MECHANICAL DESIGN AND DEVELOPMENT OF THE RB211 DRY LOW EMISSIONS ENGINE

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ABSTRACT

To meet current and proposed worldwide emissions regulations without recourse to steam or water injection, the Industrial RB211 is being upgraded with a premixed lean burn series staged combustion system. To incorporate this system a reverse flow cannnular concept was adopted. This design retains the inherent proven modular construction and is suitable for retrofit.

This paper discusses the mechanical design analysis undertaken to ensure integration of the chosen solution into the RB211. Theoretical studies, combustion laboratory tests, aerodynamic scale and full size laboratory tests, together with extensive computer modelling were used to ensure the timely achievement of this design study.

To verify the design analyses a detailed full power test programme is in place, which is to be followed by field trials with a pre-production engine during 1993.

THE GOALS

The oxides of nitrogen (NOx) and carbon monoxide (CO) emission objectives for the design, when operating on gas fuel, were set to be not greater than 25 volume parts per million (vppm) when corrected to 15% oxygen. In order to retain the existing flexibility of operation, these levels were to be achieved over a wide load and ambient temperature range. An overhaul life of 50,000 hours was the design target for the base load operation with a hot section inspection/refurbishment at 25,000 hours. Reliability, availability, performance and cost targets were also defined.

INTRODUCTION

In line with the increasingly stringent emissions regulations the present emissions output of the Industrial RB211 is being addressed. Although the RB211 is available with both water and steam injection to meet these regulations, such methods are not ideal and certainly not practical solutions for many applications. Therefore, to meet current and future emissions regulations for both existing operators and new markets, a Dry Low Emissions (DLE) engineering study has been undertaken. This study, including successful combustion rig tests, has enabled a combustion system design to be completed. The integration into the present engine design of the new features necessary to achieve the emissions objectives are discussed. Also, the design validation programme, in place to ensure that the revised engine design intent is met, is reviewed.

FIGURE 1 — PROGRAMME TIMESCALES

A significant design requirement was for the new engine to be suitable for retrofit into existing installations. The resulting constraints were for the engine overall length to remain unchanged and a limited increase in the carcass diameter. These ensured that the
existing rotating parts were retained, hence benefiting from existing experience. The target date for the introduction of a fully validated production engine into service was during the second half of 1994. This initiated design and laboratory test activity during 1990, resulting in development engines being built and tested during 1992. Figure 1 shows the outline programme. A pre-production engine, operating in a typical service installation, is planned for 1993.

THE DESIGN APPROACH
To minimise the production of NOx and CO demands close control of the combustion temperature to around 1800°K at all times. This requirement has led to almost universal acceptance of premix lean burn combustion systems. However, reducing load, hence fuel flow, with such systems results in flame out conditions being rapidly approached. Additional fuel management or air control is therefore clearly necessary to overcome this problem.

Air control was not chosen because of the inherent reliability risk of moving parts within the compressor delivery zone. Although there is an additional control complexity with fuel staging, much of the complexity is balanced with the use of modern electronic management systems with redundancy in the numbers count of electronic components and sensors.

To ensure wide combustion stability margins, a series fuel staged system was adopted and to achieve the required combustion parameters, the combustion chamber volume is approximately double that of the current design. This significant change was accommodated by conversion from the existing RB211's annular combustion chamber to 9 radially positioned reverse flow cannular combustors. Such a change offered the unique opportunity to achieve the combustion requirements by applying conservative industrial design principles, together with the possibility of improved in situ accessibility.

The integration of this industrial design with the latest aero engine technology yielded a robust engine, thus minimising the development effort necessary before entering service. Figure 2 presents a comparison of the current industrial RB211 and DLE engine and Figure 3 shows a section through both engines.

LABORATORY TESTING
To support the design activity a series of laboratory tests were undertaken. Confirmation that the technology adopted could achieve the emission targets was demonstrated utilising an in-line combustion rig with a concentric arrangement of reverse air flows. At representative base load power combustion inlet conditions a NOx level of 17 vppm with zero CO was achieved.

The air flow stability and air distribution into each of the 9 combustion zones was investigated using a scale model of the new arrangement. This model was used for both water analogy, to assess the airflow quality, and airflow measurement to quantify the losses. By biasing the airflow into the in-line combustion rig the sensitivity of combustion process to the air flow distribution and stability was determined. An in-depth review of testing described above is presented in Reference 1.

In order to reduce the prototype engine trials a full scale engine parts rig covering a single combustor sector is now available. This will be used to fully evaluate the performance of the combustor design arrangement.

MECHANICAL DESIGN
Baseline
The existing engine is constructed from five modules, all of which are fully interchangeable with standard replacements. These modules are annotated as follows:
01 — Air intake casing module.
02 — Intermediate pressure compressor module.
To preserve the successful design concept of the RB211, whilst introducing the revised combustion system, the design changes were restricted to the high pressure system module (04 module). As a result, a great many components of the current engine are unchanged, including all of the rotatives. In addition, because of the modular concept, the retrofit of current machines with the DLE combustion system is a simple exercise. The effect on the interface modules is minimal, with no changes to the intermediate casing and only minor changes to the intermediate pressure turbine module.

There are, of course, a number of changes associated with dressing items such as pipes and cabling but these are of a minor nature.

External Structure

The proportions of the new main load carrying combustion chamber outer casings evolved from the need to accommodate nine reverse flow combustors with a total volume of approximately twice the current annular system. Figure 4 presents a section through the new DLE high pressure system module (04). The choice of nine combustors satisfied the basic mechanical requirements of avoiding known vibrational modes of the turbine rotor assemblies as well as compatibility with the number of high pressure turbine nozzle guide vanes, which remains unchanged from the current design at 36-off.

The target of in situ assembly and removal of combustors and discharge nozzles impacted on the proportions of the main outer casing. The nine circular holes in the casing were required to be of sufficient diameter to extract the discharge nozzles. The ability for in situ removal of these components provides the DLE engine with enhanced maintenance features.

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The axial build procedure of the current design was preserved with no horizontal split lines introduced on any of the new casing components. Bleed valves and asymmetric off-takes were removed from the internal structure and transferred to the forward outer casing. This repositioning eliminated a source of high pressure compressor casing distortion and enabled the compressor blade tip clearances to be more closely controlled, opening up the possibility of enhanced component performance.

The existing engine combustion chamber outer casing material is Inconel (a 12% chromium steel, wrought, weldable material) which has been retained for the new outer casings.

Function of External Structure

The prime function of the external structure is to carry the various applied loads. The design criteria is therefore to achieve acceptable distortions and low stress levels yielding long lives. The key loading cases are internal pressure, bending, thermal, axial and torsional. Boundary conditions for these applied loads were obtained from the existing engine performance model, since the overall engine performance with the dry low emissions combustor is unchanged. Structural compatibility with the adjacent intermediate casing module (03) and intermediate pressure turbine module (05) under loaded conditions was resolved by the application of finite element analysis. The internal pressure and axial loading cases were investigated using 3 dimensional 20 noded hexagonal brick and 15 noded wedge element section models as illustrated in Figure 5. The proportions of the final design were established from the analysis of the calculated stress levels and deformations.
The characteristics of the final design were shown to comfortably achieve the design targets when subjected to the most severe operating conditions. For example, Figure 6 shows the even stress profile achieved at the point of mounting the HP compressor casing which was necessary to ensure no circumferential distortion.

Internal Structure

The modified components of the internal structure of the dry low emissions high pressure module (04), although radically different in appearance duplicate the functions of the existing engine structure. The new components identified in Figure 4, comprise of two rigid cones connected by nine circular cooling air transfer tubes, together with flexible diaphragms, a modified compressor outlet vane ring and split diffuser assembly. Also the HP turbine nozzle guide vane annulus has been modified to match the revised discharge nozzle entry profile.

All the detailed cooling air features forward of the front cone and aft of the rear cone remain unchanged. The 3rd stage high pressure compressor (HP3) cooling air bleed required for the turbine cooling and the rear bearing housing is now transferred through the 9 air tubes.

On the current engine the high pressure compressor delivery air and the HP3 cooling air are separated thereby reducing the pressure and temperature experienced by the external casings. This arrangement has been adopted on the dry low emissions engine with the two internal rigid cones separating these bleeds. This reduction in the operating pressure by about half on the front and rear external casings is also experienced by the flexible diaphragms.

The new components of the internal structure are manufactured from C263 material, a high strength, high ductility wrought weldable material.

Internal Structure Function

The internal structure serves to position the HP turbine nozzle guide vanes in relation to the HP compressor and HP turbine rotor assemblies as well as providing an internal cooling air path. The fundamental features of the nozzle guide vane mounting and location of the current design have all been retained. With this arrangement the rearwards axial loads are reacted at the outer chordal seal and the inner pin location positions. A single outer location feature per nozzle guide vane, allows freedom of radial thermal expansion. This in turn transfers the outer component of torque to the outer casings via 15 sliding cross key location features which allow for both axial and radial movements as highlighted in Figure 4.

The cross key locations control concentricity in relation to the outer engine casings and hence the relationship between the HP turbine rotor and stator assemblies. They are the main location feature for the rear end of the HP compressor.

Sufficient rigidity has been designed into the main pressure load carrying cones in order to minimise circumferential distortions which could be transferred to the HP compressor casings at the gas path positions. This also ensured the flexible diaphragms were not subjected to varied circumferential loadings. The thick sections of the cones required to provide the necessary rigidity give increased thermal lag, which ensures greater compatibility with the outer casings and reduces the radial thermal loads on the flexible diaphragms.

The design of the flexible diaphragms is a compromise between the rigidity to withstand pressure and net out-of-balance axial loads and flexibility to withstand the differential thermal expansions between the inner and outer structures in both radial and axial directions. Matching the thermal responses of the new dry low emissions high pressure system module (04) internal structure and the existing structure was considered an important element to preserve the present successful design concept. To demonstrate this had been achieved, a comprehensive finite element analysis was undertaken. Various types of finite element models were used, such as 20 noded 3 dimensional sectors for the air transfer tube assembly features.

To undertake the sensitivity analysis of the structure due to varying the cone thicknesses 8 noded plate element models were used. The loading conditions applied to the models covered pressure loads, thermal gradients and axial loads.

Figure 7 presents a typical axisymmetric model of the idealised internal features, and, as an example, the predicted deflection of the rear flexible diaphragm using this model is shown in Figure 8. Such models were used to optimise the shape of such a component. In this example the benefits of introducing a heatshield could be readily evaluated. The same axisymmetric model was used to investigate the transient thermal response of the HP compressor casing and the tolerance of the structure to out-of-balance pressure loads.

In every respect the final design of the new high pressure system module for the dry low emissions engine was found to be satisfactory, achieving all the design objectives with regards to stress.
levels, lives and distortions. Of course close attention was paid to the quality control respect of the finite element analysis techniques employed. Cross checks were made to confirm results using different concentrations of meshes and elements. Classic analysis techniques were also applied where appropriate to validate the correct application of restraints, material properties and boundary conditions.

VALIDATION PROGRAMME

To ensure that the design intent is met, a significant prototype and pre-production engine design validation programme is underway. Three prototype low emission engines are being utilised for testing which will cover a range of conditions up to full power. In support of the engine testing combustion laboratory tests of a single combustor sector will be carried out to fully evaluate the combustor performance parameters. The prototype engines will be used to measure the operation of each component for comparison against the design predictions and the interactions of these parts with the rest of the engine using over 1,000 pieces of instrumentation.

The instrumentation comprises strain gauges, thermocouples, total and static pressure probes as well as specialised pieces to measure such parameters as bearing loads. The output from these devices is connected into mini-computers for instant steady state and transient analysis. Data storage is provided by magnetic tape and mainframe computers for post test detailed analysis.

The emissions related performance of these prototype engines is being monitored by nine sensors which can be related to the nine individual combustors to provide a measure of their individual performance.

To support the validation programme, over 500 test hours on prototype and pre-production engines are planned on two factory facilities. Both test facilities use pipeline gas supplied direct from the nearby British Gas main pipeline. The programme will incorporate a controlled fault seeding exercise to give positive indicators for in-service condition monitoring. Confirmation of the reliability, availability and maintenance predictions for this new combustion arrangement will also be an important aspect of the validation programme.

All engine test running is being controlled by an engine management system which has been developed in conjunction with Cooper Entronics and is virtually identical to the proposed production engine system. This integrated approach has ensured a control system that provides the flexibility and accuracy necessary to meet and exceed the new requirements of the low emissions combustion system. The engine management system design strategy addressed the requirements of reliability and availability and provided a natural progression from current digital control technology.

Prototype engine testing is presently underway. The development programme will support the entry into service of a pre-production engine during 1993 for field tests to monitor emissions and mechanical integrity over an extended period in a typical mechanical driver environment.

CONCLUSION

In response of the challenge to significantly reduce the present NOx emissions of the industrial RB211, its combustion system has been radically modified. The system now incorporates a series staged premix lean burn arrangement which has demonstrated the required levels of emissions under laboratory tests.

Due to the modular construction of the engine the redesign has been accomplished with virtually no impact on the other modules. The final combustion system design arrangement, which integrates
conservative industrial design principles with the latest aero engine technology, was supported by an extensive finite element analysis.

To demonstrate that the design intent has been met a prototype and pre-production engine validation programme is underway. The operation of each component will be measured against the design predictions using extensive instrumentation. The performance of the combustion system will also be monitored to demonstrate compliance with the design goals over the required engine operating range.

REFERENCES