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DEVELOPMENT OF THE RB211-Gzero AFTERMARKET POWER UP-RATE

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Abstract

The RB211-Gzero is one of the latest and most significant developments in the Rolls-Royce aero derivative Industrial Gas Turbine product portfolio. Applied at engine overhaul as an aftermarket upgrade to the existing RB211 Gas Turbine G and C variants, Gzero offers Rolls-Royce Operators up to 10% increase in shaft power with minimal equipment modification and the same footprint, while maintaining all the key attributes that have built the reputation of the Industrial RB211 in the Oil & Gas mechanical drive and Power Generation markets.

The upgrade is engineered to deliver the extra power by increasing the engine flow capacity through focused redesign of the Intermediate Pressure Compressor (IPC), and without turbine modifications. An additional zero-stage of compression is added to deliver higher compressor flow, pressure ratio and efficiency by applying the latest Rolls-Royce aerofoil technology, as well as new materials and a new, three-stage Variable Guide Vane system. The upgraded compressor integrates seamlessly with the rest of the Gas Turbine proven core, keeping overall interfaces largely unchanged for a low risk, 'plug-and-play' upgrade which minimizes down time and package modifications, while delivering significantly more power.

An extensive engine test program was completed at the Rolls-Royce facilities in Montréal to verify all critical-to-quality attributes and mitigate technical risks ahead of the product Entry Into Service. This included the utilization of the Gas Turbine as a System to fully explore the new IPC design envelope, in combination with latest instrumentation techniques to deliver verification evidence at the component, sub-system and system levels through an integrated test program. The success of this approach in reducing development lead time and cost will be discussed in this paper.

1 Introduction

The industrial RB211 aero-derivative gas turbine has undergone several developments and improvements since its initial introduction into the Oil & Gas mechanical drive and Power Generation markets in 1974. Beginning with the initial RB211-22, proven technology improvements in compressor and turbine aerodynamics, combustion and cooling system architectures and materials capability have progressively been incorporated though the variants A, B, C, G and GT to deliver power, efficiency and reliability improvements.

To date, the RB211 gas generator has accumulated over 32 million operating hours with over 740 units sold. The majority of the installations (over 500) utilize RB211-C or RB211-G gas generators with RT56 or RT62 power turbines.

The Gzero upgrade, which is addressed in this paper, has now been developed to offer operators of these variants an aftermarket solution delivering up to 10% increase in shaft power with limited equipment modification. The upgrade package is largely contained within the gas generator, and designed to be applied during a normal engine overhaul at an approved repair & overhaul base. A power turbine capacity increase, which can be completed at site by only replacing the first stage of stator vanes, will enable the existing installation to convert the increased exhaust gas power from the upgraded gas generator into prime mover power.

The product retrofit concept is based on a similar development previously applied with success by Rolls-Royce to another product line with the Avon 200 turbine upgrade [1], which has recently seen its 100th unit embodiment.

The engine development program described in this paper has verified that the Gzero gas generator upgrade delivers the target power increase of up to 10% relative to the baseline RB211-G variant at ISO, as shown in Figure 1 below. Relative to the older RB211-C variant, the power increase at ISO is about 31%, depending on the existing package configuration. For the purposes of the comparison, data is referred to as operating at sea level, in new conditions and assuming zero installation losses.

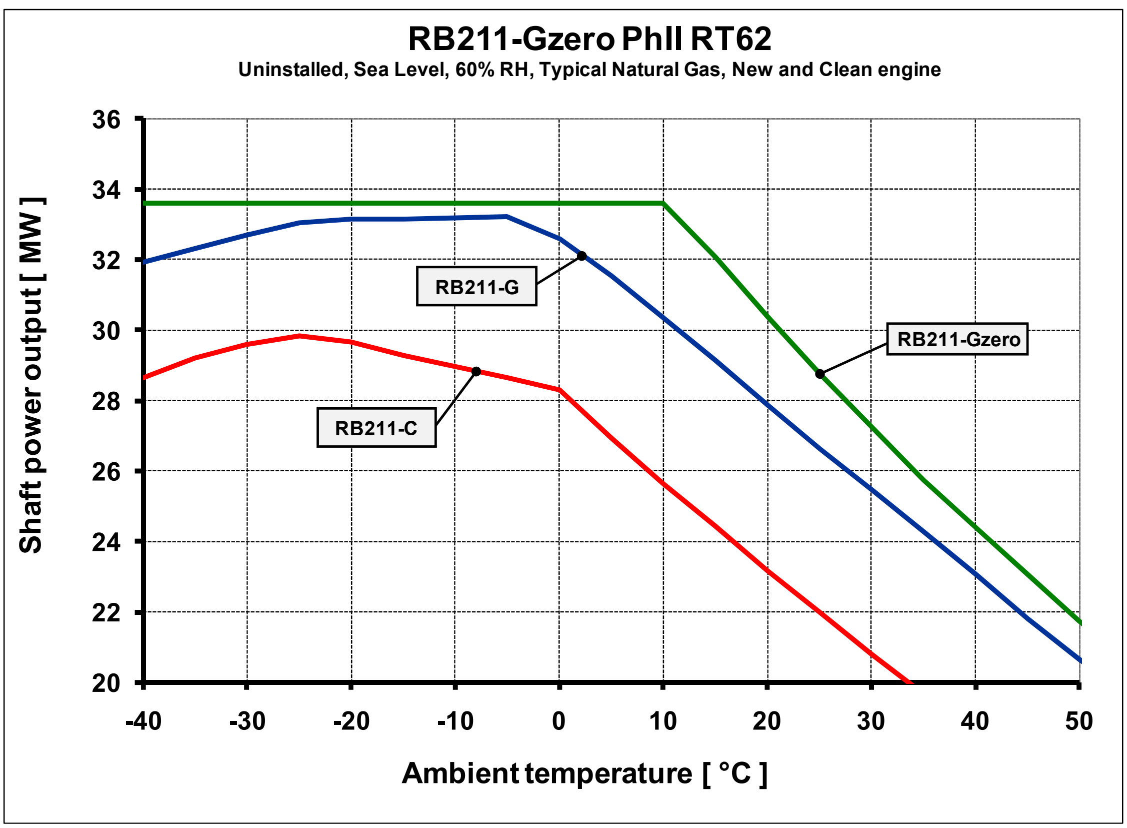

Figure 1: Shaft power output of the RB211-Gzero compared to previous variants

2 Product overview

The RB211 aero-derivative gas generator has a pre-balanced modular architecture facilitating rapid build and strip activities and, if necessary, module replacement at site. The six gas generator modules, shown in Figure 2, are the following:

- Module 1 – Air Intake Module
- Module 2 – Intermediate Pressure Compressor Module
- Module 3 – Inter-compressor Module
- Module 4 – High Pressure Compressor, Turbine and Combustion Module
- Module 5 – Intermediate Pressure Turbine Module
- Module 6 – Engine externals (not shown in Figure 2)

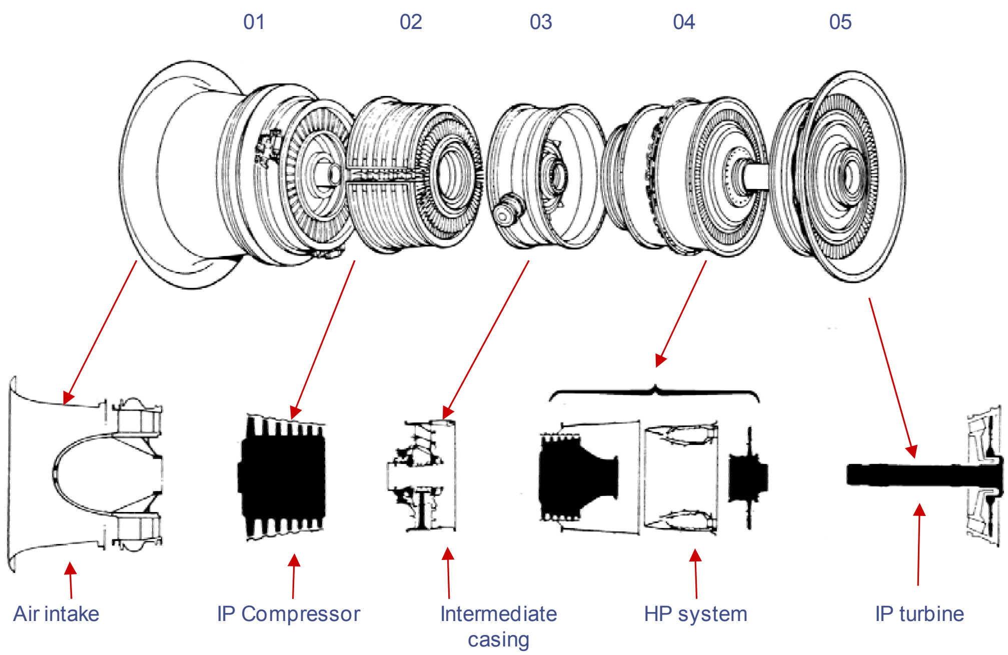

Figure 2: RB211 gas generator modular architecture

The gas generator is coupled to a free power turbine which converts the high temperature and pressure gas exiting the gas generator into mechanical shaft power.

The Gzero gas generator upgrade, shown in Figure 3 below. is contained within the cold section of the engine, with hardware modifications only applied to the 01 and 02 modules (as well as the associated externals in the 06 module).

The main modification consists in the incorporation of an additional stage at the front of the IP Compressor (zero stage). This increases the compressor flow capacity and pressure ratio, thereby increasing the exhaust gas power without significant increases in the turbine temperatures. An increase in the capacity of the free power turbine, achieved by only changing the first stage stator vanes to a standard of larger throat area, converts the increased mass flow exiting the gas generator into useful mechanical power.

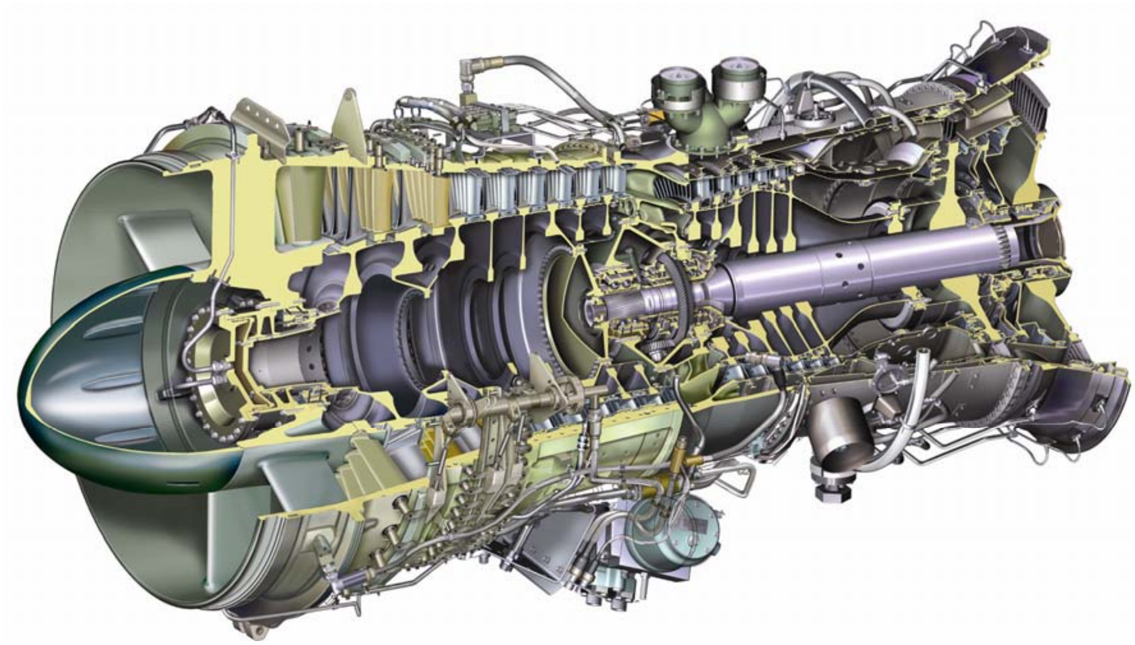

Figure 3: RB211-Gzero gas generator

A cross-section of the Gas Generator modifications is shown in Figure 4 below, which identifies the new components and those retained from the donor engine receiving the upgrade. In addition to the new turbomachinery core components, the IP Compressor variable inlet geometry system is also modified, upgrading the single stage system used on the current RB211 to a three-stage variable geometry system. The gas generator hot end modules (03, 04, and 05) remain unchanged.

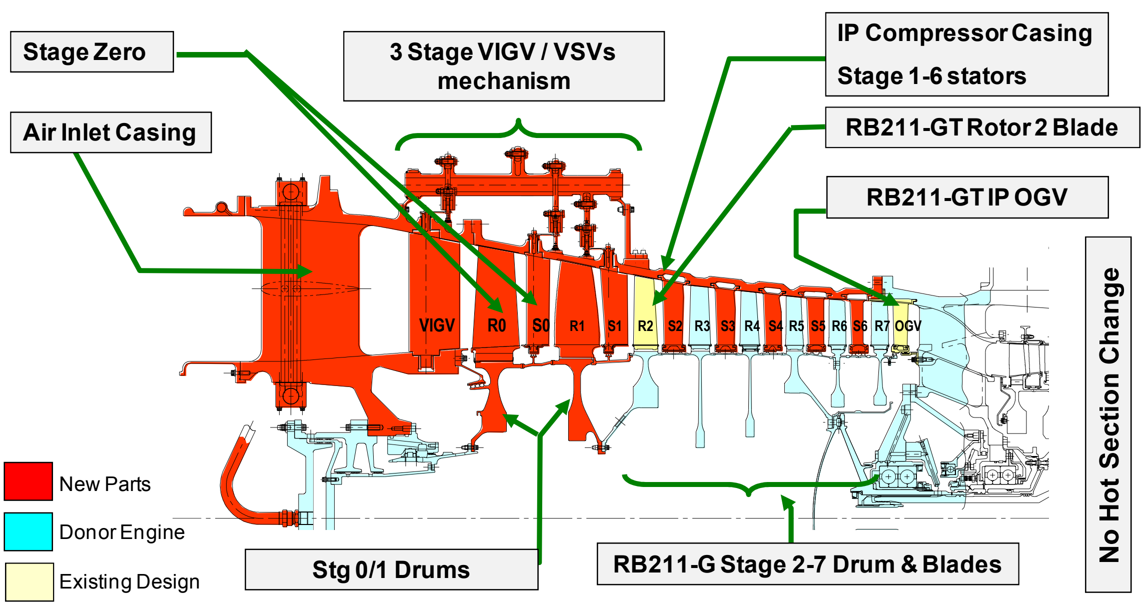

Figure 4: Cross-section of the RB211-Gzero modification

The modifications to the individual modules are described in further detail in the following sections.

2.1 Air Intake module design

In order to accommodate the additional zero-stage of IP compressor whilst maintaining the engine overall length and mount points for a “plug-and-play” upgrade, the air intake casing (module 01) was redesigned to incorporate into a single component the front extension piece used in the current RB211.

The new Air Inlet Casing (AIC), produced from a single Aluminum casting, also houses the compressor Variable Inlet Guide Vanes (VIGV) and provides pre-drilled / threaded ports with blanking plugs ready to accommodate on-line water wash spray nozzles if required. The key features of the Gzero AIC are illustrated in Figure 5. The gas path inner and outer annulus profiles have been matched to the new IP compressor, and all gas washed surfaces are machined for better control of the surface finish and air inlet aerodynamics.

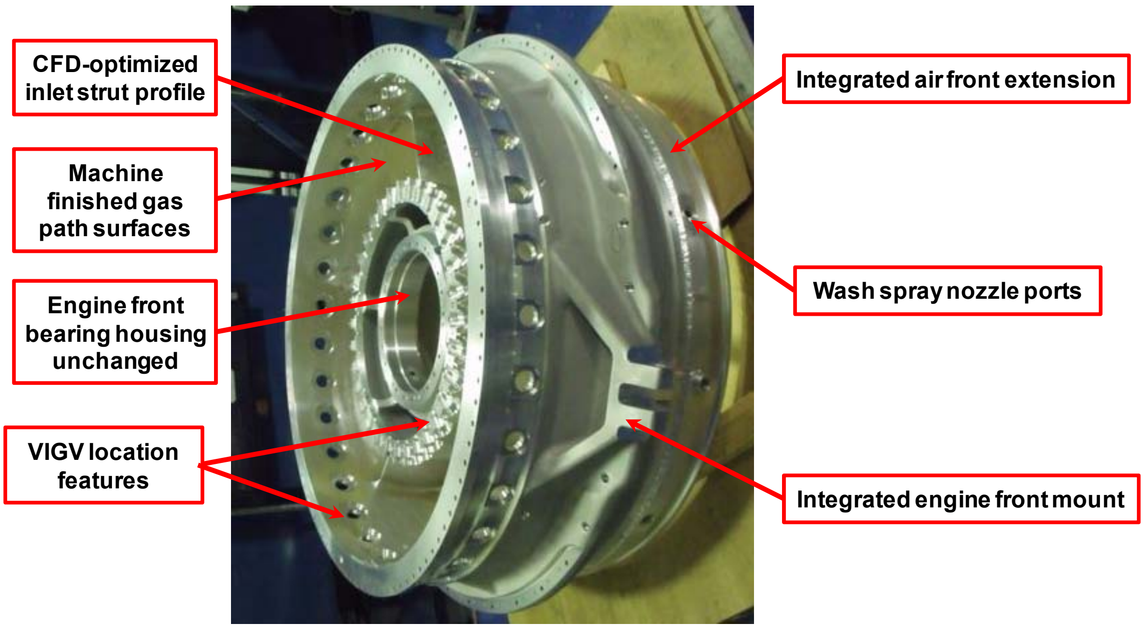

Figure 5: Key features of the Gzero Air Inlet Casing

The new casing design was fully analyzed prior to manufacturing using 3D finite element thermo-mechanical analysis techniques, under the loads applied by the engine front mount and predicted by the whole engine mechanical model for the range of operating and non-operating conditions expected throughout the engine life cycle. The casting manufacturing process was developed and verified through an extensive program including the cut-up and metallurgical examination of several test units in order to verify achievement of the required mechanical properties.

In conjunction with the Air Inlet Casing, a new nose bullet was also designed for the Gzero engine upgrade, with an elliptical profile optimized using an integrated 3D Computational Fluid Dynamics (CFD) model of the Air Inlet module and the IP Compressor, in order to achieve the ideal entry conditions into the compressor. The same model was also used to optimize the aerofoil profile for the AIC struts.

2.2 Intermediate Pressure Compressor (IPC) module design

As shown in Figure 6 below (and Figure 4 in the previous section), the donor engine stage 1 disc is replaced by a newly designed stage 0 and 1 drum assembly, interfacing seamlessly between existing components.

The use of a lightweight Titanium alloy (to replace the steel disc used on the donor 24G engine) for the new drum assembly minimizes the rotational inertia increase introduced with the zero-stage, ensuring that optimal rotor dynamics and operational agility are maintained while delivering the high material strength required by the application.

Titanium is also used for the new stage 0 and 1 rotor blades, which have been qualified at the component level for their resistance to High Cycle Fatigue (HCF) through a program of vibration bench tests prior to their verification in the engine test program (see section 3 below). The rest of the IPC rotor assembly is left unchanged.

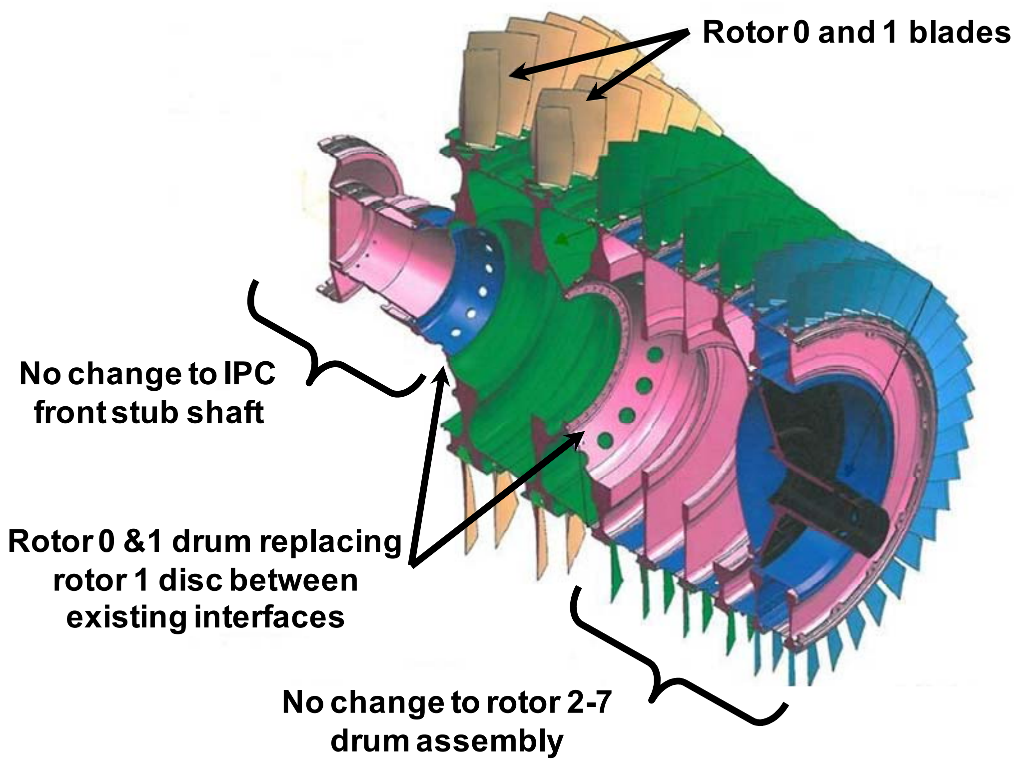

Figure 6: Gzero IP Compressor rotor assembly

In addition to the stage 0 and 1 rotor blades, new designs have also been developed for all the IPC stator vanes, incorporating the most recent technology improvements developed by Rolls-Royce for its latest aero engine products.

As part of the stators redesign, two additional stages (0 and 1) of the IPC are made variable geometry stators, thus introducing a three-stage variable geometry system as opposed to the single stage used in the baseline 24G engine variant. This design enables the optimization of the IPC flow-speed characteristics across the entire operational range, in order to maximize the compressor stability and handling at part power. The new Gzero IPC blades and vanes are shown in Figure 7 below.

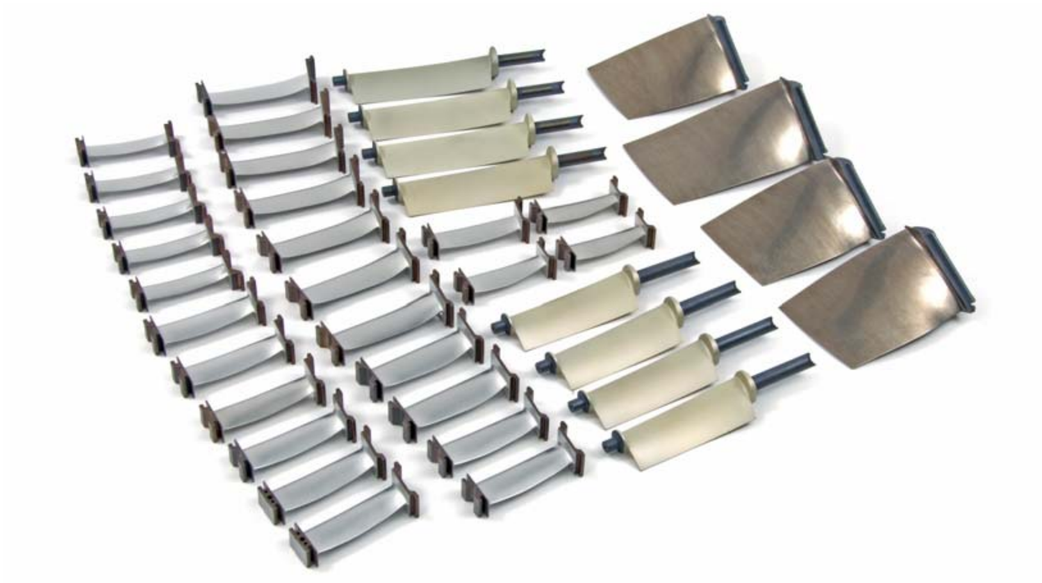

Figure 7: Gzero IPC rotor blades and stator vanes

Enclosing the new zero-stage IPC, a new casing was designed in forged Aluminium, with similar characteristics to that of the current RB211. The Gzero IPC casing, assembled to the fixed and variable stator vanes, is shown in Figure 8 below.

Figure 8: Gzero IPC Casing and stator vanes, and assembly to rotor

The latest transonic compressor design process and simulation techniques developed by Rolls-Royce were used to analyze and optimize the integrated compressor aerodynamics. Combinations of 1D meanline flow models and 2D through-flow analysis were applied to predict the characteristics of each individual aerofoil (stage loading, incidence angles, pressure ratio, and efficiency), and the overall compressor maps.

3D Computational Fluids Dynamics (CFD) was used to optimize the rotor blade design of the two front stages of the IPC (stage 0 and 1), maximizing performance and stability. The new rotor blades incorporate the Elliptical Leading Edge (ELE) technology used in the latest generation of Rolls-Royce aero engines to deliver an improvement in IPC efficiency.

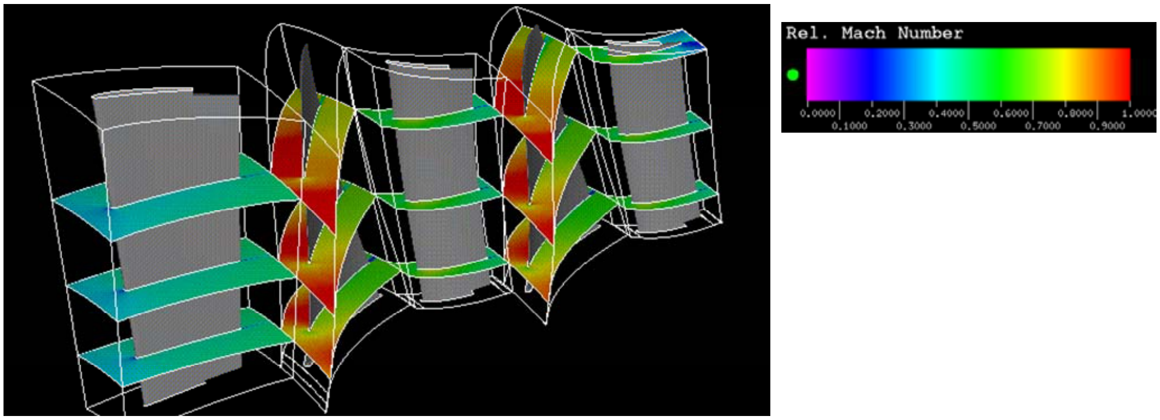

Figure 9: 3D CFD model for the optimization of the IPC stage 0 and 1 blades

The optimized design of the IP Compressor, with the incorporation of the zero-stage, delivers an approximate 10% increase in flow and pressure ratio and over 2% increase in IPC isentropic efficency, compared to the baseline RB211-24G variant.

The aerodynamic design tools were also used for an analytical optimization of the angular positions of each of the three Variable Stator Vanes (VSV) stages as a function of non-dimensional speed, in order to maximize the compressor surge margin across the speed range. Recognizing the uncertainties in this highly complex analysis, the VSV schedule developed at this stage was only used as the starting point for the on-engine optimization planned for the test phase (see section 3).

The aerodynamic design of the compressor aerofoils was iterated several times with the stress and vibration analysis, to ensure the final design satisfies the combined set of criteria.

The assessment of compressor blading strength to low and high cycle fatigue has traditionally been conducted via multiple on-engine strain gauge tests, which is very costly, scarcely reliable and has the disadvantage of not delivering verification results until the engine test phase, extending the product development cycle and increasing the associated risk level.

To mitigate these issues, Rolls-Royce has developed over the years an advanced aero-elasticity software tool named AU3D [2], [3], [4], [5] to simulate turbomachinery unsteady flows and associated phenomena. A multidisciplinary approach is used to accurately model all physical factors affecting the aerofoil aero-elastic response (including the wakes caused by upstream and downstream blading pressure field forcing, flutter and other non-integral vibrations, i.e. not generated by the blading itself), and analyze them in a unified fashion to predict stress and vibration response. The methodology and tools have been verified against strain gauge data from several engine tests, demonstrating the capability to produce good predictions of the component's physical response.

On this basis, the decision was made in the early phases of the Gzero project to utilize the aero-elasticity simulation tools to clear the IPC aerofoils designs. The tool was used to determine the vibration modes of each aerofoil, and then conduct a forced response analysis under the unsteady pressures caused by upstream and downstream blades and vanes.

With this analysis, it was possible to identify for each aerofoil the mode with the highest vibration response, and verify that it meets the required strength against High Cycle Fatigue. 3D finite element stress analysis techniques were used in conjunction with this to verify adequate strength for steady forcing and low cycle fatigue.

Using the vibration analysis techniques described above, all the stator vanes incidence angles were optimized to minimize the vibration response, and enable the removal of the damping medium that, in the current RB211, is injected in some stages of vanes and inner shrouds during assembly and overhaul. This represents a significant simplification of the engine overhaul process.

As discussed in detail in section 3 below, the vibration analysis of the Gzero IPC has then been experimentally verified as part of the Gzero engine test program, using advanced instrumentation techniques (blade tip timing) to monitor and record the on-engine vibration response of the first three rotor stages.

2.3 Engine external components design

As mentioned in the previous section, the configuration of the IPC variable geometry was changed from only one variable stator vane on the 24G to three variable stages (VIGV, VSV0 and VSV1) on the Gzero design for improved part speed performance and operability. The actuation system utilizes a pair of crankshafts (installed at diametrically opposite positions on the engine) to drive all three variable stages simultaneously using hydraulic actuators, as shown in Figure 10.

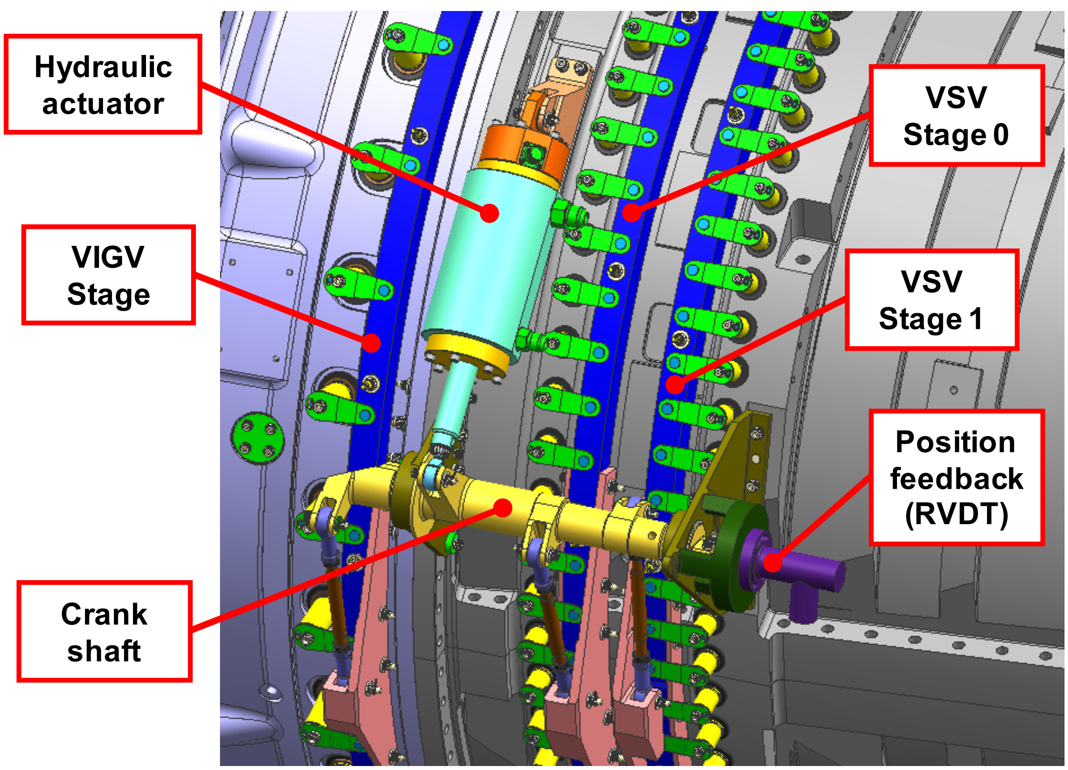

Figure 10: Gzero Variable Guide Vane actuation system

The system design, based on the Rolls-Royce aero Trent 900 engine, is such that the aerodynamic loads applied by one of the stages counteracts the other two, in order to minimize the external actuation loads. This enables the use of hydraulic components (actuators and servo valve) already in service with the industrial RB211 and Trent engines, so that the interfaces to the package hydraulic skid are kept unchanged. Similarly, the system position feedback to the engine control system is provided by the same dual Rotary Variable Differential Transformer (RVDT) device already used by the current RB211 variants, and now mounted on one of the two crankshafts.

The other functional modification made to the engine externals is the conversion of two of the High Pressure (HP) compressor Bleed-Off Valves (BOV) from a purely starting to a dual starting and handling function. This was introduced to improve the engine handling and stability during rapid transient manoeuvres like load sheds and emergency shut downs, and was achieved by connecting the BOVs to a pilot actuation air supply controlled by the engine control system through dedicated solenoid valves. This system is already proven in service with the RB211-24GT engine variant.

3 Package and Power Turbine

The key engine interfaces are unaffected by the Gzero upgrade. The overall engine length and mount positions are left unchanged, making for a "plug-and-play" upgrade concept that minimizes the required changes to the packaged installation as shown in Figure 11 below. All the package modifications are standard items already embodied on other RB211 product variants.

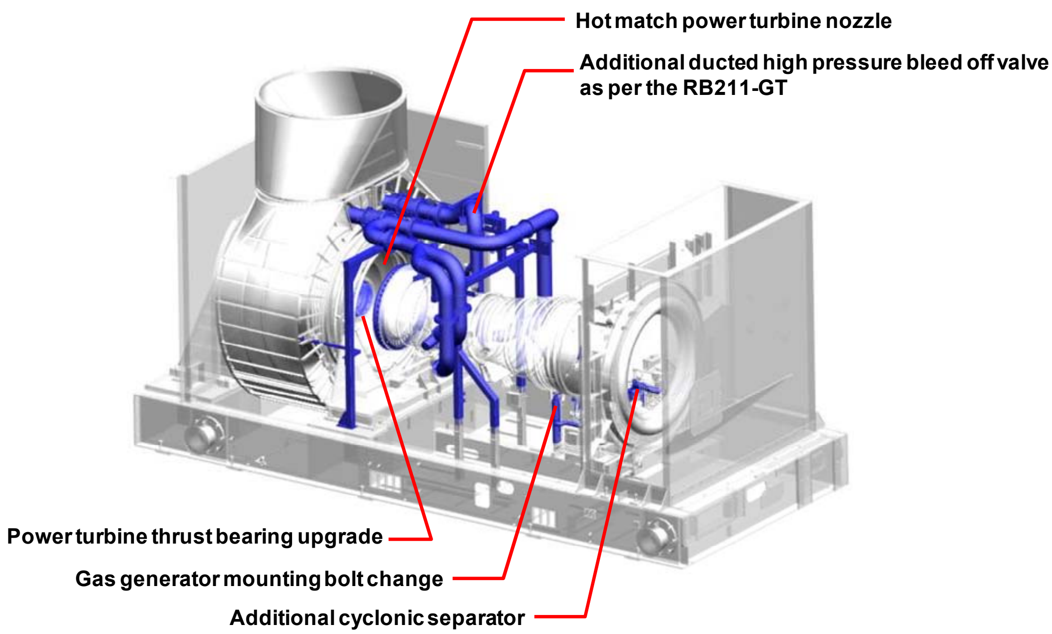

Figure 11: Package modifications required for the Gzero upgrade

In order to convert the increased mass flow exiting the gas generator into mechanical shaft power, the inlet guide vanes of the Free Power Turbine are replaced to increase the effective area. In order to reduce the development risks, the power turbine inlet vane design adopted for Gzero is an existing one already proven in service with the RB211 product. The up-flowed vanes can be installed at site during the gas generator swap time.

4 Engine test program

In order to produce a true representation of the embodiment of Gzero as an aftermarket retrofit, the engine test program was conducted using, as a test vehicle, a RB211-24G engine returning from service after 100,000 hrs of operation.

The engine was taken through a regular overhaul, and subsequently transferred to Montréal for the development testing program, which consisted of the three main functional tests summarised in Table 1 below. The tests were conducted on the gas generator only, using a calibrated nozzle to reproduce the restriction normally due to the free power turbine in the packaged installation, and recreate the same operating conditions for the engine.

Table 1: Gzero Engine Development Tests

	F0	F1A	F1B
Date	Mar 2011	Jun-Aug 2012	Aug-Sep 2012
Build specification	Baseline 24G	Upgraded Gzero with three independently actuated variable vanes	Upgraded Gzero with mechanically linked variable vanes actuation
Key objectives	Establish baseline reference for upgrade (performance, compressor surge margin, engine operability).	• VSV schedule optimization and robustness • IP Compressor blade vibration survey • IP Compressor Tip Clearance survey • Verification of various whole engine simulation models	• VSV mechanism characterization • Performance verification vs F1A • IPC and HPC surge line mapping • Load acceptance and rejection • Fuel Transfer capability verification • IP Compressor Blade Vibration Survey with fast transients • Verification of various simulation models

The initial test, designated as F0, was run with the engine in its original 24G configuration, in order to establish its exact performance for a direct and accurate measurement of the power up-rate achieved with Gzero relative to the 24G baseline.

The Gzero modification was then applied to the compressor end, and the upgraded engine taken back to test for the F1 functional test, which embodied a Development-only configuration of the variable vanes actuation system (Figure 13) allowing independent control of each of the variable vanes. This solution was introduced to enable the optimization of relative angular positions of the individual variable vanes across the operating range, to deliver the optimal engine performance and stability.

The completion of an entire new compressor mapping and optimization directly in the engine test, as opposed to the traditional approach of a separate initial test of the compressor sub-system alone in a special test rig, represented a novel approach never before attempted within Rolls-Royce at this scale.

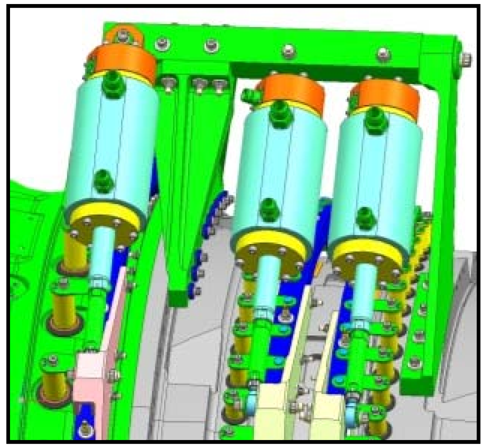

Figure 12: Variable Guide Vane actuation system for the F1A test

While delivering significant benefits in terms of reduction of the development lead time, this approach presented risks associated with the operation of a new compressor in the engine without prior experimental verification of its characteristics. Such risks were mitigated through the use of extensive instrumentation in the new IP compressor, including novel techniques to monitor in real time the static and dynamic pressures across each compression stage and detect the onset of any stall or flutter condition. In association with this, optical instrumentation [6] based on the use of laser technology (Blade Tip Timing, or BTT) was applied to the first three rows of compressor blades, capable of determining the blades vibration modes and detect the initiation of any significant vibration response to phenomena which are non-integral to the compressor sub-system like inlet distortion or rotating stall, and difficult to accurately analyse with the pre-test simulations.

Figure 13: RB211-Gzero engine at the Rolls-Royce test facility in Montréal

With the real time monitoring of this instrumentation, a step-by-step approach was then taken in the initial compressor mapping tests to progressively clear increasing power levels while keeping the hardware integrity risks under control.

The approach proved very successful, allowing the complete mapping and optimization of the new IP compressor while verifying the remainder of the engine systems at the upgrade conditions. In effect, the test was conducted with the dual purpose of a whole engine test and a compressor sub-system test, using the engine as a system to generate the entire range of operating conditions that the compressor will experience in service. This included the utilization of the engine Bleed-Off Valves (BOV) and of multiple nozzles fitted at the gas generator exit with different effective areas to move the IP compressor working line following the constant speed lines, and thus develop a representation of the compressor characteristics maps.

Using this approach, surge-free operation was verified across the entire operating range and for conditions simulating the worst stack-up of the possible causes of surge margin deterioration in service (compressor fouling, inlet distortion, different fuels, and the normal component wear between overhauls).

The variable vane schedule developed and optimized with the F1A engine test was then released to the design teams for the finalization and manufacturing of the crankshaft which mechanically links the three variable stages in the production configuration (refer to Figure 10 in the previous section). In order to accelerate the turnaround time, the component had already been partly manufactured ahead of time, so that the finished pair of crank shafts could be installed to the engine within a few weeks of defining the optimal geometry.

Engine testing then resumed with the functional test designated as F1B, which covered the final verification of compressor and engine performance and stability with the configuration that will be used in service. As well as the back-to-back verification against the F1A results, the F1B test focused on the verification of engine response to rapid transient, and particularly load acceptance and rejection manoeuvres to ensure that the load following capability provided to Operators by the current RB211 is maintained.

In parallel to the IP Compressor mapping, the F1A and F1B tests included several other whole engine and component experiments. Overall, over 1000 instrumentation parameters were applied to the engine and analysed to complete the following tests:

- Whole engine steady-state and transient performance verification;
- IP Compressor blade vibration survey, to verify the pre-test analysis described in section 2.2 above;
- IP Compressor blade tip clearance survey, using capacitance probes to verify the running clearances between the rotor blades tips and the casing;
- Whole engine vibration survey, to verify the absence of new resonance modes or other detrimental effects to the whole engine rotor dynamics;
- Whole engine temperature survey, to verify the boundary conditions used in the component level thermo-mechanical analysis.

All results aligned well to the pre-test expectations and confirmed, as shown in Table 2 below, that the key improvements targeted for the RB211-Gzero upgrade are achieved without negative impacts to the proven attributes of the RB211 that have built its reputation in the marketplace.

Table 2: Key attributes verified with the Gzero engine test

Attribute	Target	Result	Data
Power growth	**+ 10% or more**	✓	**Slightly better than expected. Initial 10% guarantee with future opportunity.**
Surge margin	**To clear operational worst case**	✓	**IPC stack-up cleared by extensive testing. HPC surge margin maintained.**
Efficiency	**No less than 24G**	✓	**Higher than 24G.**
Gas Generator Exit Temperature (TGT)	**No higher than 24G**	✓	**Lower than 24G.**
Operability	**No worse than 24G**	✓	**Fuel transfers OK, no auto-ignition. Load step capability maintained.**

Following the engine test, the test vehicle was stripped and inspected at detail. The integrity of all new components was verified through non-destructive testing, and the inspection of the overall condition of the engine hardware did not reveal any anomaly or sign of accelerated wear. Overall, the engine completed 210 hours and 168 start-stop cycles following the embodiment of the Gzero modification.

On the basis of the test results and strip inspection evidence, the Gzero engine upgrade was released for sales. The engine used as the development test vehicle, now rebuilt to a full production standard, will be used as a Demonstrator Engine throughout the Entry Into Service phase.

5 Conclusions

The RB211-Gzero upgrade, developed to offer up to 10% power increase to operators of existing units through the embodiment of an aftermarket modification of the IP compressors, has now completed its product verification phase.

Engine testing has verified that the key design objectives, and particularly the power output increase, have been accomplished while confirming that the other operational attributes of the engine are maintained.

The use of advanced simulation tools and instrumentation techniques, combined with a novel approach utilizing the engine as a system to reproduce during testing the compressor operating range experienced in service without the need for a dedicated rig test, have enabled a significant reduction in the development lead time and cost for this engine upgrade.

6 Nomenclature

AIC	Air Inlet Casing
BOV	Bleed-Off Valve
BTT	Blade Tip Timing
CFD	Computational Fluid Dynamics
ELE	Elliptical Leading Edge
IPC	Intermediate Pressure Compressor
HP	High Pressure
RVTD	Rotary Variable Differential Transformer
VIGV	Variable Inlet Guide Vanes
VSV	Variable Stator Vanes

7 References

[1] Blackburn J, Frendt G, Gagne M, Genest JD, Kohler T and Nolan B, “Performance Enhancements of the Industrial Avon Gas Turbine”, *International Gas Turbine Institute (IGTI) Conference*, Montreal, 2007, paper number ASME GT2007-28315

[2] Vahdati, M. and Imregun, M., “Non-linear aeroelasticity analyses using unstructured dynamic meshes”, *Proc. Instn. Mech. Engrs., Part C, Journal of Mechanical Engineering Science*, 1996, 210 (C6), 549-564.

[3] Sayma, A. I., Vahdati, M., Sbardella, L. and Imregun, M., “Modelling of Three-Dimensional Viscous Compressible Turbomachinery Flows Using Unstructured Hybrid Grids”, AIAA Journal, Vol.38, No.6, June 2000, 945-954.

[4] Sayma, A.I., Vahdati, M. and Imregun, M., “Multi-bladerow fan forced response predictions using an integrated three-dimensional time-domain aeroelasticity model”, *Proc. Instn. Mech., Engrs.*, Vol.214, Part C, IMechE 2000, 1467-1483.

[5] Vahdati, M., Sayma, A.I., Lee, S.J. and Imregun, M., “Multi-bladerow Forced Response Predictions for a Rig with Articulated Inlet Guide Vanes”, *Proceedings of the National 4th High Cycle Fatigue Conference*, Monterey, USA, 1999.

[6] D Knappet, J Garcia, “Blade tip timing and strain gauge correlation on compressor blades”, *Proceedings of the Institution of Mechanical Engineers*, Part G: Journal of Aerospace Engineering April 1, 2008 vol. 222 no. 4 497-506