DESIGN AND CERTIFICATION OF THE ROLLS-ROYCE BR725 ENGINE

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Abstract

The BR725 is the newest and most advanced member of the BR700 engine family and has been selected to power the Gulfstream G650™ executive jet. Based upon the highly successful BR700 engine core, the BR725 is a two shaft, high by-pass ratio turbofan which has been designed for long life on wing, low fuel burn and excellent performance. By introducing a range of advanced design features from recent Rolls-Royce development programmes as well as from the global Rolls-Royce Research & Technology programme a low risk, right first time approach was achieved. Integrated by Rolls-Royce Deutschland, the BR725 has been developed by a truly global project team working across Rolls-Royce and suppliers sites and facilities. This paper describes the highlights of the BR725 engine design and development programme which achieved all major targets and milestones, the most significant being the initial engine certification on 23rd June 2009, only 42 months after programme launch.

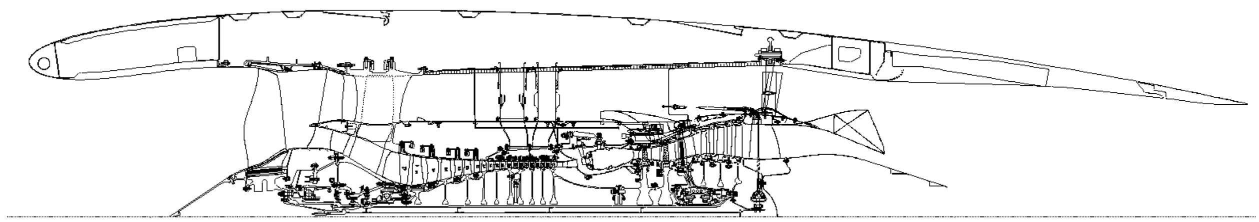

FIG. 1. BR725 General Arrangement

1. INTRODUCTION

At the end of 2005, Rolls-Royce Deutschland won the contract to be the sole supplier for the powerplants of the Gulfstream G650™. This new airframe defines the ultra-large-cabin ultra-long-range executive jet market and represents the flagship of the Gulfstream fleet. The G650™ is capable of flying at high altitudes of up to 51,000ft, achieving a range of 7,000 nautical miles at 0.85Mn and flying at a maximum operational speed of 0.925Mn.The BR725 engine, formally known as the BR700-725A1-12, has been developed as the solution to the demanding G650™ requirements and is the newest and most advanced member of the BR700 engine family.

Aero engine development in general can be considered a relatively high risk activity from both a technical and financial point of view. The market place is competitive where barriers to entry are high and key success factors are characterised by advanced technology combined with specialist knowledge. One essential element in securing an economic return from a new aero engine is the minimisation of development and series production costs. To provide a low risk, right first time solution to the G650™ requirement the approach taken was to constrain the powerplant design and development philosophy to the use of derivative or known technologies, thereby short-cutting the extensive product specific pre-launch rig and demonstrator testing that would otherwise be necessary. This approach also minimises the likelihood of technical surprises inherent within the development of either completely new concepts or extreme extrapolation of existing technology. Designs which are directly descended or interpolated from existing products also benefit from read-across by analogy rather than test when demonstrating compliance during certification. This theme underpinned the BR700 common core family [1] which produced the BR710 Corporate and BR715 Regional derivative applications which have now accumulated over 10 million hours of operation.

This paper describes the highlights of the BR725 engine design and development programme which achieved all major targets and milestones, the most significant being the initial engine certification on 23rd June 2009, only 42 months after programme launch.

2. BR725 POWERPLANT DESIGN

The BR725 is the newest and most advanced member of the BR700 engine family and continues the Rolls-Royce tradition of providing engines optimised for executive jet applications. The Gulfstream G650™ requirements can be summarised as the following:

- Maximum take off weight of 99.600lb,
- Take off distance (SL, ISA, MTOW) 6.000 ft
- Landing distance (SL, ISA, MLW) 3.000 ft
- Time to initial cruise altitude (41.000ft) less than 20 minutes
- Maximum range 7.000nm (Mach 0.85, 8 passengers, 4 crew and NBAA IFR reserves)
- Normal cruise speed of Mach 0.90

The BR725 engine, which has been specifically developed to meet these demanding requirements, is a two shaft, high by-pass ratio turbofan which is designed for long life on wing, low fuel burn and excellent performance. The general arrangement is shown in FIG. 1. It is based upon the highly efficient BR700 engine core and use technology derived from the Trent family of large civil engines, the AE3007 engine and from the global Rolls-Royce Research & Technology acquisition programme.

The key performance attributes of the BR725 can be compared to the BR710. To achieve the take off distance, the BR725 delivers a maximum take off thrust rating of 16.100lbf (SL, ISA+15K) thereby giving 4.6% more power. The engine thrust-to-weight ratio improves from 3.26 to 3.38. To achieve the time to initial cruise altitude, the climb thrust is increased by 12.6% at top of climb (41.000ft, ISA+10) The maximum reverse thrust is increased by 10.8% to achieve the landing distance. The cruise specific fuel consumption is 4% better and the nacelle drag is reduced to achieve the maximum range.

2.1. Component and Module Design

The engine architecture is based on proven technology with a single stage Low Pressure Compressor (or Fan), a 10 stage High Pressure Compressor (HPC), and annular combustor, a 2 stage High Pressure Turbine (HPT) and a 3 stage Low Pressure Turbine (LPT) driving the fan. In comparison to to the BR710, the swept fan delivers more thrust at top of climb whilst modifications to the core components contribute to the 4% Specific Fuel Consumption (SFC) improvement: the HPC with 3D aerodynamics and elliptical leading edges on blades and vanes, the HPT with tip shrouds on both rotors and a modulated turbine case cooling system and the 3 stage LPT.

2.1.1. Fan

Relative to the BR710, the fan diameter has been increased by 2 inches to 50 inch (1270 mm) to achieve the increased top of climb thrust requirements as well as to improve the cycle by increasing bypass ratio. Relative to the BR710, the bypass ratio was increased from 4.2 to 4.4. Swept fan technology which gives more flow at a speed at high non-dimensional conditions was chosen to keep the diameter increase moderate. The swept design combines slightly reduced tip speed with an optimised inlet flow distribution, which improves the blade efficiency considerably. The BR725 is the first application of the 3D swept fan technology in this thrust class of engines, see FIG. 2. The technology has been developed for large turbofan engines as on Trent 900 for the Airbus 380 application. However, the very demanding climb thrust requirements of a executive jet could not be fulfilled with the tip speed and pressure ratio of the Trent 900 fan. Therefore the 3D technology had to be adapted to the higher loading. To further improve fan efficiency, the hub to tip ratio was reduced compared to BR710, fan blade count remained unchanged. Also the composite fan outlet guide vanes were designed with 3D aerodynamics. The mechanical design of the fan was based upon AE3007 experience with an integral annulus platform. To validate the performance improvements ahead of the engine programme the fan module efficiency and characteristics were tested on a 68% scaled model rig at the Anecom test facility.

Similar to other smaller Rolls-Royce engines the fan blades are manufactured from solid Titanium. In contrast to the BR710, which has an aluminium/kevlar containment casing, the fan casing of the BR725 is made from Titanium to fully utilise the available space within the nacelle and minimize weight. This technology was also transferred from Rolls-Royce large civil engines.

FIG. 2. BR710 fan blade (left) vs BR725 (right)

2.1.2. High Pressure Compressor

The BR710 compressor was modified by locally improving particular loss generating features in the flow path with the help of computational fluid dynamics (CFD) as described in [2].

The first step was to model the existing BR710 HPC in a detailed manner including tip clearances, leakage paths in blade roots and gaps between variable vanes and casing. A model with circa 10 million grid points gave a reasonable match with existing rig test data. Analysis of the flow in the front stages showed high losses and flow disturbance in the variable stators, which reduced efficiency and capacity of the front stages. This explained some stage-wise mismatch between front and rear stages as observed in the BR710 rig tests.

The variable vanes have small bosses, or pennies, on either ends of the aerofoil FIG. 3; where penny diameter is considerably smaller than end wall chord length, which generates a significant leakage potential. As mentioned above the flow through these gaps strongly influences the main flow. The CFD results clearly showed how the cross-flow through the penny gaps generated two vortices from every vane. It was easy to show in the calculation that this cross-flow could be deleted by closing the penny gaps. Unfortunately the high number of variable vanes around the circumference did not allow simply increasing the penny size. Other means had to be found to reduce the cross-flow. This was achieved by reducing the pressure difference across the free ends of the vane with the help of so-called “no lift” end-wall sections. They concentrate the turning in the middle of the vane, where it is covered by the penny and a cross flow cannot be established. The front end and back end of the vanes have very little turning with minimal pressure difference between suction and pressure side.

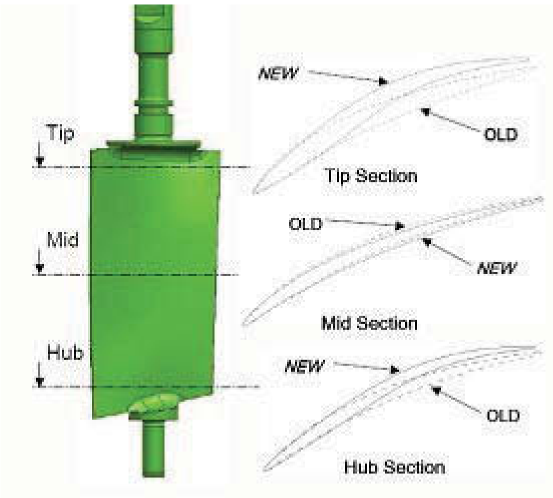

FIG. 3. “Zero Lift” end wall sections

The reduced pressure difference from pressure to suction side lowers the cross flow and reduces the flow disturbance considerably as can be seen in FIG. 4

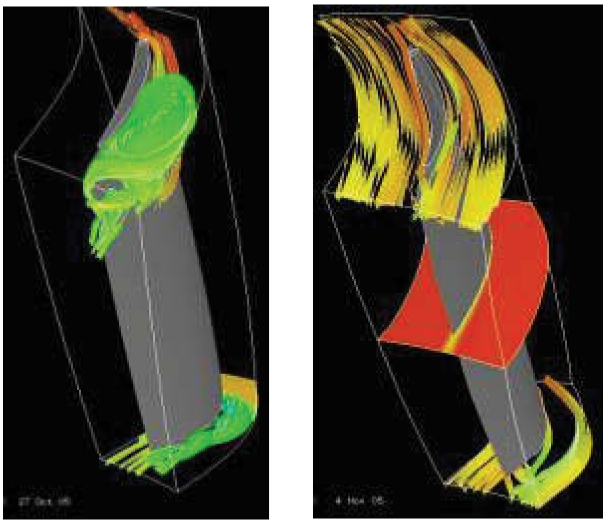

FIG. 4. Flow disturbance due to VSV gaps; original design left, redesign right

The improvements through all front stages led to a much better inlet pressure profile into the fixed geometry part of the compressor, which allowed this part to pull more flow. Therefore, the aerodynamic improvements in the front improved the matching of the front to the rear stages. Additional performance improvements were gained from an improved blade manufacturing process, which produces elliptical leading edges on all blades and vanes.

The HPC module has been weight reduced with blisks (blades integrated with the disk body) on stages 2 to 6 as seen in FIG. 5. The blisk technology has been developed within the E3E (Efficiency, Environment and Economy) technology programme funded by the German government. The research programme covered design, development, manufacturing and repair of blisks. Manufacturing technology has been developed in the Oberursel factory of Rolls-Royce Deutschland and is optimised for production of titanium blisks milled from solid.

FIG. 5. High Pressure Compressor Blisk Rotor

2.1.3. Combustor and High Pressure Turbine

The BR725 annular combustor design is based upon the proven BR715 technology utilised on regional aircraft applications. The design features twenty fuel spray nozzles, improved porting and reduced cooling flows by the application of thermal barrier coating. The resulting design delivers significantly lower emissions with no visible smoke and a longer service life.

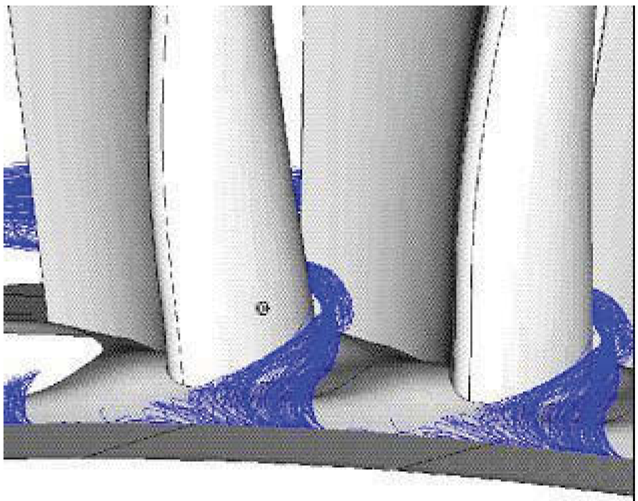

FIG. 6. BR725 HP1 Blade: CFD model with contoured endwalls and rim seal leakage flow addition

The BR725 HPT features a two stage shrouded configuration. The aerodynamic design was produced from the latest validated 3D multistage CFD methods using fully featured modelling and automatic optimisation approaches. By considering the relevant turbine details such as disc rim seal leakage flows, a new generation of profiled endwalls was defined, an extract is shown in FIG. 6. Incorporation of the latest standard of optimised aerofoil cooling designs in combination with higher grade single crystal materials, led the BR725 to having the lowest cooling flow consumption of all BR700 engine variants.

The HPT also features a newly developed modulated tip control system which has been derived from the Trent family. A schematic can be seem in FIG. 7.Cooling air is taken from the fan bypass flow and impinged directly onto the HPT casing. This system allows higher casing cooling flow at cruise conditions to reduce tip clearance of rotor blades and hence reduce over tip leakage. The system is controlled by the EEC and employs three delivery valves around the casing circumference. During high power and transient operation the cooling flow is reduced to increase tip clearance and avoid tip rubs and un-desired turbine deterioration.

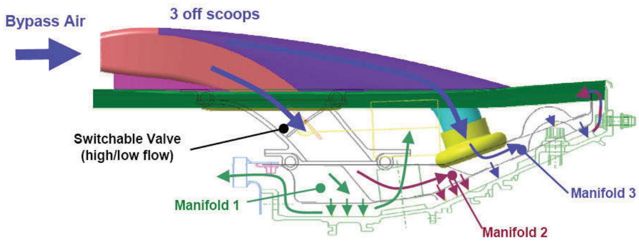

FIG. 7. Flow schematic of the turbine tip clearance system

2.1.4. Low Pressure Turbine

The G650^{TM} operates at high altitudes to be above Air Traffic Control corridors. This brings a specific requirement in terms of Reynolds number to the aerodynamic design of the BR725 LPT. The aerodynamic design is based on a cascade proven profile design style guaranteeing very low loss levels at high lift coefficients in combination with low Reynolds number ranges. To minimise airflow seperation at these conditions, the aerofoil design utilises the “as cast” condition of the blades. The high lift aerodynamic design and annulus optimisations lead to a very short lightweight three stage design, accompanied by latest steady and unsteady 3D multistage methods throughout the design. Contoured endwalls were applied to the long chord first stage nozzle guide vane, minimising the secondary losses and improving the operating conditions for the following high aspect ratio aerofoils. Vane and blade counts and aerofoil gappings were optimised to reduce the LPT noise to low levels. Moderate stage loading contributed to a very efficient overall LPT design. In addition, the lower diameter of the LPT, in comparison to the BR710, reduces the blockage in the bypass duct thereby reducing mach numbers and associated losses.

2.1.5. Installation, Nacelle, Thrust Reverse Unit

When installing a powerplant onto an aircraft a number of complex integration issues have to be considered in order to arrive at an optimised overall system at aircraft level. In this regard, the nacelle aerodynamic shape plays a major role due to its impact on drag. Rolls-Royce as powerplant supplier performed extensive analysis to minimise drag and was able to maintain the maximum outer diameter of the nacelle compared with its predecessor, the BR710, despite the increase in fan diameter.

The larger fan diameter within identical maximum nacelle outer diameter resulted in significantly reduced installation space for accessories and EBU (engine build-up unit) and provided a challenge to the fan containment system regarding the allowable containment casing deformation in case of fan blade failure. This installation challenge was solved by changes to the containment system and application of a full 3D Digital Mock-Up (DMU) for all installation activities including maintainability studies from start of the project. The fan titanium containment system, in addition to providing reduced weight, gives lower deflections in the event of a fan blade release. This allows accommodation of major accessories such as the accessory gear box, EEC, and cabin bleed system, despite the reduced physical space between the fancase and nacelle.

Similar to the BR710, the Thrust Reverser Unit (TRU) is two pivot door design. To achieve improved landing performance and meet the G650^{TM} landing distance of 3.000 ft, in comparison with the BR710, larger thrust reverser doors were necessary to achieve a reverse thrust increase.

2.2. Fan Blade Off (FBO) – Whole Engine Model

In turbofan certification programmes the demonstration of compliance to the certification requirements for fan blade failure are of particular importance due to the complexity and severity of such an event. The out of balance caused by a fan blade off event is approximately 1000 times larger compared to normal engine operating conditions. Although the probability for such an event is very low, it has to be ensured that no hazard is caused to the aircraft in the event of a fan blade failure.

BR725 compliance to the certification requirements for FBO was demonstrated by means of a full running engine test as well as analysis. The engine test was utilised to show sufficient structural strength to contain the released fan blade and to cope with the sudden unbalance during the initial impact phase as well as to withstand the loading induced by the fan out-of-balance during the run down phase. Compliance to the certification requirements for the subsequent windmilling phase was demonstrated by loads analysis based on a model validated by engine test results.

Due to the significant implications a test failure would have on budget and timescales, the engine test is carefully prepared by a variety of analyses and rig tests to ensure a successful outcome. It is essential that hardware tests and analytical approaches using Finite Element Models (FEM) are synchronised and benefit from each other, i.e. models are used to de-risk any test and test data is used to improve model prediction accuracy.

Building upon Trent 900 and Trent 1000 validation experience, during the BR725 development two main models have been used as a fundamental part of the design and certification effort for fan blade failure, namely, the Whole Engine Model (WEM) and the so called Hybrid model. The complexity of the WEM and the Hybrid models can be seen in FIG. 8 and FIG. 9 respectively. The rotors in the WEM are not visible as they are reduced to centre line representations.

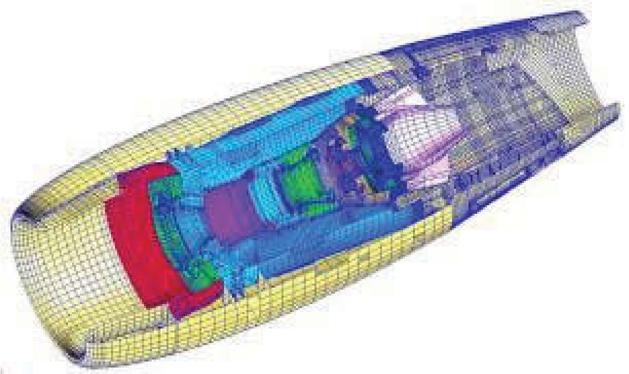

FIG. 8. Whole Engine Model of the BR725

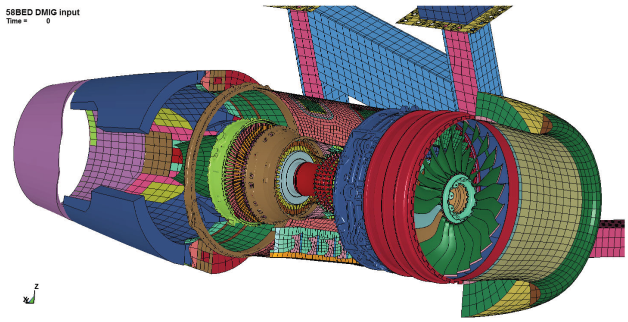

FIG. 9. Hybrid Model of the BR725

The WEM is predominantly used to predict engine behaviour during run-down and windmilling for longer duration events compared to the short event of blade impact and instantaneous out of balance effects where the Hybrid model is used. The use of explicit solvers like LS-Dyna for blade impact is proven technology, whilst for the BR725 this was further developed by inclusion of whole engine properties derived from the WEM and prediction of internal engine behaviour such as the mechanical fusing of bearings.

Prior to the FBO engine test the WEM was validated on component and sub-assembly level. The validation process starts at component level with modal testing of rotors, casings and major accessories like the gearbox. In a second step, the main sub-assemblies are modal tested to characterise main engine joints. After the FBO engine test the WEM was correlated based on test data measured and the predicted loads were used for windmilling compliance demonstration.

Prior to the FBO engine test the Hybrid model was used to de-risk the fan blade failure rig test. The outcome of the rig test was used to updated the Hybrid model and improve its prediction accuracy for the FBO engine test. The successful outcome of the engine test fully supports the chosen approach.

3. DEVELOPMENT TEST AND CERTIFICATION

Only 15 months after the first run, the BR725 achieved EASA CS-E certification on 23rd June 2009. This was followed by FAA certification on 19th December 2009.

3.1. Certification Basis

At an early stage in the programme, the certification basis was agreed and the required compliance method was defined. The engine certification basis of the BR700-725A1-12 engine is summarised in TAB 1. Certification was supported by the successful execution of a development engine test programme, a component development programme and an extensive suite of tests performed at sub-tier suppliers.

Regulation Basis	Regulation
CS-E	CS-E, Initial Issue 24th October 2003, E50 and E1030 of CS-E, Amendment 1, 10th November 2007
Special Conditions	none
Deviations	none
Equivalent Safety Findings	none
Special Issue Papers	Emissions ICAO Annex 16, Volume II, Second Edition July 1993, Amendment 5, 24th November 2005

TAB 1. BR725 Engine Certification Basis

3.2. Component Development Programme

The Component Development Programme (CDP) with over 100 tests served in principle two purposes: to gain an understanding of unit and component performance during the design phase and hence reduce risk for the upcoming engine testing; and to support the engine certification through compliance rig testing.

Testing was specifically defined to understand component contributions to the engine performance at the guarantee points and off-design points within the defined flight cycle. These encompassed:

- Aerodynamic and noise testing of a scaled version of the newly designed swept fan in the specialised AneCom AeroTest GmbH facility
- Optimisation of aerodynamic and noise behaviour of a scaled version of the forced mixer and exhaust in combination with the nacelle
- Aerodynamic evaluation of aerofoil profiles for the high lift LPT considering blade surface finish as cast

A range of other component tests were defined that concentrated on mechanical integrity:

- High Cycle Fatigue (HCF) testing for all aerofoil stages of the engine
- Low Cycle Fatigue (LCF) testing and structural testing of new components
- Fan Blade Off containment testing with a full fan, nacelle intake and intercase module

3.3. Engine Development Programme

The Engine Development Programme (EDP) consisted of 5 engines and 11 part tests. All engines were instrumented with between 400 and 2000 parameters out of a selection of 7100 possible measurement positions. This included two telemetry builds measuring over 150 rotating parameters on the low pressure spool modules and 248 on the high pressure modules.

At certification the EDP had delivered approximately 1100 hours of engine running time, which equates to 3600 flight cycles. This was only 15 months after the first development engine started testing for performance and functionality in Rolls-Royce Dahlewitz, Germany. Functional, vibration, cyclic and Type Test endurance testing were also performed in Dahlewitz. Other tests such as investigation of air and oil system, water ingestion, full engine FBO and medium bird tests were conducted at the specialised indoor testbeds of Rolls-Royce at Derby, UK. Testing in cross wind and reverse thrust conditions were performed at the outdoor facility in Stennis, US, testing in altitude conditions, including icing, at the Arnolds Engineering Development Center (AEDC), US. From this extensive engine development programme a selection of tests are described in more detail.

3.3.1. Rain and Hail Ingestion

When certifying an engine, it must be shown that the engine is capable of acceptable operation throughout its specified operating envelope when subjected to sudden encounters of rain and hail concentrations as defined in the EASA CS-E790. It must be shown that after ingestion there is no unacceptable mechanical damage, thrust loss or other anomalies.

A typical rain ingestion test is the high power casing contraction test which is performed at take-off power representing the critical case within the take-off envelope with the water input and the engine condition set to reproduce the critical altitude point in terms of core water concentration, engine shaft speeds and compressor temperature rise. Water is sprayed from a calibrated grid mounted ahead of the inlet face and injected with a uniform water distribution across the critical area of the intake throat ie. the diameter of the core to bypass splitter. The minimum spray area results from the critical rain ingestion area, the distance of the rake to the intake and the water spray stream tubes resulting from the surrounding airflow streamlines (see FIG. 10 and FIG. 11)

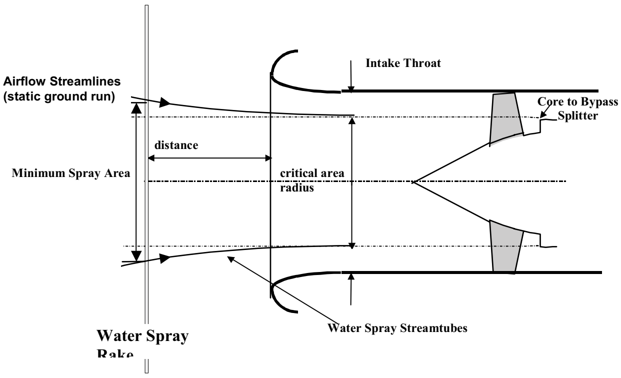

FIG. 10. Water Spray Grid Schematic

During the test, the engine was stabilised at take-off power and water sprayed at 5kg/sec into the engine for 3 minutes. No throttle movement is allowed once the water ingestion has commenced. Upon completion of the required exposure the engine was decelerated to idle and shutdown.

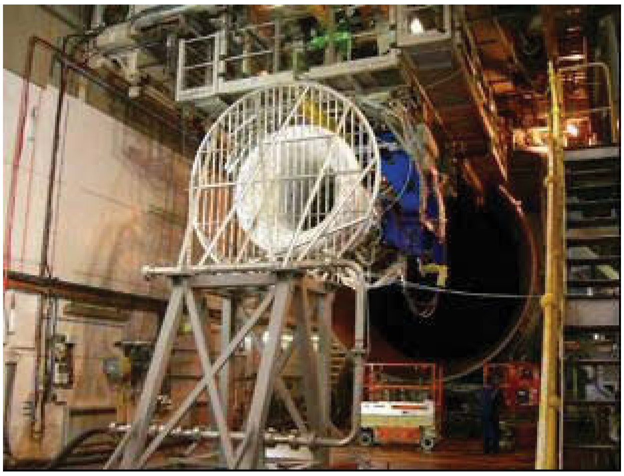

FIG. 11. Water spray grid in position during testing

Engines with wide chord fans like the BR725 are about four times as effective at preventing rain entering the engine core as preventing hail. This makes the hail ingestion test more severe for engine operability than the rain test. The highest core concentration in percentage of water and ice by weight will occur when the core mass flow is lowest, at normal descent idle. Idle is also associated with minimum compressor and combustor stability margins as it is furthest from the high power conditions at which engine operation is optimised.

The maximum hail input to the engine occurs at the maximum aircraft speed for operation in the weather associated with extreme hail and high turbulence, namely, the aircraft rough air penetration speed. For the test, instead of hail, water is ingested into the engine. The heat removal rate from the compressor in the region where ice is melting would be greater than for the same quantity of water. This is compensated by increasing the water input to account for the latent heat of fusion of the ice by 13% which, for the combustor, makes the test more severe than ingesting ice.

A ground level test was performed with water input rate and engine parameters set to reproduce the critical hail condition. Special spray nozzles are mounted at the engine core inlet behind the fan to produce a circumferentially uniform water distribution, see FIG. 12.

During the test the engine was stabilised at descent idle and water was sprayed into the core for 30 seconds. A fast acceleration to take-off power was performed whilst the water flow was continuously adjusted to match the changing engine condition. Subsequently, the engine was decelerated to 50% rated take-off power whilst maintaining water flow rate constant. Afterwards a fast deceleration to descent idle was performed and the water flow continuously adjusted.

During water ingestion testing the BR725 showed satisfactory acceleration and deceleration capability with no signs of compressor instability or flame-out. The engine performance was measured before the first and after the last low power water ingestion and showed that the engine suffered no unacceptable thrust degradation.

FIG. 12. Set-up to ingest water directly into the core engine uniformly by a ring

3.3.2. Fan Blade Off Engine Test

With the introduction of a new fan blade design, a fan blade release test is required to demonstrate that a failure would not create a hazardous situation for the aircraft, neither during the event nor for the remainder of the flight. The engine test, which is doubtlessly one of the most exciting events during the certification programme, was utilised to show sufficient structural strength to contain the released fan blade and to cope with the loads induced during the event and engine rundown.

As discussed in 2.2, due to the implications of an unsuccessful test on programme cost and timescales, all opportunities are taken to de-risk the test by carefully preparing a validation programme including analysis, modelling and component rig tests prior to the full engine certification test. An FBO containment rig test was conducted which included an intake, fan module and associated interfacing casings to ensure a representative test, see FIG. 13. Measurements obtained are used to update the WEM and Hybrid models and improve prediction accuracy. The rig also tests the high speed cameras and detonation system.

Specifically for this type of specialised engine testing, Rolls-Royce built a new test facility in Derby, UK capable of sustaining the loads and supporting the equipment and measurements required. This heavy duty test stand also provides dedicated instrumentation signal conditioning.

The engine was installed into the test bed pylon with an aircraft representative mount system supplied by Gulfstream, representing aircraft system strength and stiffness. The pylon arrangement also included a counter balance weight to simulate the sister engine, see FIG. 14. The engine and aircraft mounts were equipped with instrumentation to allow measurement of strain and vibrations during the test. Displacements where obtained using 42 laser triangulation transducers.

FIG. 13. Containment Rig installed in the test cell

FIG. 14. Engine installed in the test cell

The engine was instrumented with approximately 600 sensors, in order to control its function and to analyse loads using special dynamic signal conditioning and data recording. A high number of measurement devices for acceleration, force and stress were recorded at rates up to 15 kHz. More than 100 temperature measurement devices were fitted to control material properties under test conditions. Continuation wires allowed monitoring of the function of the bearing fuse pins. Digital high-speed cameras were positioned in the test cell to obtain data on mounts behaviour, plastic and elastic deflections of structures, fan interaction and damages.

The engine was started, warmed up for a short period at idle before being accelerated to target fan speed and then stabilised for 8 seconds prior to blade detonation. The released blade, as well as material damaged by the released blade was fully contained. . The fan rotor started orbiting almost immediately after blade release, which demonstrated the bearing fuse pins have sheared as desired. Despite the damage caused by the released blade, the trailing blade remained intact during the impact and engine run-down phase. No manual control inputs were made for 17 seconds after detonation, when the throttle lever was pulled back to idle.

Immediately after blade release the engine surged as expected, the control system activated the surge recovery logic and the engine tried to recover, but ran down after a second surge. The engine ran through several resonance frequencies. All major components such as intake, thrust reverser and accessory gearbox stayed firmly attached to the engine. Likewise all engine units, pipes and harnesses mounted on the by-pass duct and casings, stayed in place and no material was released. The engine LP system stopped automatically and safely without any input from the test crew within a minute.

After little more than 3 minutes of testing a team effort of many weeks came towards its end and delivered a successful result and a significant amount of quality data for analysis.

3.3.3. Altitude testing of the BR725

During the BR725 development program 2 engines were tested at an altitude test facility (ATF). The main objectives of the tests were:

- Verification of the predicted steady state performance including power and customer bleed off-take effects
- Validation of the operability of the engine including fast accelerations and decelerations, compressor surge margin validation, in-flight starting (windmill and starter assisted)
- Certification test in ice forming conditions
- Compliance against customer SFC and thrust guarantees
- Calibration of the engine for in-flight thrust to support aircraft certification

For consistency reasons, an obvious altitude test facility choice would have been DERA Pyestock where the BR710 carried out all its ATF experiments. Unfortunately, that facility was closed in 2001. After a detail assessment of three alternative facilities, and primarily based upon availability, cell C2 at AEDC was selected for the tests. This chamber is not the ideal facility for a BR725 engine because it is effectively too big as the cell is able to accommodate an engine with more than 100,000lbf MTO thrust and total inlet airflow of >3,000lb/s. The large dimensions of the cell (28ft diameter and 47ft length) led to a very long duct between the plenum chamber and the engine (FIG. 15).

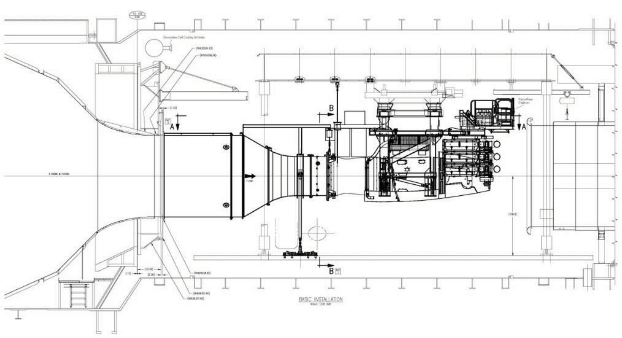

FIG. 15. BR725 at cell C2 AEDC in ducted mode

The ATF approach duct creates a different pressure and boundary layer profile at the fan face relative to a standard flight intake. These differences affect the fan performance in terms of efficiency and capacity.

The instrumented approach duct and engine intake adaptor duct were sized and designed using CFD models in the preparation phase. The design intent was to make the narrow ductwork as short as possible, to reduce the growth of the boundary layer upstream of the engine fan.

The most important performance parameters for steady state testing in an ATF are thrust, air flow and fuel flow. Significant effort was taken to reduce the uncertainties of these parameters to a minimum.

The thrust frame is mounted on four legs on the floor structure of the test cell. The upper platform carries all services required by the engine as well as the engine/pylon assembly. It may move axially by deflection of the flexures at the bottom and top of each support leg. It is restrained from lateral or yaw motion by radius arms fixed between one side of the upper platform and the cell wall structure (FIG. 16).

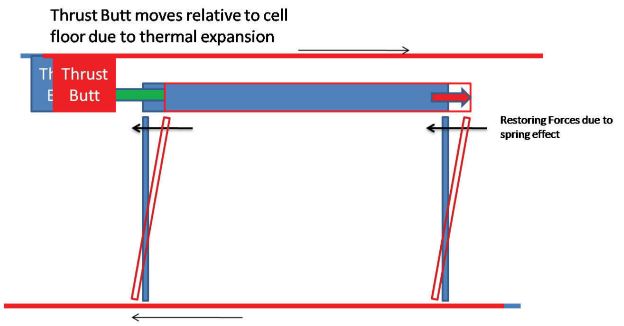

FIG. 16. Thrust measurement system

Thrust forces generated by the engine under test are reacted against a fixed structure at the top rear of the cell structure – the so-called thrust butt. The reaction forces are measured by a service load cell, which is positioned between the frame and the butt. For the BR725 load cells with a reduced thrust range (<20,000lbf) were used to reduce the uncertainty.

To have an independent source of air flow measurement, additional to the venturies in the plenum chamber provided by the facility, a dedicated parallel section in the inlet duct was introduced and equipped with static probes and boundary layer rakes. Also for fuel flow, two independent systems were used, namely, the facility provided turbine flow meters and additional coriolis flow meters installed in the fuel lines. The coriolis flow meters are the same as the standard ones used at the Rolls-Royce test beds in Dahlewitz.

ATF Test cell performance challenges

A number of surprising issues arose during the ATF test campaign which required addressing to ensure successful test completion.

A steady flow CFD was applied to investigate the aerodynamic forces acting on the engine/pylon in the test cell, in particular, to model the flow (and hence forces) around the rear of the engine, the pylon platform and static pressure "buoyancy" forces acting on the thrust system. The CFD was run at various flight and engine steady flow conditions whereas in reality a lot of the effects were transient, therefore not all effects were predicted. Forces predicted by the CFD, had to be treated with care because small differences led to large changes. Nevertheless, the analysis gave a good overview, with predicted temperatures being reasonably accurate. By calibrating against engine testing the CFD results were used to iteratively optimise the cell configuration.

The data acquisition system in the test cell also provided some challenge. The majority of the pressure transducer and temperature scanner to measure engine internal parameters were mounted on the pylon. The presence of these electronics on the pylon introduced the need for a low temperature limit (~35°C) in the cell to avoid damage to the electronic systems. The need to keep to such a low limit required cell cooling which caused thrust measurement errors and cell pressure instability at the start of the test program. Small errors in the measured force lead to large percentage effects on net thrust because of the size of the BR725 engine and the low cruise thrust relative to the capability of the test bed.

One further arising was the observation that a dominant effect on thrust error was related to temperature changes (or operation of the cell cooling systems) While the precise mechanism for the thermal effects on scale force errors was not fully understood, theories were defined to explain how the scale force may change with temperature.

To mitigate the influences seen on thrust measurement due to thermal effects, a cell temperature control scheme and management procedure was applied during the final stages of the test campaign. This had the desired effect and ensured consistent thrust readings in line with the master bed baseline. The steady state performance testing was then completed and demonstrated good alignment with the predicted SFC values. Transient testing was also performed with the engine demonstrating good and stable characteristics.

3.4. Tests in ice-forming conditions

As part of the campaign in the ATF, tests in ice-forming conditions were conducted to support engine certification. The ATF test set-up was different in that the engine had its flight intake fitted and testing was in free stream mode, see FIG. 17.

By using a full-face water spray rake in front of the engine intake, water with a defined droplet size and temperature is sprayed into the airstream to replicate the content required by the CS-E regulations. For all tests, bleed and power off-takes were set to the levels that provide minimum engine margins within the range of likely values for the flight conditions and aircraft application. The tests are grouped:

- Hold tests at altitudes of 17,000 to 25,000 ft
- Descent testing over 10,000 ft altitude change
- Ground icing (freezing fog) test

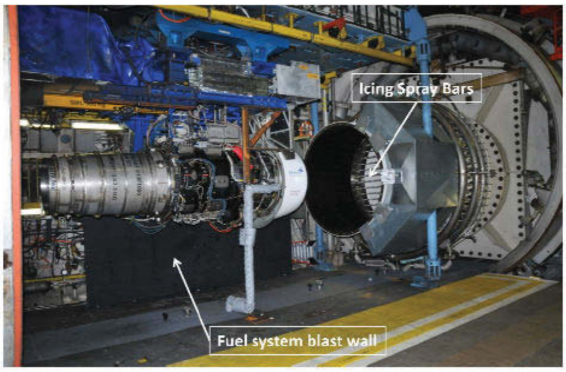

FIG. 17. Engine installed in testbed

During hold tests, the engine is exposed to the icing conditions for 30 minutes followed by an acceleration to Maximum Continuous rating. The descent testing simulates a 10 minute descent from an altitude of 15,000 ft to 5,000 ft through icing conditions while the ground icing test exposes the engine to freezing fog conditions at sea-level for 30 minutes, both followed by a fast acceleration to take off power.

During the test in icing conditions, ice will accrete and be shed in intervals from the spinner, fan blades and static parts in the front of the gas path and ingested into the engine, see FIG. 18. Delaying to switch on the anti-icing system of the intake made the test conservative and leads to additional melting and shedding from the intake lip.
The test was also used to develop adequate operating instructions for the engine under icing conditions.

Sudden drops of high pressure compressor exit temperature confirmed that ice shed entered the engine core, however, engine operation was unaffected and showed no degradation of performance throughout the test. Equally, post test inspection of the engine showed no mechanical damage.

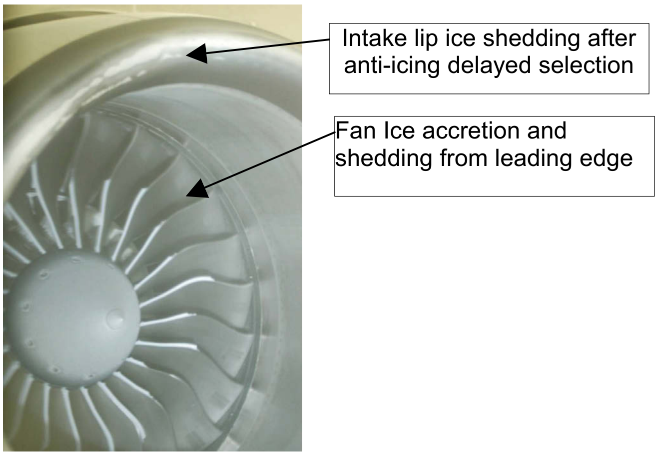

FIG. 18. Typical accretion of ice

4. FLIGHT TEST PROGRAMME

Although a lot of validation testing can be done on rig and engine test beds to demonstrate compliance with the engine certification regulations and customer requirements, flight testing is an essential part of the engine qualification. On the one hand it proves the installed performance of the engine and its sub-systems and, on the other, its integration with the aircraft systems is checked under real operating conditions. The flight test programme is also used to demonstrate maintainability and sufficient reliability in a more service representative environment.

Post engine certification, a cyclic endurance fleet leader is currently undergoing testing to demonstrate maturity in the Rolls-Royce test facility in Dahlewitz, Germany, whilst Gulfstream are conducting their G650^{TM} flight test programme from their base in Savannah, US. The flight test campaign involves 3 experimental aircraft with 6 instrumented BR725 flight test powerplants and 2 spare powerplants. First flight was achieved on 25th November 2009. The programme is planned to conduct 1,800 hours of testing, culminating in airframe certification in 2011 and entry into service in 2012.

5. PROJECT MANAGEMENT

As the Rolls-Royce centre of excellence for two shaft engines, Rolls-Royce Deutschland in Dahlewitz, Germany had the task to integrate the design and development of the BR725 dressed engine and powerplant. Since inauguration of this green field site in 1993, this facility has a proven pedigree through design, development, production, repair and overhaul and testing, and has delivered, amongst others, two new centreline engines to the marketplace through the BR710 and BR715.

To capitalise upon key specialist expertise across the Rolls-Royce Group, a global team was established. The High Pressure spool (HPC, Combustor & HPT) was designed in Dahlewitz, Germany and the Low Pressure spool was split with the fan system design in Indianapolis, US and Derby, UK and the LPT design in Bristol, UK. Transmissions, Functional and Power System integration were also led from Dahlewitz. The project also included major design/make suppliers such as Spirit Aerospace in Wichita, US (Nacelle and TRU); Hispano Suiza in Paris, France (Accessory Gearbox); Aero Engine Controls in Derby and Birmingham, UK (FADEC and hydro-mechanical units) and ITP in Madrid, Spain for design of the engine external dressings. Further, the project employed a significant number of sub-tier suppliers, test facilities and University Technology Centres leading to a significant global footprint.

The integration of the multi-site project was co-ordinated by a series of controlled design iterations which featured structured, gated reviews. Despite the demanding number of interfaces, the close co-ordination and the process control employed led to the first engine assembly passing without any problems. This paved the way to achieving the first engine to test and engine certification milestones to both schedule and budget.

6. SUMMARY

At the end of 2005, Rolls-Royce Deutschland won the contract to be the sole supplier for the powerplants of the Gulfstream G650^{TM}. By utilising a low risk, right-first-time approach employing existing technology derived from other Rolls-Royce products and the global Rolls-Royce Research and Technology acquisition programme, the BR725 two shaft turbofan design combines to deliver best performance, highest reliability and minimum operational cost. Integrated by Rolls-Royce Deutschland, the BR725 has been developed by a truly global project team working across Rolls-Royce and suppliers sites and facilities. Design, development, production and testing have been performed at several locations in Germany, UK and North America and a world wide supply chain was employed.

Supported by the textbook execution of a development test programme and overcoming challenges, such as a demanding Altitude Test Facility campaign, the project team delivered to schedule and specification. The BR725 achieved EASA certification 23rd June 2009, only 42 months after programme launch, and FAA certification on 19th December 2009. The project is on target to achieve airframe and powerplant certification in 2011 and entry into service in 2012.

7. REFERENCES

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