BERP IV
Aerodynamics, Performance and Flight Envelope

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ABSTRACT

This paper summarises the aerodynamic design and flight test performance results from the AW101 BERP IV Technology Demonstrator Programme that commenced in October 1997 and concluded in summer 2007. Aerodynamically, BERP IV represents a development of the BERP III main rotor blade whilst changes were also made to the dynamic and structural design. New blade technologies were introduced whilst the blade manufacturing process was also improved. The paper covers the aerodynamic design process including considerations on twist, aerofoils and planform shape, and the analytical and test techniques used to study and evaluate the blade performance. The main rotor was demonstrated on the AW101 aircraft from September 2006, and the paper details the hover and forward flight performance, and the retreating blade stall envelope.

NOMENCLATURE

1R	Once-per-revolution
D	Drag
IGE	In Ground Effect
L	Lift
n	Nominal rotor speed
OGE	Out of Ground Effect
TAS	True Air Speed
W	Weight
δ	Pressure ratio
θ	Temperature ratio
σ	Density ratio

INTRODUCTION

The British Experimental Rotor Programmes (BERP), in partnership with the UK Ministry of Defence (MoD) have operated since the early 1970's. The programmes have sought to advance technology in aeromechanics, materials and manufacturing to improve the design of rotor blades. The technology has been widely utilised within AgustaWestland and has enhanced the capability of the aircraft. The BERP IV programme (beginning October 1997) looked to build upon previous technology developed in BERP I, II and III in terms of composite manufacture, materials, structure and aeromechanics, but with a wider remit. The objective of BERP IV was to provide benefits across all aspects of aircraft performance and cost. Further background on the overall BERP IV programme can be found in Reference 1.

This paper concentrates specifically on the development of the BERP IV aerodynamics and the subsequent flight testing programme in terms of aircraft performance in hover and forward flight, and finally discusses the rotor retreating blade stall envelope.

Presented at the 34th European Rotorcraft Forum, Liverpool, UK, September 16-18, 2008.

BERP IV PERFORMANCE OBJECTIVES

Through continual discussions with the customer the performance objectives of BERP IV included improving the payload/range capability of the aircraft, which therefore required improvements in hover and forward flight. The eventual aim was therefore to improve the hover performance of the BERP III rotor whilst maintaining the already impressive forward flight performance.

BERP III has been utilised on the Lynx and AW101 aircraft for a number of years and has proven its performance through the Lynx World Speed Record (Reference 2) and continued service on these aircraft for the MoD and other customers, such as on the AW101 in SAR role (Reference 3). The BERP IV programme looked to develop technologies that were applicable to multiple platforms but initial developments progressed with a blade for use on the Lynx aircraft. However, in light of an impending operational imperative and due to commercial needs it was decided to switch development of the blade to the AW101. Due to the nature of the programme this had minimal disruption on the design process. The BERP IV aerodynamic improvements were a development of the existing BERP III design. The BERP III design was re-assessed in terms of twist distribution, planform shape and aerofoils. The following sections detail the design features considered in the BERP IV design process.

TWIST

To address the hover performance requirement the obvious choice was to increase rotor twist, which in-turn led to a requirement to re-examine the aerofoil philosophy. A study was conducted to ascertain the ideal overall twist and the actual twist distribution. This included numerical analysis using in-house rotor codes and Computational Fluid Dynamics (CFD), and wind tunnel testing in Phase 1 of the BERP IV programme. The WHL hover and forward flight codes were used to assist with the optimisation of the tip twist distribution to balance the requirements of forward flight and hover.

Euler CFD predictions have additionally been conducted for the BERP III and BERP IV blades utilising HMB. Various twist values between 8° and 18° were considered before finally opting for 16°, which was a good compromise between improving hover performance and the risk of high vibration. Euler CFD predictions for BERP III and BERP IV have confirmed the improvement in the loading distribution for BERP IV and hence reduction in induced power. The blade tip shape and aerofoil design were subsequently assessed to ensure compatibility with the relatively high level of twist.

PLANFORM SHAPE

The blade tip shape design philosophy was then reviewed by considering the BERP III tip shape, contemporary and new tip designs. Consideration was taken of their hover, advancing and retreating performance, with knowledge that good retreating blade performance relates directly to good hover performance through minimising the required blade area for a given cruise design point and hence profile power. Figure 1 shows various tip designs that were considered in this process. The assessment comprised of both numerical analysis and non-rotating wind tunnel wing tip tests.

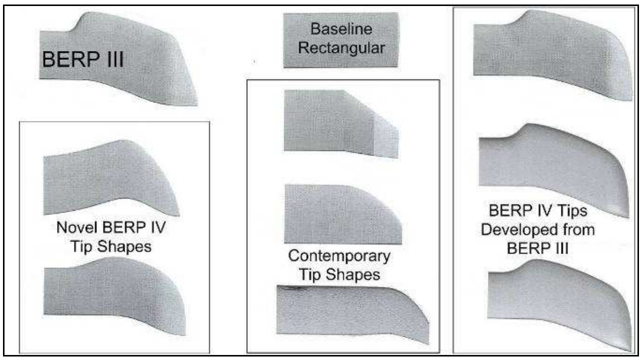

Figure 1 - Various Tip Shapes Assessed During the BERP IV Programme

Comparisons between CFD and experimental data on the BERP tip date back to 1989 when an Anglo-American collaborative programme enabled a comparison of fixed-wing wind tunnel pressure distributions and results of NASA CFD runs on the Cray YMP, Duque, Ref 4, and Brocklehurst and Duque, Ref 5. Good agreement was found with the fixed wing tests on the Lynx-BERP-planform, and subsequent high Mach number advancing blade cases instantly revealed the so-called 'shock-eating' qualities of the BERP notch and swept tip as shown in Figure 2.

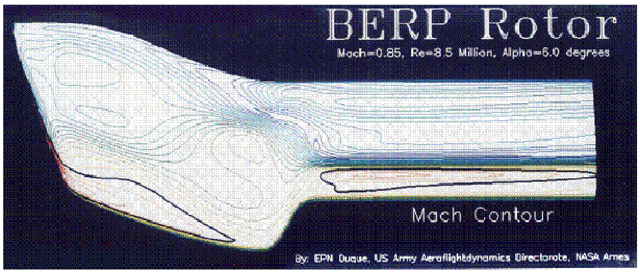

Figure 2 – Duque CFD Analysis Showing Shock-Eating Performance of the BERP Tip

Since then, CFD analysis has been used to explore design trade-offs for the advancing blade, (improving from use of a wing at constant Mach number, to sheared-Mach number, rotating blade snap-shots and full-rotor Euler as presented in Figure 3, to nowadays the possibility of full-rotor unsteady Navier-Stokes approach), while the retreating blade development has been guided by further wind tunnel tests on a specially constructed modular wing. This multi-strand approach provided a good understanding of how the tip design parameters of sweep, taper, offset, anhedral, and aerofoil selection affect both the advancing and retreating blades (and hover), and formed a sound basis for achieving design goals for BERP IV.

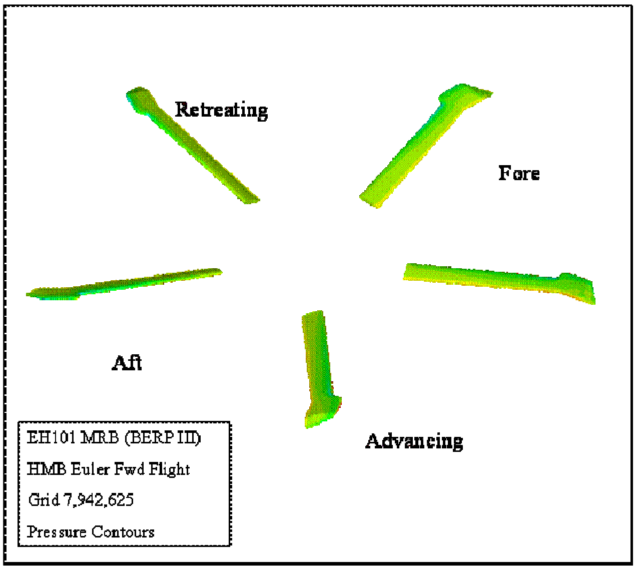

Figure 3– Full BERP III Rotor Euler CFD Predictions in High Speed Flight

The analyses concluded that the BERP tip design maintains attached flow up to the highest angles of attack and hence produces the best retreating blade performance of all the designs considered. With slight modifications to the local twist distribution, the tip design was found to be compatible with the increased twist necessary to minimise induced power in hover. Further conclusions drawn were that the thin tip section and high sweep angles at the tip produced the best advancing blade performance and leads to a low noise solution. Capitalising on the already established BERP III design philosophy with some refinements possible through improved analysis techniques would provide the optimum solution.

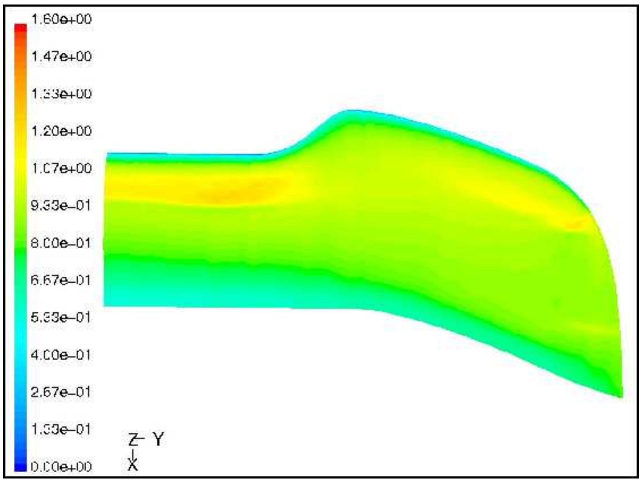

Figure 4 – BERP IV High Speed Mach Number Contours From CFD

During the early stages of the BERP IV design the advancing blade performance was assessed using a commercial, unstructured CFD code (Fluent). At this time, the simulation used a sheared Mach number profile to represent the onset flow for the tip of the advancing blade. Contours of Mach number are shown in Figure 4 for a high speed forward flight case, and as with BERP III the shock can be seen to stop at the notch and is not propagated over the swept tip surface.

The wind tunnel tests verified the final tip design by comparing a variety of tip designs with the same aerofoil sections and same nominal twist, tested under identical free-stream and incidence conditions. An illustration of the stall performance at the same high angle of attack is shown in Figure 5, which uses wool tufts to highlight regions of separated flow.

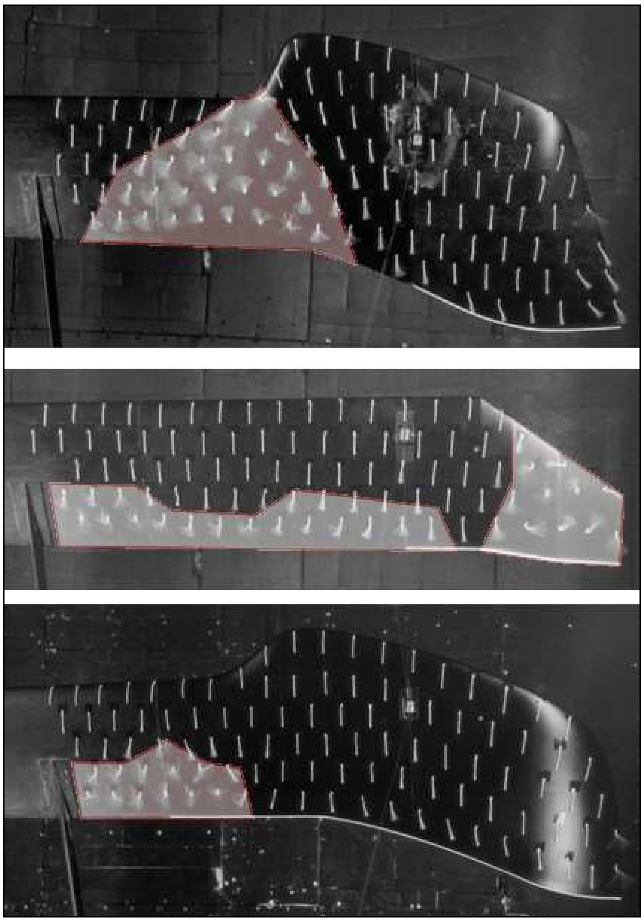

Figure 5 – Wind Tunnel Wool Tuft Comparison of Tip Stall Characteristics at High Angle of Attack

BERP III is shown in the upper figure where there is attached flow over the majority of the tip, with a highlighted area of separated flow in the notch region, evident at this high incidence. The fact that the flow in the outer tip region remains attached to such high angles helps to suppress the rise in control loads and alleviates retreating blade stall. The middle figure is a generic swept tapered tip, which shows separated flow over the entire swept tip panel with some separation at the trailing edge across the span of the blade section. The fact that the swept tip panel is stalled will result in high drag and hence poor rotor performance, and high control loads. Finally, the lower figure shows that BERP IV also demonstrates the attached flow across the tip section as it was for BERP III, but with a marked reduction in the stall in the notch region. The BERP IV tip therefore retains and improves upon the high incidence capabilities of BERP III.

Anhedral is retained in the outer tip as it has proven very beneficial in terms of hover performance and is utilised in forward flight to reduce 1R control loads. The ultimate anhedral angle is increased from 20° to 25° with a small increase in the total vertical displacement of the tip, whilst the shape has been smoothed to aid in manufacture.

Thus the planform of the new BERP IV blade retains the best features of the BERP tip, while improvements in the detailed shape have lead to savings in profile and vortex drag to provide an excellent passive blade tip design solution to classical helicopter advancing and retreating blade design questions. At the same time, the smoother outline of the BERP IV has lead to cost savings in manufacture.

AEROFOILS

BERP IV has retained the BERP III integrated design philosophy of utilising complimentary aerofoil sections, twist and tip shape. The increase in twist and desire to enhance manufacturability led to an opportunity to revise and refine the aerofoil designs. The BERP III design utilised an aft-loaded high-lift aerofoil in the outboard sections that required a reflex cambered inboard section with nose-up moment to balance the moments on the blade. With the increased twist of the BERP IV blade it was essential to have a high-lift inboard aerofoil section, which subsequently required the use of zero pitching moment aerofoils throughout the blade. In the interval between BERP III and BERP IV programmes, several aerofoils were designed and tested, and several methods for the numerical design and evaluation of aerofoils were explored. This initiative at Westland meant that a new series of aerofoils could be designed in-house to fulfil the BERP IV requirements. A new family of high-lift, low pitching moment aerofoils were tested in the ARA 2D pressurised transonic wind tunnel, which comprised static, oscillatory and ramped test conditions. The tests were conducted at Mach numbers from 0.3 to 0.8 at full scale Reynolds numbers, and at a range of frequencies and ramp rates. These results allowed comparison with the existing BERP III aerofoils and provided the unsteady aerodynamic characteristics required for use in the in-house rotor analysis methods.

The first aerofoil designed was that at 75%, to replace the RAE9645 that was used as the main lifting aerofoil section for the BERP III blade. The design remit was to produce a high lift section suitable for use at moderate to high Mach numbers that matches the RAE9645 in terms of lift and drag, but with zero pitching moment. These aims were met, with ARA wind tunnel quasi-static test data showing that at Mach numbers of between 0.4 and 0.5 the maximum lift coefficient increased by between 1% and 2%. The wind tunnel tests also confirmed that this high lift performance was achieved with a greatly reduced pitching moment. These improvements were confirmed through dynamic tests.

Through the increased twist of the rotor, the 50% aerofoil was designed to have good high-lift performance, again with zero pitching moment. The high lift and high L/D at zero pitching moment was designed to be achieved at a lower Mach number than the 75% aerofoil. The performance of this aerofoil was proven to be significantly better than that of the BERP III equivalent.

The inboard aerofoils were designed to be from the same family, which would ensure the high performance of interpolated aerofoils. This proved to be the case when interpolated aerofoils at the root and 82% radius were assessed and little modification was required for optimum performance. The fact that the aerofoils were from the same family with similar shape characteristics meant that they produced a continuous smooth surface that was ideal for high quality repeatable and stable manufacture.

A further aerofoil was designed at 86.6% at the outer edge of the notch. This was designed to replace the RAE9634 used on BERP III, to meet the specific requirements of the BERP IV tip design. The objective here was to improve the L/D performance at mid to high Mach number. The aerofoil tested was gradually refined during the final design through use of the aerofoil codes. The modifications were small and the subtle changes in characteristics have been taken into account in the rotor codes by correcting the test data using the aerofoil analysis methods.

From the outer notch station the aerofoil smoothly blends to the tip section at 95.5%, where a modified RAE9634 is retained due to its excellent high speed characteristics (Reference 6).

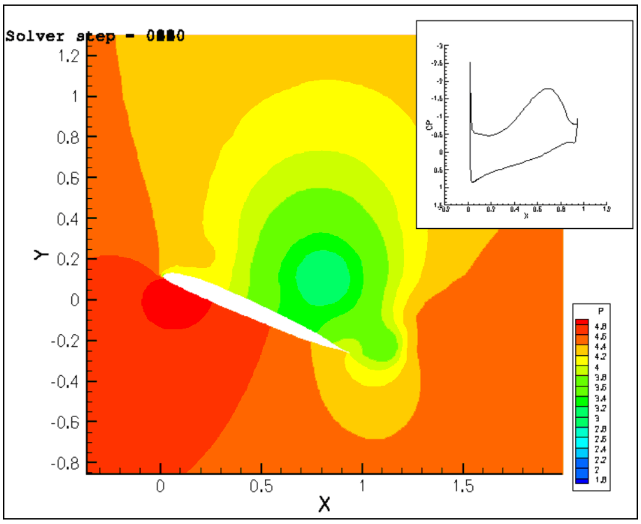

Figure 6 – Navier-Stokes CFD Predictions of BERP IV Aerofoil Ramp Performance

Throughout the aerofoil design process, a lot of emphasis was placed upon CFD analysis; initially using 2D aerofoil codes such as MSES and BVGK, and ultimately both steady and unsteady Navier-Stokes analysis were used. Recent analyses using the Helicopter Multi-Block (HMB) CFD code (Reference 7) with the SST turbulence model option has provided a good match to wind tunnel drag measurements. The unsteady simulations followed exactly the same test programme as the ARA testing, including both oscillatory and ramp testing. Figure 6 shows an example of a BERP IV aerofoil ramp case at mid Mach number and high incidence during dynamic stall using HMB.

ACOUSTIC CONSIDERATIONS

The BERP IV blade was designed to retain the excellent acoustic capabilities of BERP III. The retreating blade stall performance allowed the BERP III rotor to have a very low tip speed that is paramount to low acoustic signatures whilst the forward flight performance benefits of the tip design limit the presence of shocks on the advancing side. Figures 3 and 4 have shown the capability of the notch in stopping the shock propagating outboard until much higher Mach numbers than conventional tip designs and the BERP tip geometry eliminates shock de-localisation at the tip. This unique characteristic of BERP tips reduces shock induced noise allowing the blade to operate effectively and quietly at high Mach numbers. The combination of low tip speed, made possible because of the high retreating blade stall performance, and the benefits of the notch in forward flight have allowed the blade to operate well into the transonic regime before there is significant presence of shock induced noise. Reference 2 has shown that the BERP rotor can in fact achieve a 45 knots speed increase for the same nominal blade area and tip speed, over a conventional rectangular blade, and the benefit has been shown to increase at the higher loadings.

FINAL BLADE AERODYNAMIC DESIGN

Key features of the final aerodynamic design of the BERP IV demonstrator blade are shown in Figure 7.

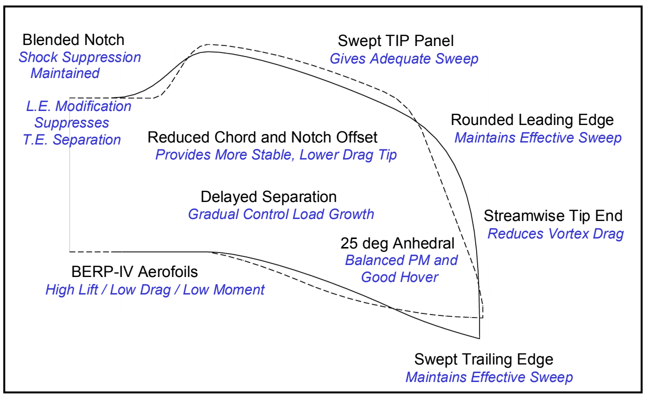

Figure 7 - Comparison of BERP III and BERP IV Tips

The complete BERP IV blade with its new aerofoils, twist and tip shape was analysed in full by a variety of methods. These included blade-element method assessments using the WHL forward flight performance code, CFD analysis of the advancing blade and anhedral studies backed up by a series of wind tunnel tests. The effectiveness of the improvements in the BERP IV design are confirmed in Figure 8, which shows Euler CFD predictions of pressure coefficient in hover for BERP III and BERP IV. The pressure contours reveal how BERP IV has retained and improved upon the good features of the BERP III blade. The suction peaks at the tip and inboard of the notch have been reduced with the loading distributed more evenly thus reducing the loading gradients.

Finally, the blade element analysis approach was used to assess the performance of the rotor on the AW101, and revealed the forward flight performance benefits at high loading conditions.

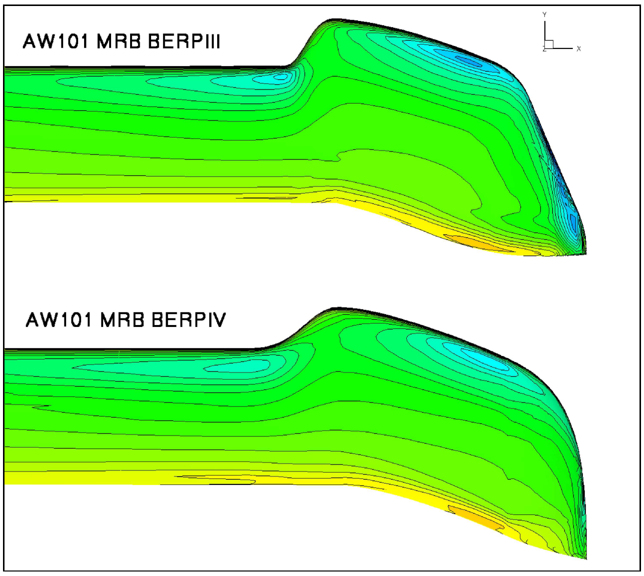

Figure 8 – Euler CFD Pressure Contours for BERP III and BERP IV in Hover

BERP IV FLIGHT TEST RESULTS

The demonstrator programme accumulated 75 hours of flying during which the rotor performance was verified at a limited number of test points, which included qualification flights for a Merlin Mk3.A urgent operational requirement. The performance element of this programme included level flight and hover performance, and flight envelope validation.

The first flight of the BERP IV demonstrator blade took place on the AW101 CIV01 aircraft on September 26th 2006 and included some preliminary performance assessments particularly in hover while first flight also achieved forward speeds up to 120 knots. The test programme continued on the dedicated test aircraft (ZJ117) with first flight taking place on January 12th 2007 (Figure 9). Within the test programme the aircraft demonstrated a maximum speed of 198knots TAS and operated at the increased take-off weight of 16500kg.

Figure 9 – BERP IV Trials Aircraft First Flight

Hover Performance
A tethered hover technique was utilised to provide the definitive hover performance of the BERP IV equipped ZJ117 aircraft (Figure 10). The tethered hover technique allows rapid gathering of data at a range of aircraft weights in OGE and IGE conditions. The testing included variations in main rotor speed giving an assessment of the effect of Mach number on hover performance.

Figure 10 - Tethered Hover

The test technique involves varying the tension in the cable with collective pitch thus providing a variation in thrust. The aircraft was positioned directly over the tether point and the cable kept vertical through the use of ground marshals. All testing was conducted in early morning conditions with wind speeds of less than 3 knots. Cable lengths of between 10ft and 120ft were used to simulate IGE and OGE conditions. The clear benefits in hover performance of the BERP IV main rotor blade are demonstrated in Figure 11 with comparison to the BERP III rotor. Benefits of greater than 5% were achieved, which will greatly enhance the payload/range capability of the aircraft. The figure also shows the quality of the original performance predictions providing great confidence in the tools and predictive techniques utilised in the design process. As expected, the test programme confirmed the minimal effect of Mach number on rotor performance up to the conditions tested.

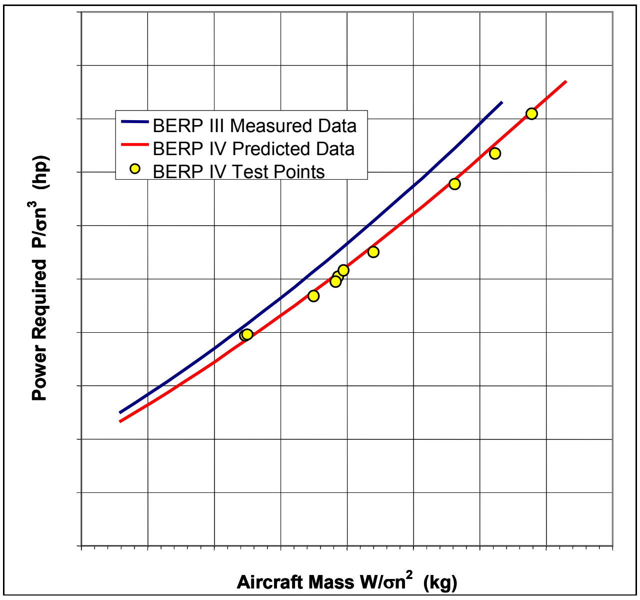

Figure 11 - Hover Performance

Forward Flight Performance
The forward flight performance assessment covered both power consumption and flight envelope exploration. Figure 12 summarises the performance test flight conditions, including steady 30° banked-turn flights for flight envelope confirmation.

The performance flights were conducted on the ZJ117 aircraft at four weight conditions, and at a chosen weight 2 separate $n/\sqrt{\theta}$ conditions were flown to assess the effect of tip Mach number on forward flight performance. Level flight performance testing was conducted using the constant W/δ test technique, whilst maintaining a constant equivalent main rotor tip Mach number, which ensures that a constant value of $W/\sigma n^2$ is achieved. All testing was conducted with strict limits on the rates of climb and descent.

The design aims of the programme were to maintain the forward flight performance of BERP III whilst improving hover performance. However, some forward flight gains were expected due to refinements in aerofoils and the tip design, particularly at the high loading conditions where the blade would be operating closer to its limits. The predicted benefits at high loading conditions are important to meet the expected future growth of the AW101 aircraft. These expectations were realised in the level flight performance tests, which showed near identical performance at the lower loadings but significant improvements at high $W/\sigma n^2$. Figure 13 shows a comparison of BERP III and IV performance at a constant high $W/\sigma n^2$ where performance benefits up to 10-15% in power are evident that can also be translated into significant gains in forward speed for a constant power.

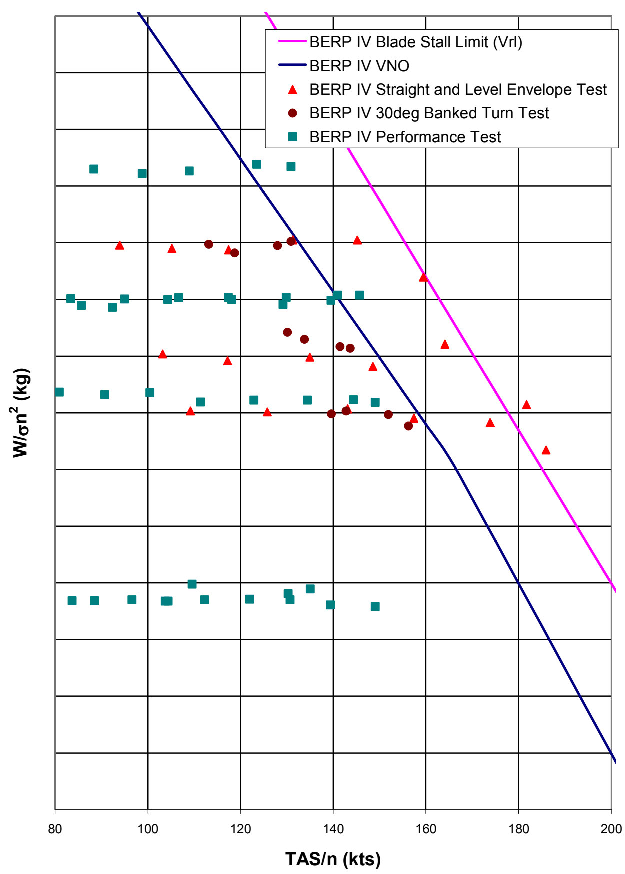

Figure 12 – BERP IV High Speed Performance Test Conditions

Performance testing at a fixed $W/\sigma n^2$ but varying $n/\sqrt{\theta}$ showed that within the range tested there was little or no change in performance of the aircraft with variation in $n/\sqrt{\theta}$. This verified the high Mach number performance of the BERP IV blade and demonstrated that the rotor could operate to lower temperatures without detriment to performance.

The benefits in both hover and forward flight performance capability clearly have a benefit on the mission capability of the aircraft. In fact, typical mission improvements for the Merlin Mk3.A through use of BERP IV include a 26% increase in radius of action for a troop transport mission, 20% greater load for an external lift mission or 19% greater time on location for a surveillance mission.

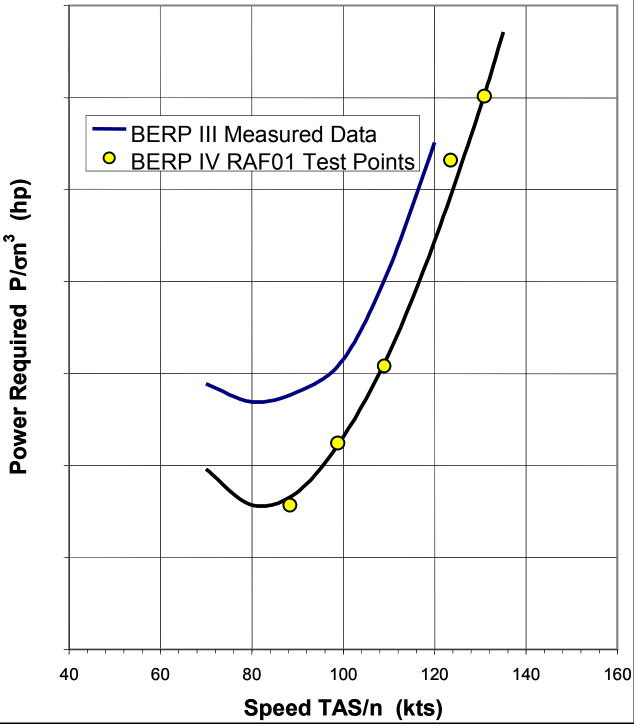

Figure 13 - Forward Flight Performance

Rotor Limited Flight Envelope

Where appropriate, an aircraft flight envelope is limited by the onset of retreating blade stall, which is in-line with UK Def Stan 00-970 requirements. This ensures that the aircraft does not encounter blade stall within the operational envelope. The onset of stall is most clearly indicated by the rise in pitch link loads, but is indicated also by power and control angle divergence. Careful attention is also paid to the control load waveforms around the azimuth that can provide definitive signs of stall on the rotor.

Prior to flight testing, the rotor envelope was identified through the use of a WHL rotor performance code that incorporates a Beddoes unsteady aerodynamics model (Reference 8) and elastic torsion modes to provide a full stall-flutter analysis capability. Taking into account the aerodynamic and dynamic design changes between BERP III and BERP IV, it was predicted that BERP IV would have a retreating blade stall advantage of at least 12 knots at each loading condition, over the already impressive BERP III envelope, and so the rotor limited flight envelope reflected this 12 knots speed increase. Hence, the flight envelope of the BERP IV equipped AW101 was produced based on the expanded rotor envelope and declared as the test envelope.

The flight envelope investigation included both steady level and banked turn flight up to 60° both port and starboard to the limits of the declared envelope. There were no handling or vibration cues to the pilot during these flights that showed the presence of stall on the rotor. Post-flight analysis of the peak-to-peak pitch link loads, power and control angle divergence, and control load waveforms showed no signs of the onset of blade stall at any of the conditions tested. These results confirmed the acceptability of the flight envelope but also showed that the 12 knots increment was clearly an under-estimate. However, time limits on the programme meant that no further opportunity was available to redefine the flight envelope through further testing. Future rotor testing on a productionised version of BERP IV may provide an opportunity to expand the already extensive rotor envelope to further enhance the capabilities of the aircraft.

CONCLUSIONS

The aerodynamic design and performance of the BERP IV Technology Demonstrator Programme main rotor blade has been described. The design aims have been presented and the paper has detailed the mix of computational analysis and wind tunnel testing utilised to meet these aims. The performance goals were matched and exceeded, resulting in

- Reduction of hover power by approximately 5%
- 10-15% saving in cruise power at high $W/\sigma n^2$
- Improvement in stall envelope of greater than 12 knots

These performance benefits will undoubtedly improve the mission capability of the AW101 aircraft and all the technology developed is fully transferable to various aircraft platforms. The rotor additionally incorporates many other benefits not covered in this paper including reduced vibration and reduced through life cost and has already been adopted virtually unchanged as a production blade for the UK MoD and is anticipated to enter service within 2008.

ACKNOWLEDGEMENTS

The authors would like to thank the UK MoD for their support in the successful completion of the BERP IV Programme. The work was funded by AgustaWestland and the MoD under contract no. FBG/01054. Thanks are also extended to the BERP IV team for their assistance with compiling this paper.

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