second part of this work package studied the possible improvement and optimisation of the airframe to reduce the drag.

Work package 2 focused on the validation of the CFD simulations by running a wind tunnel test campaign, aiming at validating the CFD methods developed in Work Package 1.

Work Package 3, performed by the University of Bristol, aimed at developing their own optimisation techniques, and adapt them to the specific requirements associated with the development of tilt rotor wings. It also focused on the simulation of vortex generators for the wing, optimising their location and implementing vortex generator models in the CFD methods to replace the complex direct simulation of this device.

Work Package 4 looked at the development of CFD methods for the design and validation of tilt rotor aircraft. It was performed by Leonardo Helicopters and the University of Glasgow, in a close cooperation. The work covered the validation of multiple CFD methods for the simulation of tilt rotors, before focusing on rotor design and optimisation approaches. This work package also covered the coupling of acoustics methods from Leonardo Helicopters with HMB, and the development of higher-order schemes in HMB, to improve the quality of the acoustics predictions.

Work Package 5 focused on the more complex CFD simulation: the University of Glasgow used the HMB solver to simulate a full tilt rotor aircraft in flight, with the possibility of using rotating rotors or actuator disks, while Leonardo Helicopters carried out a study of the Vortex Ring State (VRS).

3. HIPERTILT'S ACHIEVEMENTS

In this section, the work performed in HiPerTilt will be described, focusing firstly on the aerodynamics developments relating to the airframe, before moving to the ones relating to the rotor.

3.1. Work Packages 1 and 2

The first step in the development of new optimisation approaches for the airframe was the validation of the CFD software in use in Leonardo Helicopters: Fluent [8], AeroFOAM [9] and HMB [7]. Four aerofoils were selected for this test, for which experimental data were available, all having a high thickness representative of the section of a tilt rotor aircraft wing. The high thickness is required for the presence of a shaft connecting the nacelles at each end of the wing, for safety reasons. All solvers gave satisfactory results, especially Fluent and HMB. The former was selected for further work, due to the experience of staff members working on the project. Further validation based on aerofoil simulations will be performed after results from the wind tunnel test from work package 2 will be made available. This test is scheduled to occur early in 2017.

The next step was the validation of Fluent for the simulations of the whole aircraft. The first test case selected was the ERICA airframe, that was tested in the NICETRIP project [1], and is shown in Figure 2. The results of this comparison proved good, with only a slight difference in the prediction of the onset of stall, which could be linked to the fact that the wind tunnel and the model support were not simulated. The results were thus deemed satisfactory, and a simplified geometry of the AW609 airframe (datum case) was simulated. Of particular interest was the propagation of the flow separation at the wing trailing edge, and along the span at high incidence (Figure 3). It was decided that the geometry optimisation should focus on delaying the onset of this flow separation, aiming at delaying the onset of buffet.

The work continued with the optimisation of the wing aerofoil. The main objective was to reduce the drag of the datum wing, while taking into account the constraints linked to tilt rotor wings, including the space requirement for the inclusion of the shaft connecting the two nacelles. Bernstein polynomials were used to describe the shape of the aerofoil, and an in-house optimiser, based on genetic evolutionary algorithms was developed. Two approaches were tested: the first one modified the whole aerofoil, the second one only modified the flaperon. In both cases, improvements were achieved at high incidence, and the stall was delayed. The airframe wing was then updated with the optimised section, and the wing twist optimised, showing a decrease in the drag at high incidences, and a delay in the drag divergence caused by the stall.

The focus of the optimisation was then shifted to the parts of the airframe that were shown to have a strong influence on the onset of the stall on the wings: the wing/fuselage junction and the shape of the actuator fairing, at the wing/nacelle junction. The surfaces to be optimised were parameterised in Altair HyperMesh [10]. The optimisation of the surfaces allowed to further delay the onset of stall and the associated high increase in the drag. Overall, the fully optimised design was able to reduce the drag of the airframe in cruise condition, as well as delay the stall, as shown in Figure 4. The onset of buffet, created by the trailing edge separation on the wings, was also significantly delayed.

3.2. Work Package 3

The first part of the work of the University of Bristol focused on aerofoil optimisation [11]. Two methods of aerofoil parameterisation were developed during the project: Singular Value Decomposition for full aerofoil optimisation and Radial Basis Functions for the optimisation of part of an aerofoil (such as a flap). A gradient based optimiser and a gravity based global search method were tested. OpenFOAM [12] was used to determine the aerofoil polars. During the whole optimisation process, meetings were held with Leonardo Helicopters to understand the constraints linked to the specifics of tilt rotor aircraft. The resulting optimisation was able to reduce the drag at cruise conditions, and delay the trailing edge separation at higher incidences, meaning a delayed onset of buffet.

Finally, the University of Bristol focused on the simulation of vortex generators [13], and optimised the spacing, placement and shape of the vortex generators on a NACA64(4)-421, which is representative of the thick aerofoils used for tilt rotor wings. Both rectangular and trapezoidal vortex generators were assessed. The drag could be decreased at cruise conditions, compared to the current design of vortex generators for the AW609, and the obtained optimised design is shown in Figure 5. Furthermore, various vortex generator source models were tested, to reduce the cost of CFD simulations of aerofoils with them.

3.3. Work Package 4

The first step was the validation of the currently used aerodynamics methods for the specific simulation of tilt rotors: the free-wake panel method ADPanel [14], and the CFD solvers HMB [7] and Fluent [8]. Leonardo Helicopters used the rotor of the XV-15 [15] as a reference for the current work, this rotor is the only tilt rotor freely available in the open literature. The XV-15 is shown in Figure 6. This choice was also influenced by the freedom to share and compare the results with the University of Glasgow's own simulation, without any restriction on both sides. Meanwhile, the University of Glasgow performed their own validation of the HMB solver, using the XV-15 rotor, as well as the comprehensive database available for the S-76 rotor [16] (as shown in Figure 7), and the JORP propeller, allowing to demonstrate HMB for simulating rotors and propellers. This was completed by a comparison with the NICETRIP database later in the project, once it became available. All developed methods were validated, as shown in Figure 8 and this exercise in Leonardo Helicopters also proved an opportunity to train young engineers in the use of the various available aerodynamics methods.

The University of Glasgow then interfaced HMB with BENP [17], the acoustics prediction tool in use in Leonardo Helicopters. This work was done with a high level of exchanges between the two partners, including a placement of the researcher at Leonardo Helicopters. This led to the ability now in Leonardo Helicopters to couple the use of HMB and BENP. Furthermore, the University of Glasgow also developed their own FWH tool, to allow them to produce their own acoustics predictions, which was not possible with BENP due to its lack of availability in Glasgow. In order to decrease the dissipation of acoustic waves in the flow field, the University of Glasgow also developed and implemented higher-order schemes, aiming at improving the tonal noise acoustic field in the vicinity of the rotor.

The main task in Work Package 4 for Leonardo Helicopters consisted of developing a new approach for optimising tilt rotors [18]. The XV-15 rotor was chosen as a reference for this study, and the aim of the optimisation was to improve the hover figure of merit and propeller efficiency, while keeping geometrical constraints imposed on the original aircraft. After extracting the conditions experienced by each aerofoil section along the blade span in both helicopter and aircraft mode, a new aerofoil optimisation method was applied. Bernstein polynomials were used to define the aerofoil shape, and the use of a gradient-based Adjoint Optimisation Method, developed by the University of Glasgow [19], for a multi-point objective function was enabled by multiple meetings between them and Leonardo Helicopters. The newly generated aerofoils were then used for an optimisation of the blade sweep, twist and chord, using the ADPanel panel method, and the results were validated using a CFD simulation with HMB, showing a clear improvement in both hover at high thrust, and aircraft mode at all speeds, as shown in Figure 9. The University of Glasgow also performed a demonstration of the Adjoint Optimisation Method on a full XV-15 rotor, proving that this optimiser could be applied to a full rotor directly.

3.4. Work Package 5

The University of Glasgow demonstrated HMB on a complete tilt rotor aircraft in all possible configurations, using the NICETRIP geometry. Simulations at various experimental test points corresponding to all three flight phases (hover, cruise and transition) were selected and run with HMB [7], as shown in Figure 10. The Chimera mesh approach was selected, allowing for easier modifications of the positions of the airframe components (nacelle, outer wings, rotors), and the rotors were also replaced with various models of actuator disks in some cases, to assess the ability of the actuator disks to capture the changes in the wing loads due to the passing rotor blades. The obtained results compared well with the experimental data from the NICETRIP project [20], and the whole aircraft have been successfully tested at Leonardo Helicopters to assess the possibilities this new capability will offer.

Finally, the Vortex Ring State (VRS) was studied in Leonardo Helicopters [21]. This flight condition is important for tilt rotor aircraft design and defining the conditions in which it may occur, to prevent the pilots reaching such conditions, is an important part of the flight tests of a new aircraft. Simple momentum theory based models were tested to predict the onset of VRS, and a new methodology to assess the location of the VRS area in the flight domain was devised. Finally, the HMB and Fluent CFD software were assessed for the simulation of rotors in VRS, using multiple approaches to evaluate the best way to simulate this case. Both solvers produced similar results, predicting a high variation of the loads in the VRS region.

4. EXPLOITATION AND DISSEMINATION

The HiPerTilt project allowed all partners to have a deeper understanding of the specifics of tilt rotor aircraft aerodynamics. The newly developed tools, taking into account industrial requirements, have already been used in Leonardo Helicopters, and will also be applied to future tilt rotor aircraft being developed, such as the demonstrator in Clean Sky 2. Furthermore; all the software developed in HiPerTilt were also designed to be applicable to conventional helicopter simulations.

Young engineers gained experience in the use of CFD methods, which will allow them to study more complex cases. This was particularly highlighted by simulations in the Vortex Ring State study, which required a high level of skills. This study also explored new approaches to define the boundary of the flight envelope, which can be reused for future products.

The project also improved the visibility of the partnering universities, who used the opportunity to publish their work in many renowned conferences. The developed tools can also be reapplied in other domains, such as fixed wing aircraft, or even wind turbines.

Finally, the project helped developing a privileged link between Leonardo Helicopters and the Universities of Bristol and Glasgow, and trained research staff in the rotorcraft domain, aware of the industrial needs and requirements for CFD.

5. CONCLUSION

The HiPerTilt project allowed Leonardo Helicopters to develop its ability to simulate tilt rotors using CFD tools. The development of the new software was performed by the Universities of Bristol and Glasgow, with a strong involvement from engineers in Leonardo Helicopters. These tools were then integrated in optimisation procedures that have since been applied to the design of current and future tilt rotor aircraft within the company. Furthermore, they were developed since the beginning of the project to be also applicable to standard helicopters, rather than strictly focusing on tilt rotor aircraft.

To reach a high level of compatibility between the software developed in the universities and the company requirements, frequent meetings were held between the involved partners on all tasks, on a monthly basis when possible, benefiting from video conferencing facilities when travel was difficult to organise. For the tasks requiring more exchanges; various placements at Leonardo Helicopters were offered to the researchers of the universities; allowing for better communication between the partners, and a more efficient integration of the developed tools into the company's operating procedure. This constant exchange of information between the partners was key to the success of the project.

ACKNOWLEDGEMENTS

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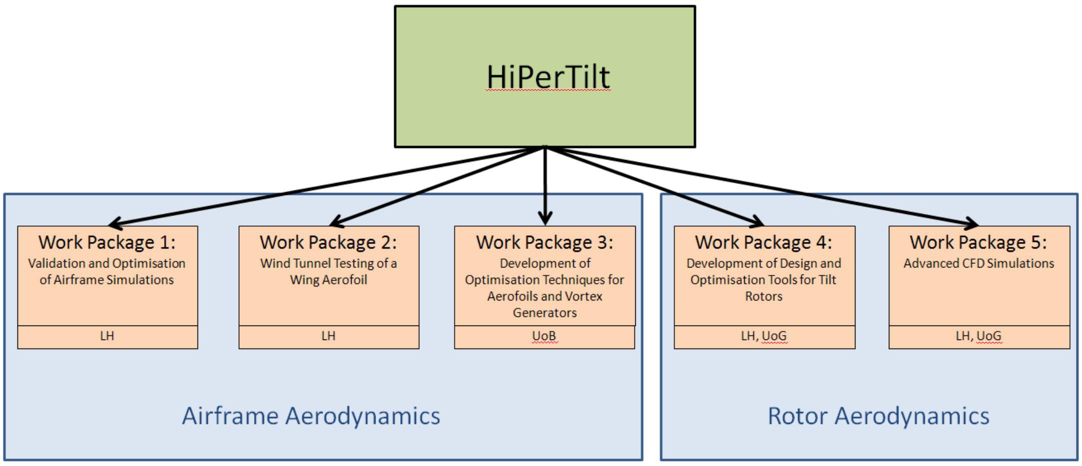


Figure 1: Work Package Distribution in HiPerTilt, describing the partner(s) taking part to each work package (LH: Leonardo Helicopters, UoB: University of Bristol, UoG: University of Glasgow).

Figure 2: The ERICA Model Being Tested in NICETRIP [1].

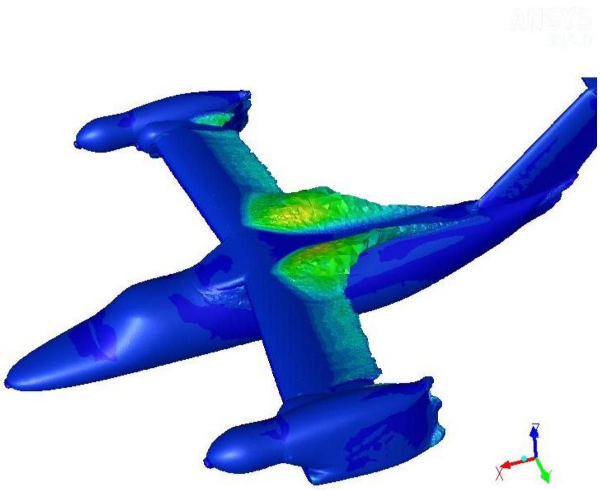


Figure 3: Datum Airframe: Flow Separation Propagation Across the Wing During Stall.

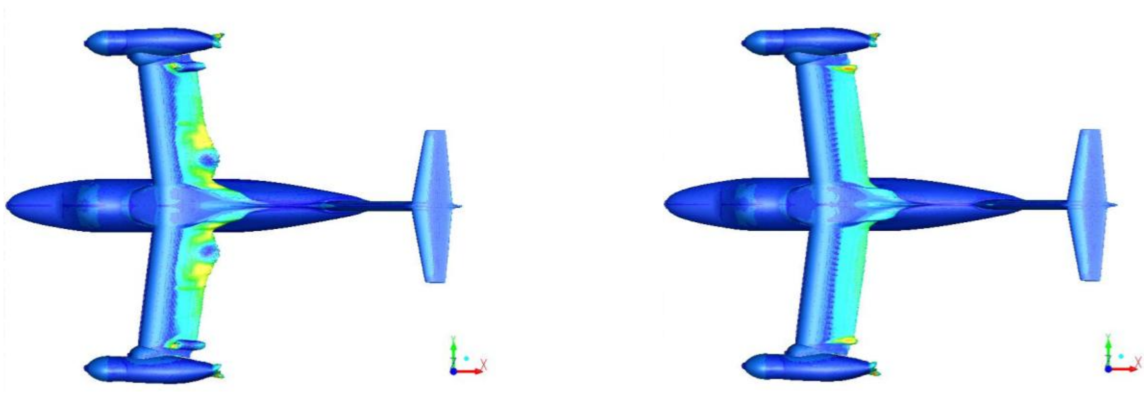
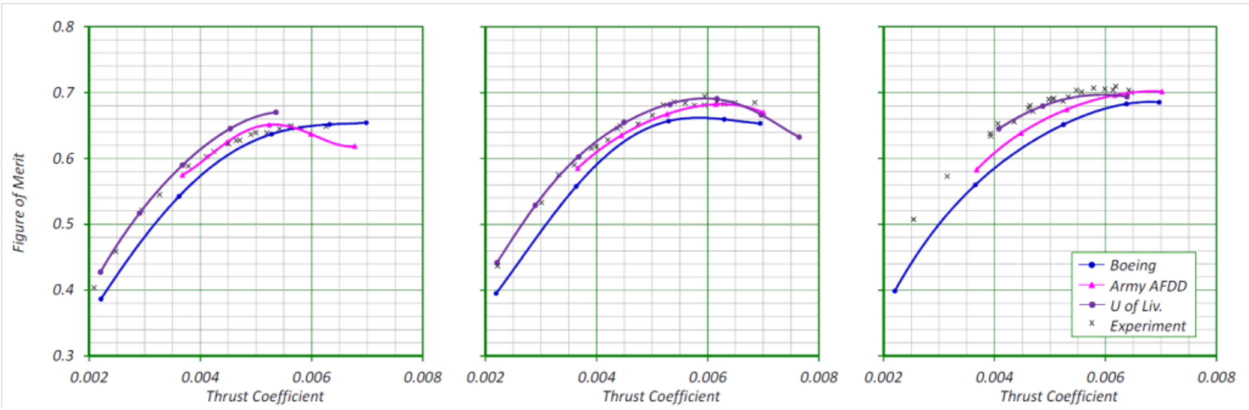


Figure 4: Comparison of the Stalled Areas Between the Datum Aircraft (Left) and the Optimised One (Right).

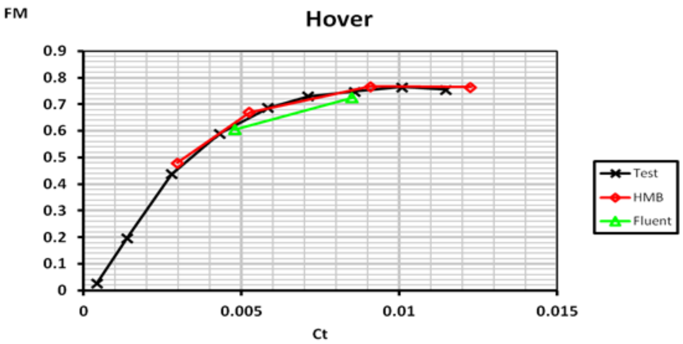
Figure 5: Comparison of the vortex generators and the trailing vortex before (left) and after (right) the optimisation, based on the NACA64(4)-421 aerofoil, performed by the University of Bristol [13].

Figure 6: The XV-15 Aircraft, [15].

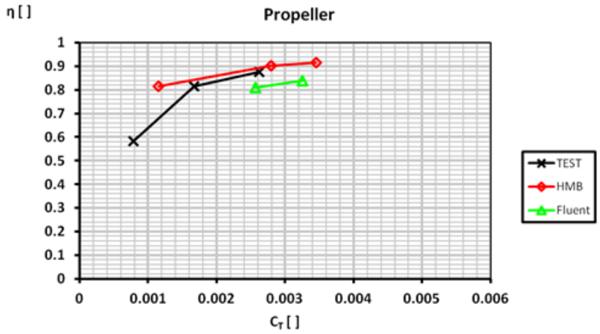


Rectangular tip Swept-taper tip Anhedral tip

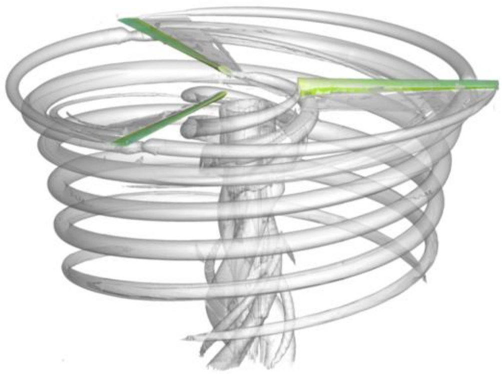
Figure 7: Validation of the HMB Solver and Comparison with Other CFD Solver using the S-76 Rotor with multiple tip geometries, University of Glasgow [16].



a) Comparison of the predicted Figure of Merit with Experimental Measurements

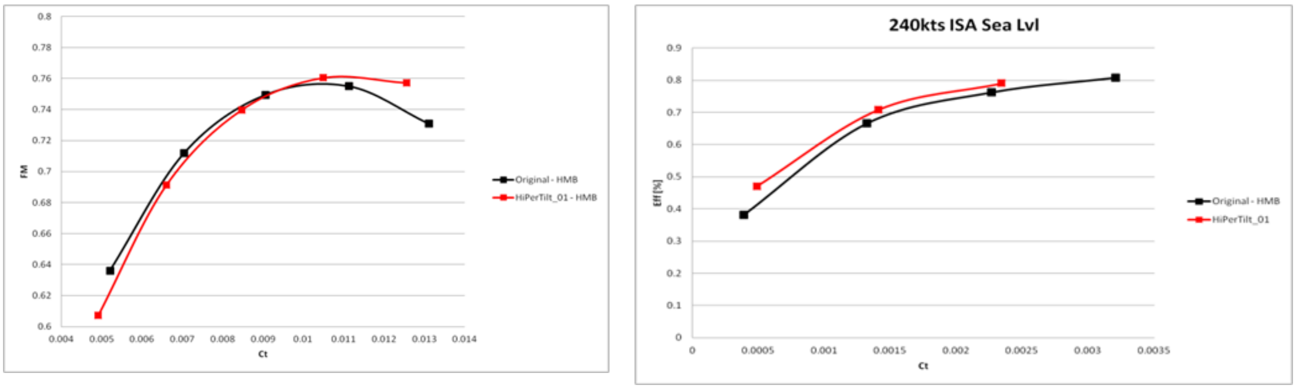


b) Comparison of the predicted Propeller Efficiency with Experimental Measurements



c) Isosurfaces of Q-criterion

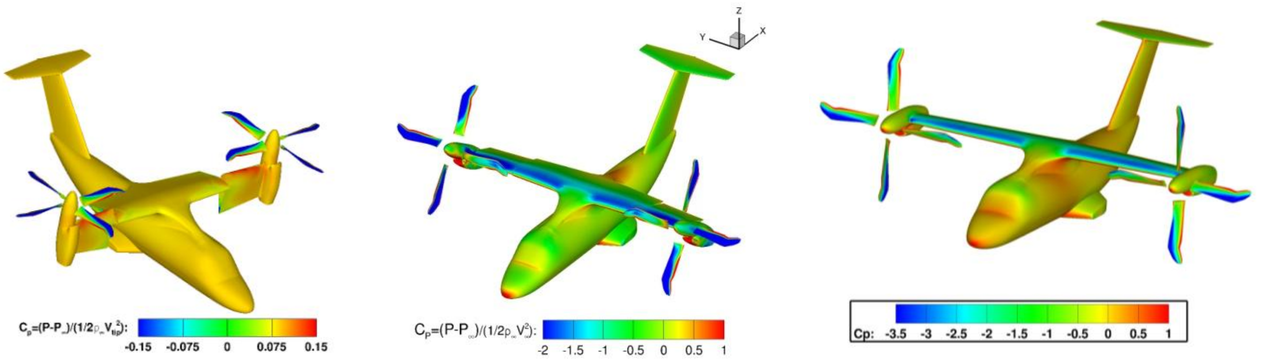
Figure 8: Validation of the CFD solvers using the XV-15 rotor, [18].



a) In Hover

b) In Cruise

Figure 9: Comparison of the Figure of Merit (hover)/Efficiency (Cruise) of the Original and Optimised Rotors, [18].



a) In Hover

b) In Transition

c) In Cruise

Figure 10: Pressure Coefficient Distribution on the ERICA in Various Flight Modes, University of Glasgow [20].