BERP IV
THE DESIGN, DEVELOPMENT AND TESTING OF AN ADVANCED ROTOR BLADE

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ABSTRACT

The British Experimental Rotor Programme has been maturing new rotor technologies since 1975, and has provided advanced rotors for the Sea King, Lynx and AW101 aircraft. The BERP IV programme addressed high technical risk early, and focused on targets to improve performance, survivability and cost. A multi-disciplinary engineering/manufacturing team approach was used. Extensive use was made of simulation to develop the new rotor blade design in a 'virtual' environment, allowing the programme to be shortened compared to previous programmes. This paper reviews the processes and design features developed to satisfy the generic technical objectives applicable across a range of platform types. The technology was demonstrated on an AW101 and this paper covers the specific design features of the demonstrator blade and flight test results. The development of a production version of the demonstrator blade is summarised.

INTRODUCTION

In partnership with the UK Ministry of Defence (MoD), the British Experimental Rotor Programmes (known simply as 'BERP') have, since the early 1970's, enabled major advances in aeromechanics and manufacturing technology, developing a capability which has given AgustaWestland products a strong position in the world market place and provided UK military forces in particular with significant improvements in operational capability.

The purpose of the programmes has been to provide a singular focus for otherwise discrete packages of research and development funded by industry and the UK MoD. The programmes deliberately addressed the development of high risk technology outside the framework of a production contract, providing generic advancements across all aspects of rotor design, manufacture and test. These developments have subsequently been exploited in production environments with low risk to programme cost and time.

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BERP HISTORY

The timeframes of the programmes performed prior to BERP IV, their technical objectives and end products are summarised below.

BERP I (1975-1978)
The objective of the first BERP programme was to provide UK industry and the MoD science branches with experience in composite rotor blade design, manufacture and qualification process development.

The programme culminated in the design of the Westland Sea King composite main and tail rotor blades. This first composite main blade matched the mass, dynamic and profile properties of the Sikorsky derived metal blade. However, enhancements in blade profile consistency resulted in a 5% reduction in fuel burn when the blade was introduced into service with the Royal Air Force and Royal Navy.

Figure 1 - BERP I : Westland Sea King

BERP II (1978-1980)
The BERP II programme expanded on achievements in BERP I, further developing composite manufacturing techniques and expanding the availability of qualified composite materials to be employed in future programmes. The programme also included the development of advanced aerodynamic design concepts including the BERP tip and advanced aerofoil sections that were later flight demonstrated during the BERP III programme. The ultimate objective of the work was to enable subsequent production of composite rotor blades with advanced aerodynamic shapes.

BERP III (1982-1985)
The BERP III programme was a continuation of BERP II and included further aerodynamic design refinement and composite manufacturing development and culminated in the flight demonstration of the BERP III blade on the Lynx aircraft. The true back-to-back comparison of the advanced aerodynamic design compared to the original rectangular tipped metal blade for the same sized rotor operating under the same conditions showed a significant improvement in rotor capability [Reference 1]. A demonstration of benefits of the enhanced rotor performance came when a Lynx helicopter claimed the World Speed Record in 1986, a record speed of 216 knots; a record that still stands today, nearly 22 years later (Figure 2).

Figure 2 - BERP III : Westland Lynx

Subsequent to this successful technology demonstration, BERP III technology was exploited on both the Lynx and AW101 (then EH101) aircraft. The Lynx used the BERP III derived Composite Main Rotor Blade as a retro-fit and the AW101 (Figure 3) used the technology in its initial design. The Lynx and AW101 aircraft best illustrate the benefits gained. Both aircraft are able to operate with some 40% higher blade loading compared to more conventional rotor technology, allowing additional lift for a given rotor size and weight.

Figure 3 - BERP III : AgustaWestland AW101

BERP IV PROGRAMME OUTLINE & OBJECTIVES

The BERP IV programme commenced in October 1997 with a much broader remit than previous BERP studies. Where previous programmes had typically focussed on a single objective of materials development or aircraft performance enhancement, the BERP IV programme launched with the objective of providing wide ranging benefits across all aspects of aircraft performance and cost. Specific emphasis was placed on the rotor in service, with a strong focus on the need to address through life cost drivers in future blade designs. Programme studies were, where possible, to be platform generic in order to provide a range of design tools and knowledge that could subsequently be applied at low risk to any aircraft type.

The programme objectives were expressed as follows

- Technologies required to reduce through life cost, including reduced design complexity, increased design robustness and improved production quality.
- Performance enhancing measures covering payload/range and environmental benefits, including increased hover and forward flight performance and reduced vibration.
- Enhanced battlefield survivability.

The generic nature of the programme made it inappropriate to place hard targets against each of the objectives, as different exploitation paths would inevitably require a different balance of attributes. Emphasis was therefore placed on the improvement of fundamental rotor capabilities, providing a secondary benefit of de-coupling the programme from shifting requirements that so often hinder technology development. The programme asked itself demanding questions across all design aspects, and in doing so provided a strong focus toward simultaneous demonstration of numerous significant advancements to be realised in a single design.

The programme was subdivided into three phases, providing clear progression through technology maturity and enabling periodic re-affirmation of the programme's content and direction. The three phases may be summarised as follows

- Phase 1: Technology assessment. Candidate technologies typically at technology readiness level 3.
- Phase 2: Technology selection & integration. Candidate technology options downsized to those able to be matured to TRL6 in the final phase. Blade design schemes for AgustaWestland Lynx and AW101 aircraft were prepared.
- Phase 3: Detailed design, manufacture & test. Beginning with the design scheme prepared in phase 2, the final demonstrator blade design was compiled. Manufacturing began with structural test specimens and concluded with flight-worthy blade production. The phase concluded with flight demonstration to validate aerodynamic and dynamic characteristics and performance.

It should be noted that requirements capture underwrote each phase of the programme, and continued to verify programme content and objectives up until the conclusion of the flight demonstration task.

The benefit of the demonstration programme's generic objectives was realised when it was agreed to switch from a Lynx demonstrator aircraft to an AW101 late in phase 2. The decision was taken on commercial grounds and in the light of an impending operational imperative, and the manner in which studies had been conducted prior to this date enabled the change of target demonstrator to take place with minimal disruption.

Whilst the programme was a technology demonstrator, all processes and procedures adopted during the blade's design, manufacture and test were applicable to full scale production. This ensured that benefits of process improvement from the programme reached forward into subsequent production programmes immediately. Additionally, it also allowed the demonstrator blade to be put into limited production over a very short timescale due to the ability to use flight test and structural qualification evidence accrued under the demonstrator to contribute in part to the production clearance.

BERP IV ORGANISATION

At programme launch a dedicated team was assembled with representatives from each key area through which the blade would ultimately be designed, manufactured and tested. The multi-disciplinary team and the concurrent design and manufacturing processes proved fundamental to the programme success. This approach gave wider joint ownership of the design, and resulted in imaginative solutions that enabled the final design to simultaneously achieve all objectives set.

The opportunity was also taken to include representatives from the MoD organisation. This brought the MoD personnel closer to the design task, and allowed them to play a role in the decision making process that led to the final design. In so doing, the MoD customers became team members, and in addition to contributing knowledge from specialist areas within the MoD technology organisation (Dstl) the MoD personnel also provided critical links back into the user community, enabling a regular two way exchange with operational personnel.

Figure 4 - The BERP IV Design Team in front of demonstrator aircraft ZJ117

REQUIREMENTS CAPTURE

The technology integration and selection tasks addressed those aspects of a rotor blade programme typical of contemporary rotor demonstrator programmes, with improvements sought in blade dynamics, aerodynamics, construction, materials and manufacturing. However, in addition to these baseline technology developments, reviews were conducted internally and externally in order to benchmark design and manufacturing tasks, and to capture customer requirements and experience on rotor aspects.

Within AgustaWestland each team representative was given the opportunity to critically review their own processes and tools. Beneficial changes that contributed to programme aims or reduced timescale and financial risk were then pursued, and resulted in significant investment in manufacturing and structural testing processes that later enabled those activities to be undertaken at greatly accelerated pace.

A conscious decision was taken to push the capture of future rotor requirements through the MoD procurement organisation and out to the front line squadrons. In addition to reviewing future MoD procurement aspirations, the programme actively engaged with personnel from all three Services in order to fully understand their rotor related operational experience both good and bad, for the UK rotary wing fleet. This information was used to direct studies under the programme's stated aims of reduced through life cost, and was also used to assemble a catalogue of 'best practice' blade features such as preferred blade picketing fixtures and blade attachment configuration. The manner in which requirements were captured led to a strong emphasis within the programme team to 'make a difference for the user', and this succeeded best on those aspects where the flow of information from the Services had been greatest.

In reflection of current Gulf theatre operations the requirement for improved resistance to sand erosion either through provision of role fit protection or as a capability of the basic blade design was clear (Figure 5).

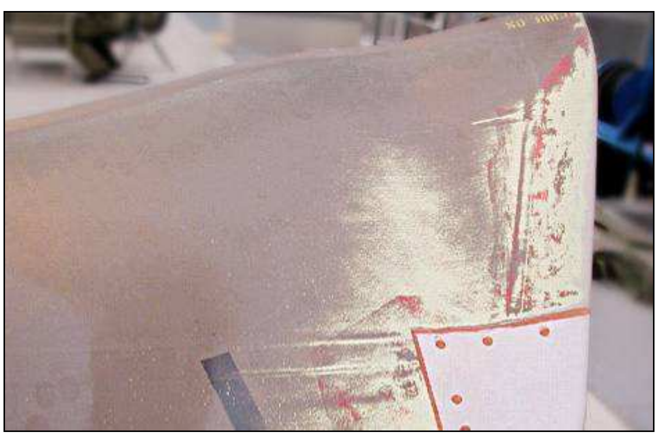

Figure 5 - Sand Erosion on AW Lynx Blade Tip

The need for enhanced resistance to impact damage (Figure 6) was a unanimous conclusion from all three Services consulted, and as a result strong emphasis was placed on the incorporation of a robust blade trailing edge structure and a mechanically fastened tip.

Figure 6 - Tip Strike on AW101 Blade **(Crown Copyright)**

BERP IV DESIGN PROCESSES

The programme included further development of a number of enhanced design tools that were initially developed in a separate integrated blade design and manufacturing initiative. Whilst the new design was compiled against the programme's requirements the basic construction architecture was common with the BERP III AW101 blade, including retention of the unique tip planform which was re-verified as the best design configuration available to achieve performance goals set. The design process began with the compilation of guidelines that would be used to steer the design toward its final solution with an optimised balance of the target attributes. Each specialist area within the multi-disciplinary group was responsible for the generation of design constraint 'rules' that were deemed essential by their discipline to meet the programme aims. These rules were then continually re-appraised during the design process, as understanding of materials, processes and the design matured. The compilation of design guidelines had the effect of introducing design feature details developed during previous phases at the start of the final design process. This prompted interaction between the team disciplines and the programme objectives as the design evolved, enabling informed trade-off decisions to be made that struck the best balance across all objectives. Rules were also derived from the UK MoD battlefield helicopter user survey, ensuring that those features deemed conducive to reduced in-service cost were preferentially considered during the design evolution.

An aerodynamic definition of the new blade was created maximising aircraft performance enhancement in alignment with the programme objectives, based on an understanding developed in earlier phases of the practical limitations that the new dynamic design features would allow. Target dynamic properties were initially generated constrained by the aerodynamic profile and observing objectives and guideline rules set. These were then used to generate a small number of 2D finite element model sections detailing the composite lay-up. The blade section analysis also observed the rules set by the team, and used material property data taken from the material test programme. The achieved dynamic properties were then passed back into a dynamic design assessment in order to assess whether the deviation from original target properties provided adequate dynamic characteristics. This process allowed the blade design to rapidly evolve to a stage where a viable blade construction was ready for preliminary design review (PDR) followed by further detail design consideration. Post PDR data was also suitable to allow tooling design to commence, enabling what is typically one of the longest lead-time items within such programmes to commence early.

Detail design commenced with the generation of 3D finite element models from the 2D sections, for both ply shape generation and, where complexity required, strength analysis purposes. On completion of the 3D model for a component and the associated strength analysis, a critical design review was held to record design 'freeze' and release of tooling data for manufacture.

Further details of the dynamic design, blade design and blade strength analysis processes are discussed in the relevant sections.

BERP IV TECHNOLOGY DEVELOPMENTS

Aerodynamics

The BERP IV aerodynamic design was carried out within the context of an integrated design process and as such all design features proposed for aerodynamic performance reasons were also assessed from the perspective of all the other design disciplines; only those aerodynamic features that were acceptable to the rest of the team were accepted for further development and ultimately allowed on to the demonstrator blade.

The blade aerodynamic design requirements flowed directly from the overall programme objectives and the operational aspects of the requirements capture activity carried out in Phases 1 and 2. The first and most significant requirement was to further increase hover performance, then, anticipating that this may have an adverse effect on forward flight performance, the second design requirement was to at least maintain the same high level of forward flight performance as that of BERP III.

The design solution chosen to address the hover performance requirement was, not surprisingly, increased blade twist. Work carried out during BERP IV Phase 1, which included numerical analysis and model rotor wind tunnel testing of various blade designs with overall twist values ranging from 8° to 18°, concluded that a value of 16° was a good compromise between good hover performance and the risk of high vibration (see Dynamics below). The aerodynamic design process that followed considered blade tip shape and aerofoil design that were compatible with this relatively high level of twist

Early in the BERP IV programme a number of new and contemporary tip shapes were considered and assessed; the aims being to benchmark the previous BERP III tip shape, to identify the most promising features for good hover and advancing and retreating blade performance and then define the general concept to take forward into the demonstrator blade design. The assessment took the form of numerical analysis (panel method, Euler and Navier-Stokes) and non-rotating wind tunnel wing tip tests including lift, drag and pitching moment measurement, boundary layer and flow visualisation and wake traverse measurements. A selection of tip shape concepts that were considered are shown in Figure 7.

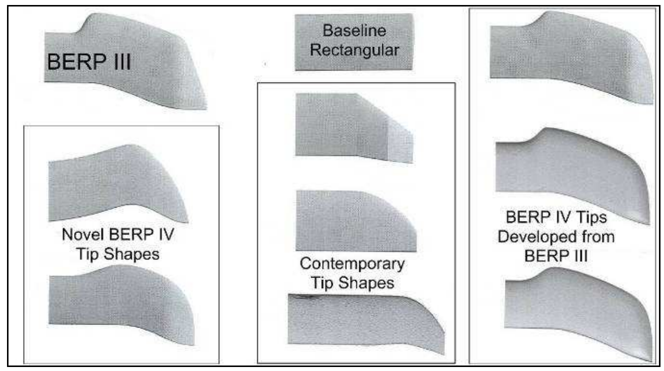

Figure 7 - Various Tip Shapes Assessed During BERP IV

An initial forward flight assessment compared the BERP III tip, other contemporary and generic advanced tip shapes and some early novel BERP IV tips. The overall conclusions were that the BERP III tip produced the best retreating blade performance inasmuch as it is best able to maintain attached flow conditions to the highest angle of attack, and that, in general, the thinnest tip aerofoil section and the most tip sweep produced the best advancing blade performance. The only tip shape that was able to combine good retreating and advancing blade performance was the BERP III tip. The philosophy of designing for good forward flight performance, particularly retreating blade stall is also entirely compatible with that for good hover performance, since it minimises blade area for a given cruise design point and hence profile power. Furthermore, the use of twist to control hover induced power does not conflict with this tip design. The BERP IV tip therefore builds on, and further refines, this successful philosophy (see Reference 1 for a more detailed description of the BERP III blade). The BERP IV tip was designed with the benefit of analysis tools and techniques that were not available when the BERP III tip was designed, so therefore contains a number of improvements. The primary design features of the BERP IV tip are summarised below and illustrated in Figure 8.

- The tip has a more smoothly blended notch geometry (the feature at the inboard end of the forward chord extension) that acts to reduce drag
- The increased tip chord is fundamental to the tip's high incidence capability. This is retained in the BERP IV

design and is optimised for reduced profile drag, whilst still maintaining the high incidence performance.

- The extreme tip has more progressive swept leading edge that becomes streamwise at the tip. This produces a stable tip vortex with low vortex drag.
- The swept tip ensures good high Mach number performance, with the effective sweep maintained out to the tip
- Anhedral is used in the outer tip; this has proven very beneficial in terms of hover performance and has therefore been retained. The shape of the anhedral has been made smoother to aid manufacturing and the ultimate angle has been increased from 20° to 25° with a slight increase in the total vertical displacement of the tip.

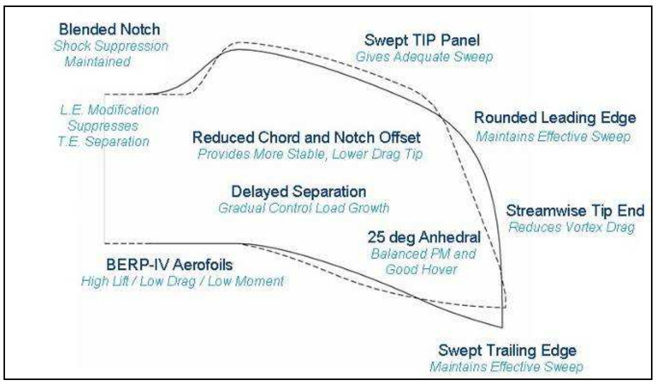

Figure 8 - Comparison of BERP III and BERP IV Tips

The final BERP IV tip shape was verified by analysis and wind tunnel test. As an example, Figure 9 shows the high angle of attack stall performance of three different tips. All the blades in this test utilised the same aerofoil sections and were tested under the same incidence and freestream conditions. Wool tufts are used to highlight separated flow. The upper figure is the BERP III tip which clearly shows a large area of attached flow over the tip, while an area of separated flow (highlighted) exists in the notch region inboard of the tip. The middle figure is a generic swept tapered tip and shows separated flow over the entire swept tip panel and a degree of trailing edge separation is observed all along the span of the model. The lower figure is the final BERP IV tip which clearly shows the same beneficial attached flow characteristics over the tip as BERP III, and also shows a significant reduction in separation inboard. The BERP IV tip has a small lift benefit over the BERP III tip at the highest incidences. Although the swept tapered tip has a lower surface area, the drag divergences more rapidly than either of the BERP tips.

The resultant BERP IV tip shape concept has been applied to two blade design schemes, one for the Lynx and another for the AW101. Although both blades share the same design philosophy the difference in basic blade aspect ratio results in different aspect ratio tips. Careful consideration is given to the appropriate tip aspect ratio for each specific application. The basic technology and design tool development in Phases 1 and 2 have allowed the application of BERP IV across a wide range of platforms and scenarios

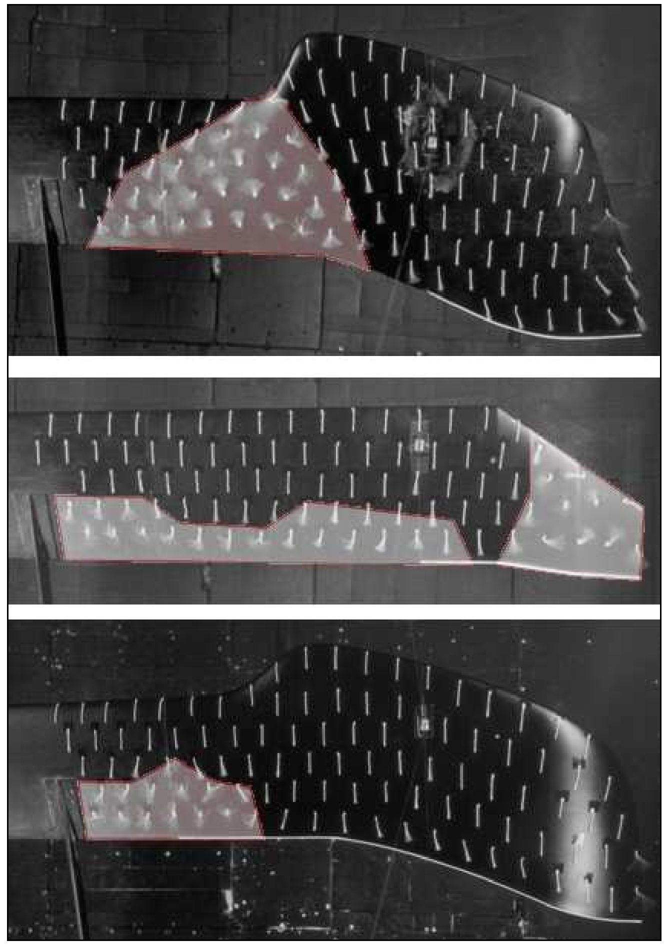

Figure 9 - Comparison of Tip Stall Characteristics

In keeping with the previous BERP III design philosophy, the BERP IV blade aerodynamic design is an integrated one with complimentary aerofoil sections, tip shape and twist. However, in contrast to BERP III where it was possible to use an aft-loaded high lift aerofoil section with associated nose-down pitching moment in the outer span of the blade, that was balanced by a reflex cambered aerofoil section with nose-up pitching moment in the inboard region, the high twist of the BERP IV blade necessitates the use of high lift sections inboard and consequently zero pitching moment aerofoils everywhere.

One further aerodynamic design requirement results from manufacturing considerations. The BERP III concept utilises spanwise regions where the aerofoil section is held constant, with short transition areas between. From a manufacturing perspective, these short transition areas can cause problems with fibre orientation during ply lay-up and cure. To ease this, a more progressive transition between aerofoil sections was required.

With these requirements in mind, a series of highly efficient, low pitching moment aerofoils were designed in-house in

AgustaWestland and tested in the ARA 2D pressurised transonic wind tunnel in both static and dynamic (oscillatory and ramp) conditions. Aerofoils were defined at the blade root, the 50% and 75% span positions, the 82% span position (inboard extremity of the leading edge notch) the 86.6% span position (outboard end of the notch) and the 95.5% span position. The first aerofoils designed were those at 82% and 50% span. The aerofoil at 82% span was designed as a high lift section at moderate to high Mach number with zero pitching moment and replaces the RAE9645 section used in the BERP III blade. With careful design and advances in design methods and optimisation it was possible to produce an aerofoil section that matches RAE9645 in terms of lift and drag but, unlike RAE9645, does so with zero pitching moment. Recognising that high twist dictates a high lift aerofoil section inboard, the 50% span aerofoil was designed for high lift and high L/D at zero pitching moment, but at a lower Mach number range than the outer aerofoil. The resultant aerofoil has significantly better lift performance than its BERP III equivalent and also has a zero pitching moment. In order to ensure smooth transitions between aerofoil sections, the initial designs of the 75% and root aerofoils were a linear interpolation and a linear extrapolation respectively from the 82% and 50% span sections. The performance of the resultant interpolated and extrapolated aerofoils was assessed and found to be remarkably good; little modification was needed to achieve optimum performance. The reason that these aerofoils performed well was that the 82% and 50% sections were of the same basic family, with similar shape characteristics. The full set of aerofoils inboard of the tip are therefore all high performance sections that form a good continuously smooth surface, ideal for high quality repeatable and stable manufacturing.

In the tip area, a new aerofoil with improved lift/drag characteristics was designed to suit the specific conditions at the outer edge of the notch; this replaced the RAE9634 section used in BERP III. This was then blended smoothly to a slightly modified RAE9634 section at 95.5 % span; this thin low-camber aerofoil being retained for its excellent high speed characteristics [Reference 2].

Overall, the new tip shape and aerofoils section represent an improved balance of design features that influence advancing blade, retreating blade, and hover performance. In particular, the outer tip edge is now more streamwise and the notch refinement reduces the tendency for any local separation at high angles of attack. The high angle of attack performance and reduced drag of the new tip was confirmed in a series of wind tunnel tests. Advancing blade characteristics were confirmed by CFD, against requirements specific to the AW101. Compared to BERP-III, the new tip has better chordwise balance, giving improved stability and some relief in control loads. From the structural viewpoint, the more gradual blends help with the composite lay-up improving product consistency and reducing additional manufacturing inspection time.

In addition, the blade aerodynamic design respects a number of multi-disciplinary requirements; in particular the blade shape has been developed with manufacturing specialists to eliminate any geometric feature that might compromise high quality repeatable manufacturing processes.

The final BERP IV demonstrator blade aerodynamic design, which maintained the same rotor radius and blade chord as the predecessor BERP III blade, is illustrated in Figure 10.

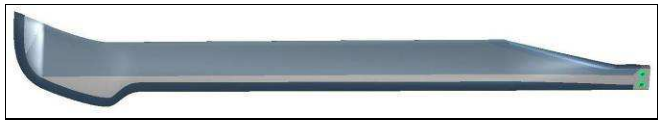

Figure 10 - BERP IV Demonstrator Aerodynamic Design

Dynamics

Blade dynamics and aeroelastics studies in BERP IV focussed on a range of methods and technology development in support of the programme's aim to provide generic technology solutions across a range of potential candidate aircraft. The generic technology developed was then specifically assessed in the context of two candidate aircraft (AgustaWestland Lynx and AW101) in order to better understand the interaction between dynamic and other design features.

The dynamic design of the demonstrator blade was primarily driven by the desire to further reduce fuselage vibration in the chosen demonstrator aircraft, the AW101, particularly for the weight growth aspiration of future variants. The design had to accommodate constraints imposed by the BERP IV team in order to observe the programme aims. A number of design features, most notably the robust trailing edge skin construction and a mechanically fastened tip were also required as an integral part of the design solution.

Figure 11- AW101, Royal Air Force Merlin Mk3

The calculation of vibration remains one of the biggest challenges facing blade designers due to the many complex aeroelastic interactions involved in generating the source of fuselage vibration, namely the five per rev head loads. The issue is further complicated by the response of the elastic fuselage to the loads.

Throughout the design process steps were taken to minimise the risk associated with the complex nature of the physical mechanisms involved. Empirical corrections based on analysis, model rotor tests and flight test results were applied during the vibration calculation to account for known deficiencies in the theoretical analysis. The process for correcting for the effects of twist was as yet untested, and therefore represented an element of significant risk.

To account for the interaction between the predicted 5 per rev head loads and the elastic fuselage, transfer functions derived from flight test of the development AW101 were obtained. It was assumed that the fuselage elastic transfer functions would remain valid for the BERP IV test vehicle. The transfer functions effectively apply a weighting to each of the head loads, and varied depending on the aircraft configuration.

A method had to be defined whereby the vibration characteristics of a particular blade design could be encapsulated by a single parameter calculated across the speed range of interest. Choice of the parameter had to ensure that fortuitous phasing of the vibration generated by the individual head loads did not incorrectly favour design solutions when optimisation was being carried out at a single forward flight speed and also had to reflect the effect of a design on vibration over a reasonable extent of the aircraft. A vibration index was chosen to satisfy those requirements, derived from a root sum squared summation of vibration across a selected number of points in the fuselage.

Firstly, the impact of the increased twist on vibration was estimated by taking the BERP III blade and increasing twist to 16°. The resultant vibration index is representative of the vibration level to be expected if no attempt were to be made to dynamically tune the blade. The vibration index is calculated using the Westland aeroelastic code R150. The vibration index for the dynamically un-tuned 'BERP IV' blade is shown in Figure 12 and is compared with the levels calculated for the datum BERP III blade.

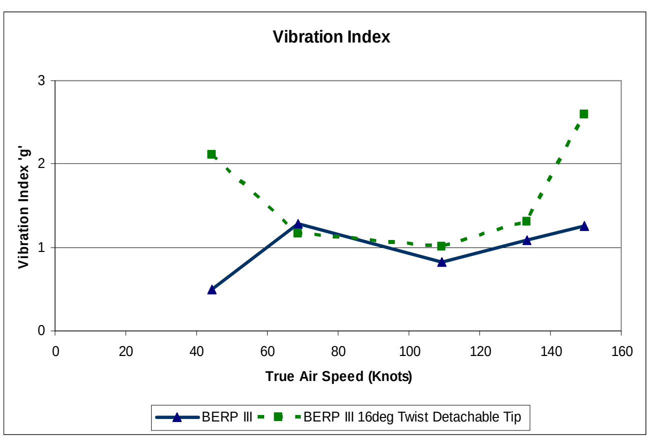

Figure 12 - Predicted Effect of Twist on Vibration Index (ACSR Off)

The modified blade exhibited significantly higher vibration index levels at both low and high speed compared to the baseline BERP III blade. The BERP IV blade design objective was therefore to contain the level of vibration (as given by the vibration index) to be no worse than for the BERP III blade.

It was also noted that the increase in twist and the inclusion of the detachable tip had a significant and detrimental effect on the vibratory control loads, as illustrated in Figure 13. It was therefore considered essential that vibratory control load should be included in the BERP IV design process, and that BERP IV vibratory control loads should be no greater at low speed than existing BERP III levels. The addition of this design iteration represented another challenging optimisation task in the design of the blade, but experience gained up to this point ensured that a solution quickly converged.

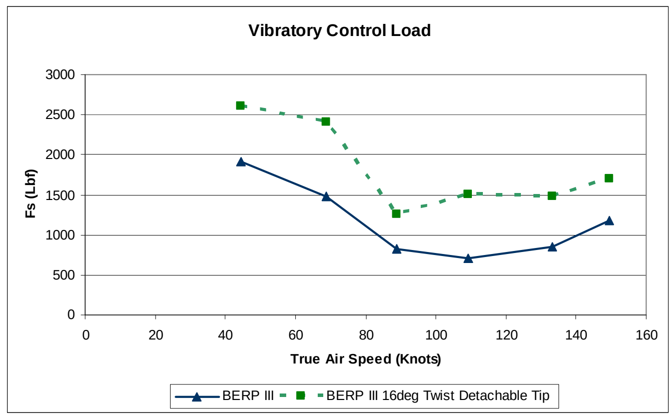

Figure 13 - Predicted effect of Twist on Control Loads

As part of BERP IV, work was initiated to develop an in-house blade structural optimiser (SOLVITE) code. This produced preliminary designs of the internal structure of rotor blades to minimise vibration in the aircraft. The stiffness and inertial properties of this preliminary design could then be used as targets to develop a detailed structural model later in the design process. As development of the optimiser progressed, the capability of minimising blade strains or control load was also introduced.

The structural optimiser links a gradient-based optimisation procedure with an eigenvalue analysis of the blade and a rotor vibratory loads prediction software. The internal structure of the blade is altered by the optimiser until the vibration, blade strain, or control load is minimised.

The stiffness and inertia properties of the blade are modified by altering the dimensions of the components in the structural model. The components are the width of the nose moulding, the spar sidewall thickness and the thickness and width of the trailing edge tab stiffener. In addition, the amount of aeroelastic flap-lag coupling stiffness K_{45} and chordwise cg distribution can be optimised.

The structural optimiser has the capability of optimising any one of three parameters: vibration at a number of fuselage locations, the reserve factors at a number of locations within the blade, or control load. The hub loads, blade loads or control loads are calculated by an internal forcing function that is derived from the 'in house' loads prediction software, R150.

The optimisation is constrained by a range of parametric limits to control, namely blade mass and/or 1^{st} mass moment, combined with composite ply lay-up restrictions to meet blade manufacturing requirements.

The optimiser was applied to a model rotor blade design which was wind tunnel tested during phase 2. The predicted vibratory loads were successfully correlated against the test measurements to validate the design procedure.

The structural optimiser was applied to the design of the BERP IV blade and was successful in significantly reducing the design time in comparison with traditional design approaches. As a result of the utilisation of this powerful design tool, the dynamics group were able to explore a wider range of design concepts with the rest of the design team, leading to a significant change in the dynamic characteristics of the BERP IV blade to minimise vibration.

Following the innovative research of Dr E Smith [Reference 3] in 1992, AgustaWestland continued the development of blade aeroelastic tailoring concepts to reduce blade vibratory loads. The initial work was focused on reducing vibration using both structural and inertial modal couplings between flap and torsion. These couplings were generated either by the orientation of the composite plies within the blade or by tailoring the chordwise cg along the blade. In both concepts the spanwise tailoring was designed to be focused on the region of maximum displacement or curvature in the particular flap modes of interest. The effect of introducing the coupling is to move the effective modal frequency in a similar fashion to the induced kinematic pitch-flap coupling often present on tail rotors.

The aeroelastic tailoring concept was incorporated into the structural optimisation analysis for blade design and was successfully correlated in Phase 2 against wind tunnel test results for an aeroelastically tailored model rotor.

Further development revealed the potential of these couplings to have a significant effect on control loads. In the BERP IV blade design, both structural and inertial tailoring concepts were employed. The combination of blade aeroelastic tailoring techniques and structural optimisation have been successfully used in the blade design to minimise both vibration and control loads.

The dynamic performance of the final design is reviewed in the flight test section.

Materials

A programme of materials selection was commenced in phase 1 with a benchmarking exercise, characterising a number of new fibre/resin combinations against the existing material suite used for the Lynx and AW101 rotor blades. This process sought to adopt a new material system that provided both technical and commercial advantages. A tougher resin system and improved fibre mechanical properties were sought in order to open the design 'window' within which an acceptable strength blade design could be developed. At the same time the longer term commercial stability aspects of new materials were considered in an attempt to introduce more stability to production raw material costs. The opportunity was taken to replace traditional woven fabrics with a non-crimped fabric, providing two benefits. The non-crimped fabric resin pre-impregnated was supplied in a form that was equivalent in thickness to approximately three layers of woven fabric, resulting in a threefold reduction in ply lay-up time. Additionally, the non-crimped solution featured a through (Z) stitch construction, and as a result a trailing edge skin manufactured from non-crimped fabric pre-preg provided a four-fold increase in damage tolerance over the equivalent uni-directional fibre pre-preg based design. The final selected resin and fibre systems were:

- 950-1 resin (Cytec Engineered Materials)
- S2 glass fibre (Advanced Glassfibre Yarns)
- UTS & T700 carbon fibre (Toho Tenax and Toray Industries, respectively)
- 4 ply non-crimped fabric (Saertex)

The opportunity was also take to assess new adhesives, with emphasis on improved strength and manufacturing process benefits.

In support of the objective to improve the service life of the erosion shield for operation in sand laden environments it was decided to adopt a non-metallic shield as the sole means of erosion protection. This configuration had the added benefit of reducing erosion shield cost over the more conventional titanium shield, but presented challenges with respect to rain erosion endurance. The chosen erosion shield was initially selected from over sixty candidates on the basis of sand and rain erosion endurance, and was then subject to a test programme to confirm its properties. In addition to a test programme to characterise the mechanical properties of the self adhesive tape selected (3M 8542HS MB), rain endurance testing was carried out at the Cavendish Laboratories at Cambridge University and in the University of Dayton Research Institute's rain erosion rig located on Wright Patterson AFB. Testing confirmed adequate adhesion properties and acceptable rain endurance for the initial trials flying planned, but also indicated the criticality of adherence to the surface preparation procedures during tape application and the need for careful consideration of design detail in order to prevent water ingress beneath the aft edges of the tape.

A material property characterisation programme was carried out on the entire selected materials suite to provide physical, static and fatigue properties for design data, establishing allowable material strength properties for both unaged and aged material. Fresh data was inserted periodically into the design process, ensuring that design evolution from the dynamic definition forward was executed using the most mature data available.

Structural Design

The composite BERP III derived blades currently in service on AW101 and Lynx had been designed on 2D and 3D CAD systems that were limited compared to CATIA V4 and V5 used today. The ability to interpret data from these systems for manufacturing purposes (composite material ply shapes and spar foam core 3D profile) was limited, and lead to a process of rolling updates and adjustments during development phase in order to obtain an acceptable component. The BERP IV blade became the first rotor blade totally designed by AW to use CATIA, benefiting from full 3D modelling capability and the ability to accommodate composite materials.

The blade lay-up design was initially schemed in 2D NASTRAN\PATRAN sections against the dynamic property targets set. The 2D modelling used material properties from the coupon and test element programme, and also observed an agreed set of design and manufacturing rules evolved by the multi-disciplinary design team and qualification standards. Manufacturing design rules for material construction limitations (ply drape, foam crush during consolidation, etc.) had been compiled through a process of experimentation prior to commencing the final design phase, such that the design assembled in the virtual environment acknowledged the real world constraints it would face during manufacture.

The achieved dynamic properties using NASTRAN\PATRAN were then assessed by the dynamics team, and through a process of iteration an acceptable target blade lay-up was then defined. Where required by complexity, early use was made of 3D NASTRAN\PATRAN modelling abilities in order to quickly assess specific design features (Figure 14). This included the ability to export the model into the NASTRAN/PATRAN finite element model environment to enable strength analysis to proceed in parallel. Each composite material ply was designed observing the manufacturing constraint set, and the complete composite blade construction was built up to provide individual ply shape definitions to the manufacturing engineers using CATIA.

The traditional drawing review and signature procedure was also replaced with a new process. This allowed the specialist community to view models as they were developed via a standard desk-top PC, providing early visibility of the design to the entire team. Brief design update reviews were also scheduled twice weekly to allow key risks to be highlighted for consideration by the team as the design developed. The process ensured that when model approval was finally sought during a group review of the CATIA model it had been thoroughly evaluated, and could be quickly approved.

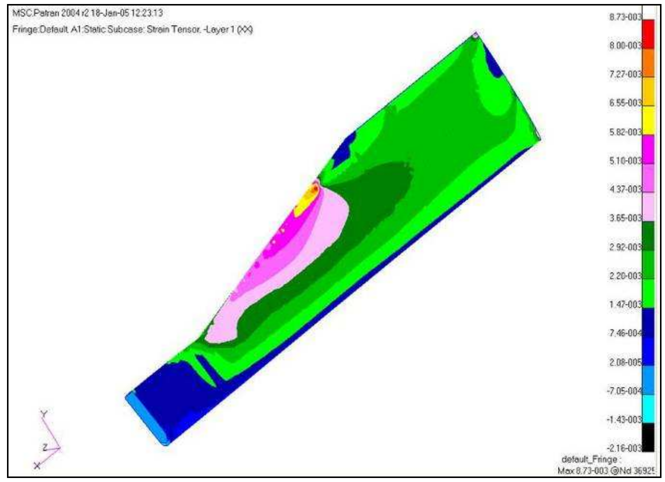

Figure 14 - Root End 3D Finite Element Model

Blade Strength

The strength analysis of the BERP IV demonstrator blade design involved analysis and assessment of the blade's features dependent on the degree of complexity of the feature. Each individual feature was analysed using a combination of one or more of the following methods

- 2D section stress analysis using basic theory
- 2D section FEA analysis
- 3D FEA analysis
- Structural test element test results

During the initial stages of the design careful consideration was given to the most cost and time effective route to generate design data and investigate new design concepts. To validate the analyses, a series of feasibility test spars, uniform section untwisted spar elements, were structurally tested.

Plain sections of the blade could acceptably be analysed using basic stress theory, and where necessary such analysis was supplemented with 2D finite element analysis.

Models derived from the blade design work were imported into the NASTRAN\PATRAN environment to enable 3D models to be constructed of the more complex features, or those features with complex loads applied. NASTRAN\PATRAN was utilised for the vast majority of the modelling, but Abaqus was also used in the tip region.

The primary analysed areas were:-

Tip

The tip was modelled for two separate reasons. Firstly the 2D section property approach to analysis could not be applied because of the shape change through the region. Secondly the 3D model was used to analyse the effect of pressure loading over the tip region. Both these applications utilised a fully detailed composite model of the region.

Outboard test specimen

The outboard test specimen was modelled to ensure that the short specimen length was adequate to allow the loads to fully diffuse into the structure. The model was developed from the 2D slice at a mid-span radial station which was extruded to give a 3D model, the re-enforcing ply doubler stacks were then applied to this. The model was run successfully proving acceptable length

Midspan

The midspan was modelled in a similar way to the outboard test specimen, however this fully detailed model was used to predict the onset of flap buckling.

Root Transition

The root transition was developed into a fully detailed 3D model with the appropriate geometric twist and the rapid change in material thickness ordinary 2D and engineers bending did not apply.

Analysis concluded in a series of test data sheets against which the full scale testing was then executed. Four types of test specimen were used in the structural evaluation of the BERP IV main rotor blade. Described as follows:

- Material Coupon Data
- Root end lug structural elements
- Detachable tip glass fibre/bolt shear coupons
- Trailing edge honeycomb bond coupons

The set of achieved test results was then reduced by appropriate strength variability factors to give design allowable strains and stresses, for the principal blade components. Mean strength S-N curves were generated for the individual blade components, from which a preliminary blade fatigue life statement was compiled prior to first flight. Prior testing of spar structural elements indicated that the S-N curve shapes used for the BERP III AW101 blade characterisation were applicable to the BERP IV blade, confirming that experience with the BERP III blade could be used to assess the new design with confidence despite the many new features adopted.

For the purposes of a technology demonstrator those degradation factors associated with a production rotor blade (strength degradation due to combinations of hot/wet conditions and/or the presence of barely visible impact damage) were initially omitted from the test programme. When the blade design was selected for limited production use these factors were re-assessed, and subsequent test specimens were tested with BVID features and achieved results factored to allow for a hot/wet factor based on coupon testing and previous experience with BERP III.

The methodology developed under BERP IV enabled a much greater complexity task, that of analysing a blade structure with increased complexity over previous designs, to be completed more efficiently and with less risk of emergent work during the ground test activity than prior blade development programmes. This contributed positively to both programme risk and cost, as well as timescale.

Manufacturing

In the early phases of the BERP IV programme the support rendered by the manufacturing engineers centred on development of manufacturing design rules and support to design scheme assessments. In addition to this, however, significant effort was also placed on process improvements.

A series of design rules conducive to ease of manufacture were developed and fed into the preliminary design activities within the dynamics design tools, CATIA and NASTRAN\PATRAN. These rules centred on detail design aspects such as the compression behaviour of the core material cured within the spar and limitations of material drape around 2D curvatures. An extensive programme of material testing supported the activity, providing a much greater detailed understanding of the materials suite.

Figure 15 - Final Stage of Manufacture

Design rules also considered design features against cost-effective manufacturing techniques. A detailed assessment was made of each sub-assembly within the blade with the objective of cost reduction of the component not only at the point of manufacture but also through-out its life cycle. The assessment determined whether new manufacturing equipment should be provided to reduce cost, other whether design features should be adopted to suit existing manufacturing processes. The opportunity was taken to confirm that the most novel characteristic of a BERP rotor, its tip planform and proposed aeroelastic tailoring features, did not adversely impact unit cost.

Design schemes prepared embodied the manufacturing rules, along with rules from other discipline areas, from the outset. Each scheme was also critically reviewed by the multi-disciplinary team and where necessary design rules were refined.

Process improvement placed significant emphasis on the characterisation of the thermoset composite cure cycle. COMPRO (Composites Processing Analysis and Design Software) modelling of the chosen resin system, developed by Convergent Manufacturing Technologies Incorporated of Vancouver, Canada, was used to produce the most cost effective cure cycle for the BERP IV Demonstrator blade. The aim was to produce a cure cycle which is designed to ensure that the composite material in the blade is fully cured in the shortest time possible whilst also ensuring that no damaging exothermic reactions occurred. The model also identified the optimum location for thermal survey points, ensuring that the full range of cure conditions were recorded.

The benefits of early involvement of the manufacturing discipline in the design process were realised in the final blade production phase. The result was a 'right first time' outcome, with the moulding quality of the first spar proving so consistent that no anomalies could be detected by the non-destructive testing equipment used for routine production. The benefit to the programme was one of both time and cost, with the ability to produce a consistent and acceptable component saving almost 18 months of development when compared to the same activity in previous programmes.

Structural Testing

Traditional testing techniques require the root end and transition (inboard) sections of the blade to be tested separately as two distinct tests conducted consecutively on the same test specimen. Each test only achieves the required test loading at one spanwise position on the specimen, and the inclusion of centrifugal (CF) loads on the specimen results in a perpendicular component of the load (CF_Y) being introduced as the specimen deflects (Figure 16). This load tends to counteract the applied flap and lag loads. Prediction of the perpendicular load magnitude is not straightforward, as it is subject to unquantifiable factors associated with bearing resistance. The testing is further complicated by the perpendicular load inducing premature failure of the rig bearings, in turn, resulting in poor test reliability.

In order to achieve an acceptable load distribution the Stress Office required the test to provide a load distribution over a metre section of the specimen instead of the single point, as was required on earlier specimens. The Structural Test Laboratory addressed this target with two key changes. Firstly, basic rig architecture was revised to address the restoring CF force problem. The traditional cantilever layout was abandoned in preference to new design that semi-constrained the specimen at both ends. This allowed the load application in each of the axes to be separated. The large CF load is applied in isolation to the bending and torsion loads (see Figure 17 - Figure 19), reaction struts were used to ensure the load application pivots at both ends of the rig remained aligned, and (where required) torsion loads were applied to the specimen adjacent to the specimen attachment bracket. Flap and lag loads were applied at the opposite end of the specimen, with the load application pivots of the flap, lag and CF forces remaining in alignment in order to minimise cross coupling between the different load applications.

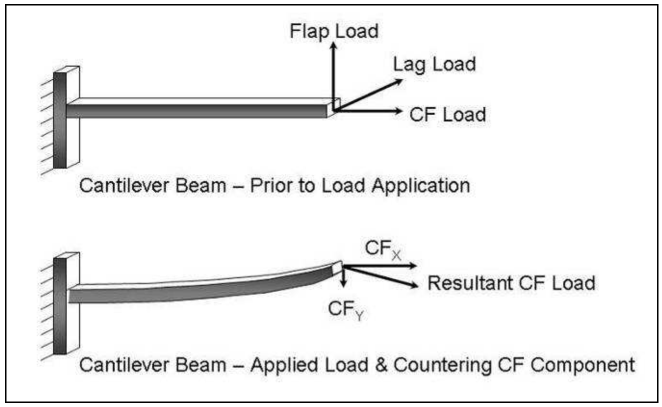

Figure 16 –Layout of Tradition Test Procedure

The chosen rig architecture also then allowed a second innovation to be employed. A secondary loading system was introduced in the form of an active hydraulic servo controlled prop that placed a limited amount of additional load on the specimen mid-span. In order to achieve the necessary degree of control of the two actuators on the active prop and the four other test actuators (providing flap, lag, torsion and CF loads) a system was devised using "Iterative Harmonic Control Loop" theory. This system used a mathematical model created within the control system which uses the inverse of a statically derived matrix to calculate the necessary control loads for the test actuators to apply. The loads were further refined by an iterative correction of magnitude and phasing of the control loads using in house developed software. The new system devised enabled the test to achieve a loading distribution that matches more closely the loading distribution experienced on the aircraft. This allowed a test on only one specimen to be used to qualify the strength of the blade when two specimens would normally be required. The test method reduced the number of tests and therefore the time taken to complete the testing by almost 50%.

The structural testing of an intricate composite structure such as a rotor blade remains a highly complex task, however, and the opportunity was also taken to use theoretical modelling techniques to analyse proposed test configurations and specimens in advance of test. The purpose of the analysis was to avoid where possible premature specimen failure that can often occur due to the application of unrepresentatively high test loads when attempting to accurately replicate in-service load conditions. Such premature failures can be common and extremely time consuming, as the failure requires that the test be halted pending specialist analysis of the failure, specimen repair, and any necessary test modification. To reduce the risks associated with this situation, the Structural test of the BERP IV blade sections was modelled (Figure 20). Two models were created of the test specimens and the fittings used to support the specimens in the test rigs. Notably, some of these fittings are made out of flexible materials, i.e. rubber, and the analysis had to be non-linear. The size of the models was of the order $1x10^6$ degrees of freedom and were performed using Abaqus software.

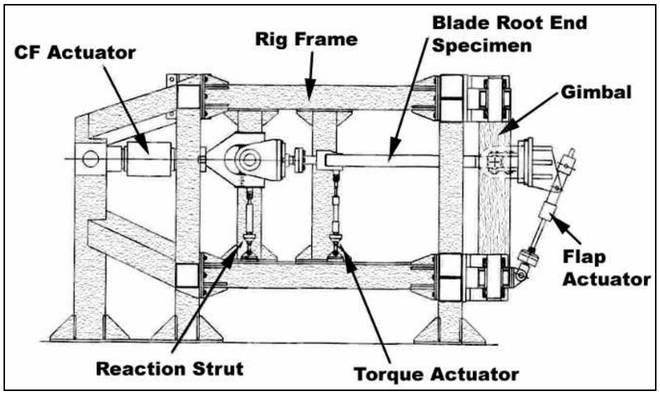

Figure 17 – Rig Side View

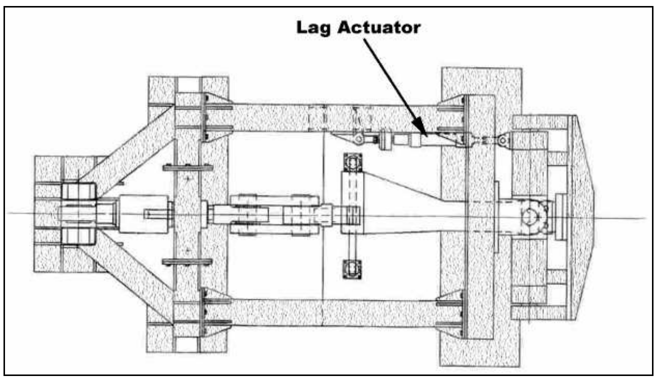

Figure 18– Rig Plan View

Figure 19 – New Gimbal Test Rig

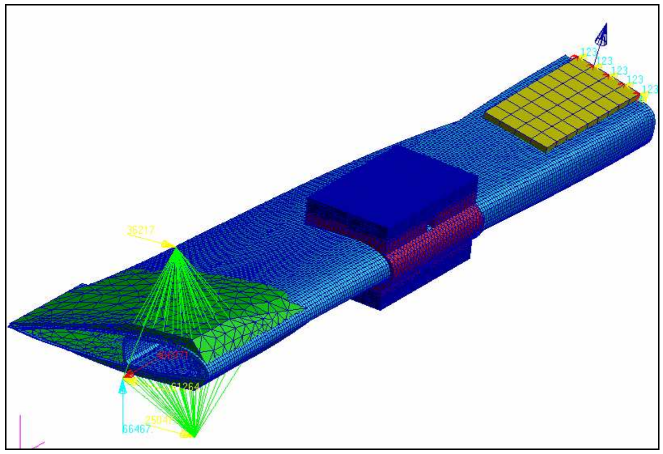

Figure 20 - Structural Test Section Model

A programme of ballistic testing was conducted in order to confirm the characteristics of the new blade. A series of impacts were carried out on spar structural elements subjected to a range of four point loads from 43% to 150% design ultimate load. Preliminary testing indicated that the size and content of the blade's nose moulding had the potential to cause the 12.7x102mm B32 API round to ricochet off the specimen when struck at a perpendicular angle of incidence. An impact trajectory was therefore selected that provided a repeatable damage mechanism, with the shots passing in through the rear wall corner and out immediately aft of the nose moulding. Figure 21 and Figure 22 below illustrate a test specimen under load and a detail view of damage sustained.

Figure 21 – Ballistic Test Specimen Under Load

Figure 22 - Impacted Specimen

BERP IV DEMONSTRATOR BLADE DESIGN

A modular blade design configuration was employed. It was recognised early on during the design that the demonstrator blade would contain a number of features that may be undesirable in a future production blade, either through unresolved technical risk or because future requirements dictate a different balance of attributes. Where possible therefore the design was configured to enable deletion or modification of certain key features whilst still enabling the dynamic design solution to remain unchanged, and for the new design to benefit in part from structural qualification evidence accrued. The final demonstrator blade design is summarised in Figure 23.

The contribution of individual blade attributes to programme aims are detailed in table 1.

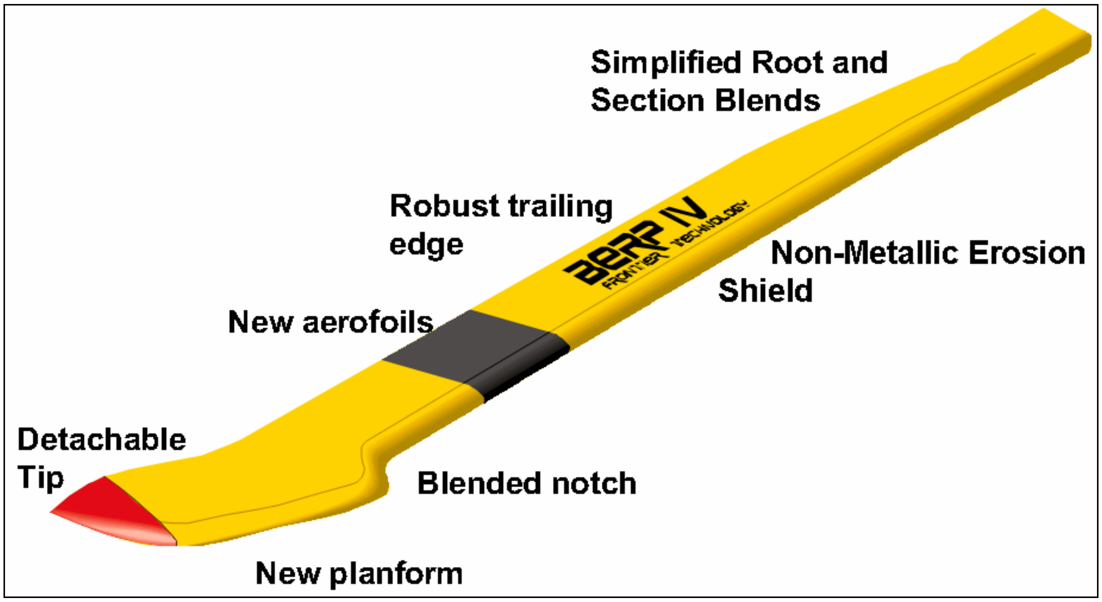

Figure 23 - Demonstrator Blade Features

Attribute	Feature	Comments
Cost	Reduced curvature tip planform & notch	Provide a smooth fibre path for the composite material, resulting in improved manufacturing product consistency
	Simplified root end and aerofoil section blends	
	Non-crimped fabric trailing edge	Significantly reduced the manufacturing complexity of the item by reducing parts count and labour content. Improved robustness providing lower in service maintenance burden.
	Detachable tip	Reduced service maintenance burden to tip strike damage
	Non-metallic shield	Major improvement of erosion shield life for operations in sand laden environments
Performance	New aerofoils	Enhanced hover and forward flight performance
	New tip planform	
	Increased span-wise twist	
	Structural optimisation & aeroelastic tailoring	Vibration levels of baseline BERP III rotor aircraft preserved or reduced at higher all up weight. Control load increase suppressed.

Table 1 – Demonstrator Blade Features & Attributes

BERP IV FLIGHT TEST RESULTS

The demonstrator programme culminated in a limited flight test programme of 35 hours duration intended to verify the performance of the new rotor at a limited number of test points. This flight test programme was then supplemented with an additional 40 hours as a result of the Merlin Mk.3A urgent operational requirement, using the same test aircraft and building on data already gathered. Test flying included

- Dynamic component loads gathering
- Level flight & hover performance
- Airframe & Engine vibration
- Handling qualities
- Battlefield signatures assessment

To get experience of flying BERP IV on two aircraft, an initial 5 hour demonstration programme was undertaken on AgustaWestland company demonstrator AW101 (CIV01). This aircraft is equipped with GE CT7-8E engines rated at 2500hp. First flight took place on September 26th 2006, including a limited engine handling assessment, hover and low speed airfield manoeuvres, and forward flight up to 120 knots. First flight on the dedicated trials aircraft (ZJ117), which is equipped with RTM322-02/8 engines rated at 2000hp, took place on January 12th 2007. Trials flying concluded on 9th November 2007, which included an additional programme of flying in support of the UOR clearance. During that time the maximum speed demonstrated was 198 knots TAS, and the aircraft operated comfortably at a take-off weight of 16500kg (compared with 15600kg current AW101 maximum mass and 14600kg as the initial design max gross weight for Merlin Mk.3).

The enhancements in blade manufacturing processes were clearly demonstrated during trials flying; blade interchange-ability had been further improved to the stage where little or no tracking adjustments were required when changing blades.

Figure 24 - BERP IV Trials Aircraft First Flight January 12th 2007

Hover Performance

Definitive hover performance tests were performed with ZJ117 using a tethered technique with various cable lengths covering IGE to OGE (Figure 25).

Figure 25 - Tethered Hover

Tests were carried out in near zero wind conditions (less than 3 knots) and the technique involved varying the tension in the cable with varying collective pitch. The aircraft was positioned directly over the tether point and the cable kept vertical throughout the test by use of ground marshals positioned on the aircraft longitudinal and lateral axes. Four different cable lengths were used to provide different hover heights from 10ft to 120ft. In addition, to assess the effect of Mach number on hover performance, tests were also carried out at different rotor speeds. Typical results for an OGE hover are shown in Figure 26, where BERP III and BERP IV measured data are compared with the benefit of BERP IV clearly shown. The benefit of BERP IV over BERP III is in excess of 5%. The figure also shows the accuracy of the original performance predictions.

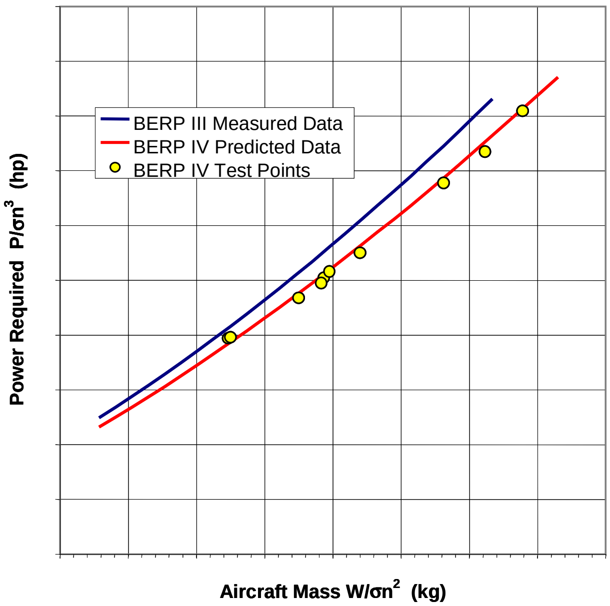

Figure 26 - Hover Performance

Forward Flight Performance

The forward flight assessment covered both power consumption and flight envelope exploration. For the cruise power assessment the aircraft was flown at constant referred mass, $W/\sigma n^2$ (or CT/s), and constant referred rotor speed ($n/\sqrt{\theta}$) over a range of forward speeds. Although one of the original design aims of the BERP IV programme was to improve hover performance whilst maintaining the same level of forward flight performance as BERP III, the design changes introduced through the revised tip and aerofoils did promise some benefit. At low values of blade loading where the BERP III blade is not working anywhere close to its limits, little benefit was expected. However at higher loadings, and those typical of future growth aircraft applications, some benefit was expected. The flight test results confirmed these predictions. At low $W/\sigma n^2$ the BERP IV results were virtually identical to the BERP III data, but at the higher values of $W/\sigma n^2$ significant benefits were seen. Figure 27 shows a comparison of forward flight power for a constant $W/\sigma n^2$. Power reductions of up to 10-15% were observed.

An assessment of rotor limited flight envelope was also carried out. In line with UK Def Stan 00-970 requirements the AW101 flight envelope is limited, where appropriate, by the onset of retreating blade stall (usually indicated by the rise in pitch link loads). This ensures the aircraft does not encounter blade stall within the operational envelope. Taking into account the aerodynamic and dynamic design changes between BERP III and BERP IV, it was initially predicted that the BERP IV blade would have a retreating blade stall advantage of approximately 10 knots TAS. A flight envelope was then produced based on the expanded rotor envelope and declared as the test envelope. During the trials a flight envelope investigation, including steady level and sustained banked turn conditions, was carried out within the limits of the declared envelope. At no point within the declared envelope did the vibratory pitch link loads show any sign of the onset of retreating blade stall, nor were there any pilot cues in terms of handling or vibration that indicated the onset of blade stall. The assumed 10 knot increment was clearly an under-estimate, but there was no time within the limited BERP IV flight test programme to redefine the flight test envelope and repeat the blade stall investigation.

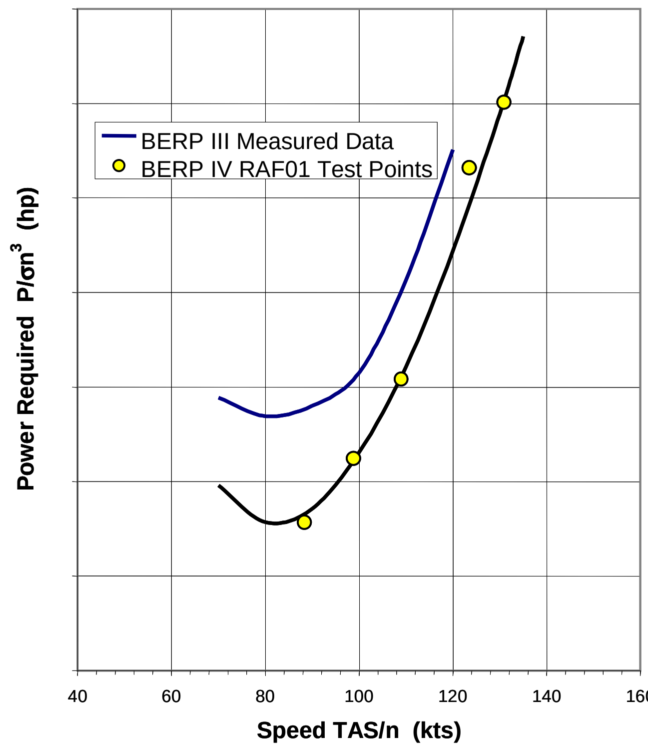

Figure 27 - Forward Flight Performance

Vibration

Throughout the flight trial, data from a total of 36 airframe accelerometers were recorded. Data was obtained for both BERP IV and BERP III blades to allow a direct back-to-back comparison, and vibration characteristics were assessed across a wide range of steady and dynamic flight conditions. Vibration results are summarised here in terms of a vibration index, which is the RSS (root sum squared) summation of all cockpit and cabin accelerometer measurements for a given flight condition. The comparison of level flight vibration indices, calculated from the test data, for the BERP III and BERP IV blades are shown in Figure 28. This data has been obtained with the ACSR (Active Control of Structural Response) active vibration control system turned off. These results indicate the success of the BERP IV design in reducing vibration at source. Furthermore, this measured data shows that the BERP IV blade has exceeded its original design objective which was to recover BERP III levels of vibration with a high twist blade. The test results here clearly show an overall reduction in cabin vibration.

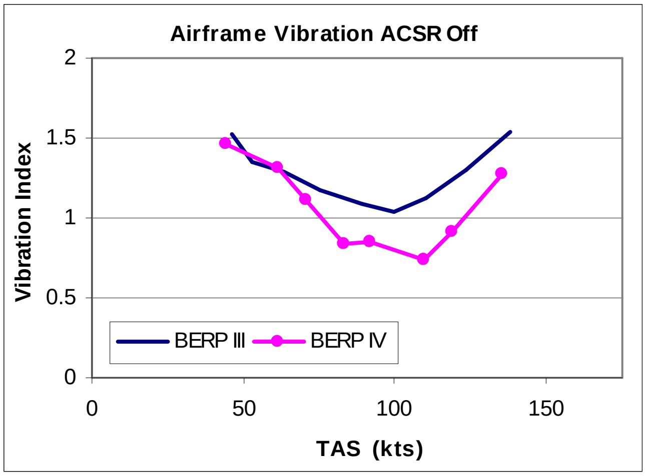

Figure 28 - ACSR Off Vibration

Although the ACSR off results show the success of the BERP IV dynamic design, and have also been used to confirm the effectiveness of the blade dynamic design tools, the AW101 is normally operated with the ACSR system switched on. Figure 29 therefore shows a comparison of vibration indices for BERP III and BERP IV. With ACSR system on, the BERP IV blade vibration performance is generally better than BERP III and at the highest speed a significant improvement is evident.

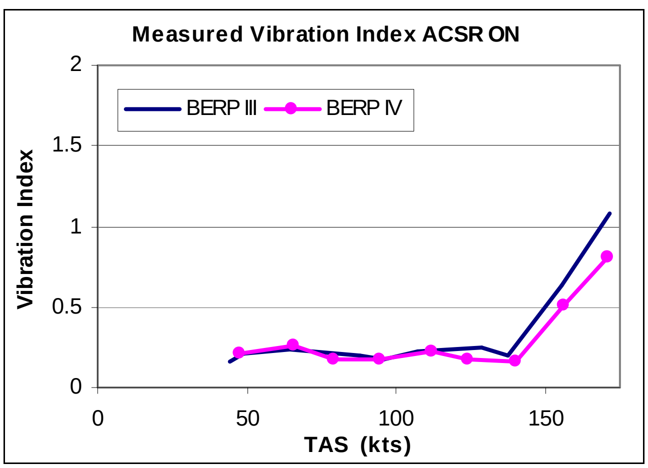

Figure 29 - ACSR On Vibration

Figure 30 illustrates the benefit of BERP IV on the ACSR system. The figure shows the RMS 5R loads for all ACSR actuators. With the exception of the very lowest speed point, the 5R actuator loads are reduced throughout the speed range when the BERP IV blade is fitted, clearly showing that the ACSR system requires less energy to control vibration with the BERP IV blades fitted compared to BERP III.

In addition to the vibration benefit in steady level flight, the BERP IV blades produced a marked reduction in vibration during transitions from forward flight to the hover. During this manoeuvre the 5R vibration levels were consistently about half those measured with the BERP III blades.

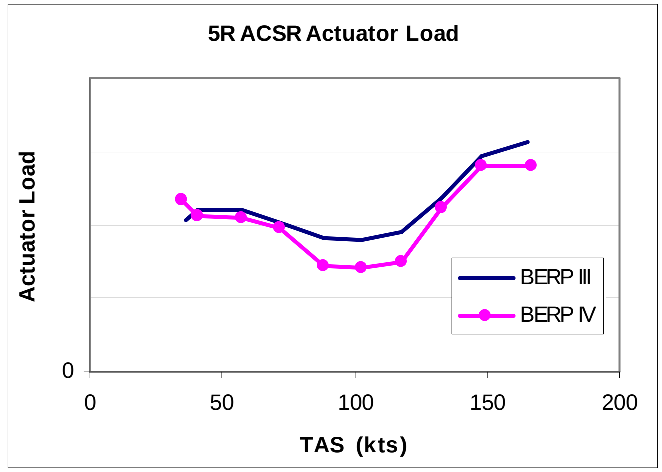

Figure 30 - ACSR 5R Actuator Load Comparison

Overall, the BERP IV blade dynamics objective of using structural optimisation to contain vibration to be no larger than BERP III values has been achieved and exceeded. The measured vibration index and the individual accelerometer results consistently show the BERP IV vibration levels to be the same as or better than those of BERP III.

Handling Qualities

The handling qualities assessment compared the aircraft handling characteristics with BERP IV blades fitted to those with BERP III blades fitted and included the following aspects

- Control & trim
- Longitudinal static stability
- Lateral static stability
- Manoeuvre stability
- Spiral stability
- Response to cyclic control step inputs

Control and trimability tests were carried out in forward level flight between 40kts and 1.1Vne in increments of 0.1Vne for various weight and cg combinations. Stick slopes and change of attitude with speed are similar, showing similar handling characteristics with BERP IV and BERP III blades. Tests were also carried out in 30°, 45° and 60° banked turns and also in autorotations between speeds of 55 and 115 knots; no differences were found between BERP IV and BERP III.

Longitudinal and lateral (directional) static stability was assessed over a speed range of 65 to 130 knots and demonstrated acceptable positive stability, with both BERP IV and BERP III showing very similar characteristics. Manoeuvre stability, assessed in 30° and 45° wind-up turns, was also found to be positive and BERP IV was again found to be very similar to BERP III.

Spiral stability was assessed by applying lateral cyclic to achieve a specified bank angle from a wings level trimmed condition, then returning the controls to the trim position and observing the aircraft response. In all cases the response with the BERP IV rotor was the same as that of the BERP III rotor and there was an immediate and smooth recovery to wings level flight.

Figure 31 - Trials Confirmed Good Handling Qualities

Control response tests were performed where 1 inch step inputs in cyclic were applied in the fore and aft and lateral directions in hover and forward flight. Subsequent attitude and rate responses showed very similar behaviour for BERP IV and BERP III.

Overall, throughout the airborne handling tests undertaken, it was clearly demonstrated, both subjectively and objectively, that the BERP IV rotor had no effect on overall aircraft handling qualities; the aircraft consistently behaved in the same way as with the BERP III rotor.

Loads Data Gathering

Prior to first flight the monitor limits for blade stress at the strain gauge locations along the single instrumented blade were set, based on a deliberately over conservative assumption of the flight spectrum. These parameters were then observed in real time via a telemetry link as the flight envelope was progressively expanded. A number of flight test points at a range of aircraft weights and CG trim positions were specified by the Stress team, based on prior experience of those flight conditions for the BERP III rotor that generate the highest loads.

Overall recorded flight loads were well within initial estimates, and whilst recorded Vne loads were in alignment with predictions the loads encountered in the remainder of the flight envelope were lower. A conservative approach had also been used to set the loading regimes used in the blade ground test, hence once flight loads had been recorded the achieved fatigue test results were re-visited in order to extend the fatigue life estimate of the demonstrator blade in the light of the lower loads recorded.

Analysis of flight test data centred on the use of two sets of load survey data, derived from loads survey flying performed on both the initial demonstrator aircraft (CIV01) and the dedicated trials aircraft (ZJ117). AW proprietary fatigue damage analysis programme DUMBO IV was used to calculate safe lives for individual components of the blade structure, using the load survey data sets. The resultant analysis enabled the declared safe life of the rotor blade to be updated from that initially calculated against structural test evidence alone.

The DUMBO IV fatigue damage analysis programme has three main stages that are used to calculate safe lives of blade components or features.

First the flight results database is interrogated to extract reversal and mean flatwise and chordwise bending moment data for the flight conditions in the spectrum. A conservative approach was used in that data from all the various aircraft AUW/cg/altitude combinations were grouped for each condition and the most damaging for each flight condition subsequently extracted from each group.

Secondly, the programme calculates profile strains (or stresses at the root end lug) from blade bending moments selected from extracted flight data.

Finally the programme calculates the low frequency and high frequency fatigue damage rates and hence safe lives, using a range of input data including the predicted flight usage spectrum, factors to allow for a limited test data population and component S-N curves derived from structural testing.

Figure 32 - Underslung Loads Data Gathering

The low frequency analysis determines the maximum and minimum condition strain (or stress, as appropriate) from the extracted calculated data and then performs a range mean pair analysis. This analysis includes flight sequence effects by grouping associated data together (as specified in the spectrum) and appropriate occurrences of flight manoeuvre and ground-air-ground cycles are used.

The high frequency analysis was performed predominantly using a cycle counting technique, which provides a high fidelity calculation of the damage rate of a condition, particularly those associated with manoeuvres.

In summary, there were no load exceedences in any flight condition flown and acceptable component lives were calculated on the basis of ground and flight test results.

Rotor Downwash

During the flight trials the opportunity was taken to measure downwash and sidewash on the ground underneath and in the wider vicinity of the aircraft (Figure 33). The test data showed that for the comparable weight and environmental conditions the downwash produced by the BERP IV rotor was the same as that for the BERP III rotor.

Figure 33 - Rotor Downwash Measurement

Effect of BERP IV on other Aircraft System

Throughout the flight trial the aircraft was operated within the limitations of the various aircraft systems such as engine and transmission operating limits and other structural limits. None of these existing limits were exceeded with the BERP IV rotor, nor was the flight trial limited in any way by these other constraints. This confirmed the suitability of this design as a retro-fit onto the exiting fleet without modification.

Rotor track and balance characteristics were assessed several times during the trial due to the need to swap between BERP III and BERP IV blades. The BERP IV blades exhibited a high degree of consistency across the population of test blades and virtually no variation of track with forward speed. This is due to the high degree of consistency in aerodynamic and dynamic characteristics between blades, that, in turn, results from repeatability and consistent quality of manufacture.

BERP IV PRODUCTIONISATION & FUTURE DEVELOPMENTS

With demonstration successfully concluded attention is now turning toward exploitation on the AW101 and other aircraft. This process has already begun with the RAF, with blades being produced and released for service for the Merlin Mk.3A. Further work is also under way to expand the qualification of the rotor, including icing trials during winter 2008-2009.

The generic developments under BERP IV will enable exploitation across a wide range of aircraft types. The advanced nature of the new generation aerofoils and dynamic design technologies enable significant performance benefits to be provided to any candidate aircraft with no impact on dynamic component fatigue lives. Additionally, utilisation of new materials and adoption of best practice, such as blade attachment, picketing and mass balance features will enable a significant reduction to in-service costs.

Figure 34 - Exploitation is Next Step for BERP IV

CONCLUSIONS

The BERP IV Programme builds on three previous programmes that have provided major advancements in UK rotor technology since the early 1970s. The programme successfully concluded in summer 2007 with a flight trial on an AW101, verifying the achieved performance of the development rotor against the programme's objectives.

The programme's aims were stated as

- Technologies required to improve product first and life cycle cost, including reduced design complexity, increased design robustness and improved production quality.
- Performance enhancing measures covering payload/range and environmental benefits, including increased hover and forward flight performance and reduced vibration.
- Enhanced battlefield survivability

A number of discrete technologies were developed to address these objectives and the programme culminated in the design of a single demonstration blade that encompassed all aims. Flight test results of this rotor fitted to an AW101 aircraft confirmed achievement and exceedence of performance goals, which are summarised as

- Reduction of hover power by approximately 5%
- Reduction of cruise power, with approx 10-15% saving under typical hot and high conditions
- An improved blade stall envelope of a least 10 knots
- Vibration levels maintained at very low levels with a reduction compared to BERP III at high speed
- Vibration levels halved in transitions from forward flight to the hover
- Aircraft handling characteristics were unchanged compared to BERP III in both steady and manoeuvring flight
- The introduction of the BERP IV blade had no adverse effect on any other aircraft system or component, confirming the suitability for retro-fit

The demonstrator blade design has now been adopted virtually unchanged as a production solution in support of a UK MoD urgent operational requirement. The production blade is now qualified and is anticipated to enter operational service in 2008 The modular nature of the blade's design will enable the future production AW101 designs to be tailored to the required capability mix whilst still benefiting from accrued structural qualification evidence.

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