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THE DESIGN OF THE ROLLS-ROYCE TRENT 500 AEROENGINE

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Abstract

The Rolls-Royce Trent 500 gas turbine aeroengine entered service in August 2002 powering the Airbus Industrie A340-600 aircraft. This is the latest development in a continuing business and engineering strategy that has generated a major share of the market for engines of this type. The Trent 500 provides significant reductions in fuel consumption, noise and gaseous emissions compared to previous engines in this class. Several improved design procedures made important contributions to the successful design and verification of the engine.

Keywords: Trent 500, Design tools

1 Introduction

The demands from the market for large civil engines are extremely competitive. The engines must deliver the operational requirements of thrust, fuel consumption and weight, be delivered on time and reduce the impact on the environment. All these requirements, many of which are conflicting, must be achieved at the lowest non-recurring unit cost.

The product goes through a gated process of conceptual design, detail design and verification in tight project time scales that demand strict adherence to quality procedures but allow the designers to exercise creativity.

These projects inevitably employ several thousand engineers, to bring the product to service, who have a wide range of skills, knowledge and experience. Work is carried out on many sites and countries needing communications across and between a large number of organisations.

New engine projects provide an opportunity to incorporate lessons learnt from previous projects and introduce new technology and methods. The Trent 500 is a good example of where this has been done and has resulted in significant benefits.

Academia played a significant role in the successful design and verification programme.

This paper describes the requirements, the design philosophy and some of the key tools that ensured that the Trent 500 was completed on time, met the requirements and successfully entered service.

2 Rolls-Royce Product Strategy

A successful aero-engine company requires a large enough market share, Rolls-Royce is currently over 30%, to support a full capability across the entire range of aero-engine supply. This means being able to offer a competitive product on each major aircraft application.

An aircraft manufacturer requires an engine that is tailored to their particular needs for each of the aircraft it offers to the market. However to design, develop and support in service unique engines would be time consuming and extremely expensive. This has been addressed in Rolls-Royce by having separate small, medium and large engine strategies.

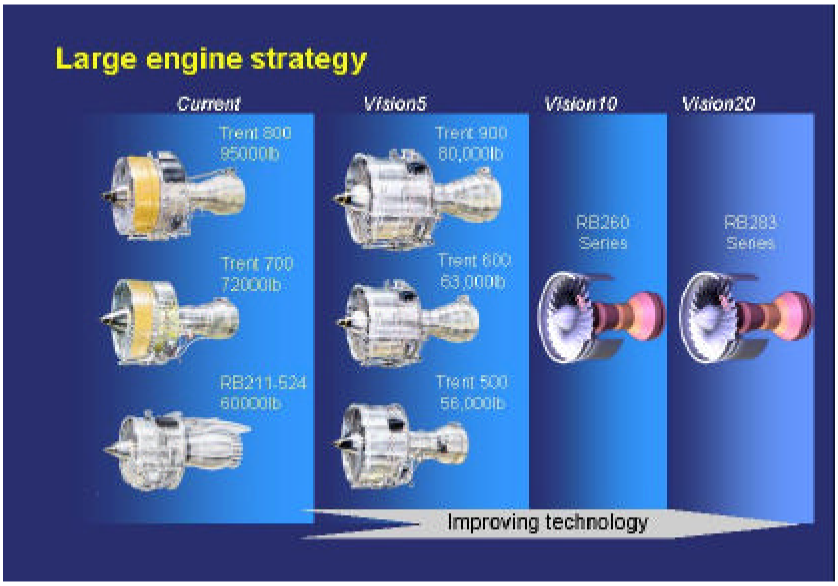

Figure 1. Rolls-Royce Large Engine Strategy

The basis of these strategies is that for each market sector the appropriate engine architecture is chosen and the capability acquisition programmes to meet the future objectives are enacted. These strategies are designated Vision 5, 10 and 20, the anticipated horizons for the incorporation of new capabilities, see figure 1. With this acquisition it is then possible to upgrade the product portfolio to incorporate technologies, as they become proven and available. Capability includes technology, facilities, methods and, perhaps most importantly, the right people. This results in an engine product family, wherein capability is developed once but used many times across the product portfolio.

3 The Airbus Industrie A340-500/600

Airbus Industrie identified a market need, for the first quarter of the 21st century, for a family of aircraft that was capable of flying 7,300 nautical miles with 378 people or 8,000 miles with 305 passengers.

This was accomplished by extending their already successful A340-200/300 family of aircraft, which had been in service for some years. The major changes were to increase the length of the fuselage and the size of the wing but retain the four-engine configuration.

Consequently the new aircraft had an increased maximum take-off weight (MTOW) requiring engines of higher thrust than those of the A340-200/300. Operational experiences meant that Airbus required an engine with 60% more thrust and better fuel efficiency.

The A340-500/600 was scheduled to enter service in 2002 if it was to meet the airlines' needs.

The environmental objectives for this aircraft were also very demanding with aggressive targets for noise and emissions anticipating future legislation and the requirements of specific airports' needs.

At the beginning of 1997 Airbus were well advanced in their studies and needed to select an engine. The Trent family could provide such an engine, which was in the preliminary design phase and was designated the Trent 500. This suited the Airbus needs as it could provide a high technology, efficient engine that would be built on proven service experience and mature technology. Advances in design verification techniques and the fact that the engine had a service proven heritage provided them with an assurance that their requirements would be met at the time of delivery.

4 Trent 500 Description

The Engine Attributes Requirements

Engine requirements come from a number of sources, the airlines, the airframer, the certifying authorities and internal Rolls-Royce business objectives. These must be expressed as a set of attributes such as performance, unit cost, and weight. There are a number of issues associated with these attributes.

Performance

The prime function of the engine was to deliver the increased levels of thrusts, in this case 56,000 lb. for entry into service although it would be certified at 60,000 lb. to give growth capability.

The amount of fuel consumed by the engine needed to be 8% better than the current engines. An engine with low fuel consumption gives a number of benefits, the obvious one being the reduced fuel cost, which is a significant part of the overall aircraft operating cost. An environmental benefit also results as there is less carbon dioxide and nitrous oxide emitted. In addition the aircraft MTOW needed to achieve the maximum range, with a given payload of passengers and cargo, can be reduced, lowering unit and operating cost. Alternatively the aircraft can carry more passengers and cargo, hence increasing revenue, for a lower take-off weight.

Deterioration

The fuel consumption will increase during the engine's life as parts wear or as the engine accumulates dirt from the atmosphere. In extreme cases the deterioration can limit the passengers or cargo that can be carried on a flight. Hence there was a target of <2% increase in fuel consumption in 3000 flights due to engine deterioration. In addition an engine is certified to operate within specified temperatures and on reaching this limit has to be removed for overhaul. It is important therefore that there is sufficient margin in the engine's design to cater for temperature deterioration as well as worsening fuel consumption.

Unit Cost

There is constant pressure from the market place to provide aerospace products at an affordable price. This in turn requires reductions in manufacturing cost. In order to design for these reductions it is essential to have accurate cost models so that design and manufacturing effort can be directed to the appropriate areas.

Weight

The weight of the engine has two impacts, the contribution to the MTOW in its own right and the effect it has on the wing and the attachment structure. As with unit cost, a low value is important as is the ability to predict it accurately.

Maintenance Cost

As fuel efficiency has been improved over the past 30 years, then maintenance cost has become more significant to airlines as an element of the total operating cost.

The main factors governing this cost are time on wing and the cost of the overhaul once the engine is in the maintenance shop. The engine reliability, spares cost and component part lives are therefore a key factor in reducing maintenance cost.

Environment

The aircraft was to be quieter than others in its class. A benchmark for noise is the London Heathrow Quota Count (QC) System, which takes aircraft measured data, for departure and arrival, and places them into noise bands, the noisiest being subjected to restrictions. The take-off criterion is the average of sideline and flyover noise and for arrivals the approach noise. The A340-500/600 was required to be capable of meeting the London Heathrow QC2 requirement for take-off and QC1 for approach, between 92.9-95.9 EPNdB and 89.9-92.9 EPNdB respectively. Most currently operating large aircraft are above 96 EPNdB.

Gaseous emissions were also to be the lowest in its class of engine and be capable of meeting all current and proposed legislation.

The conflicts

It can be seen that there were a number of requirements that the engine needed to achieve all of which were advances on previous engines in this class and in a number of cases conflicting. A major objective therefore was to optimise the design to achieve a balanced product that satisfied all the requirements.

Optimising the Product

Reduced fuel consumption is achieved by improving the thermal or propulsive efficiency of the engines. Higher component efficiencies, higher overall pressure ratios (OAPR) and higher turbine temperatures (TET) increase thermal efficiency. However component efficiencies throughout the industry are now approaching the physical limits and high pressure and turbine temperatures tend to lead to higher unit and operating costs.

Reducing the level of thrust generated for a given airflow, the specific thrust, will increase the propulsive efficiency of the engine. This gives a lower exhaust jet velocity hence lowering take-off noise but increasing the amount of air needed to achieve the desired thrust. A larger engine results, tending to increase weight, aerodynamic drag and unit cost.

The drive for higher thermal and propulsive efficiencies can increase temperatures and speeds within the engine. This necessitates using sophisticated and expensive materials, which are difficult to process, and which tend to increase unit and maintenance cost.

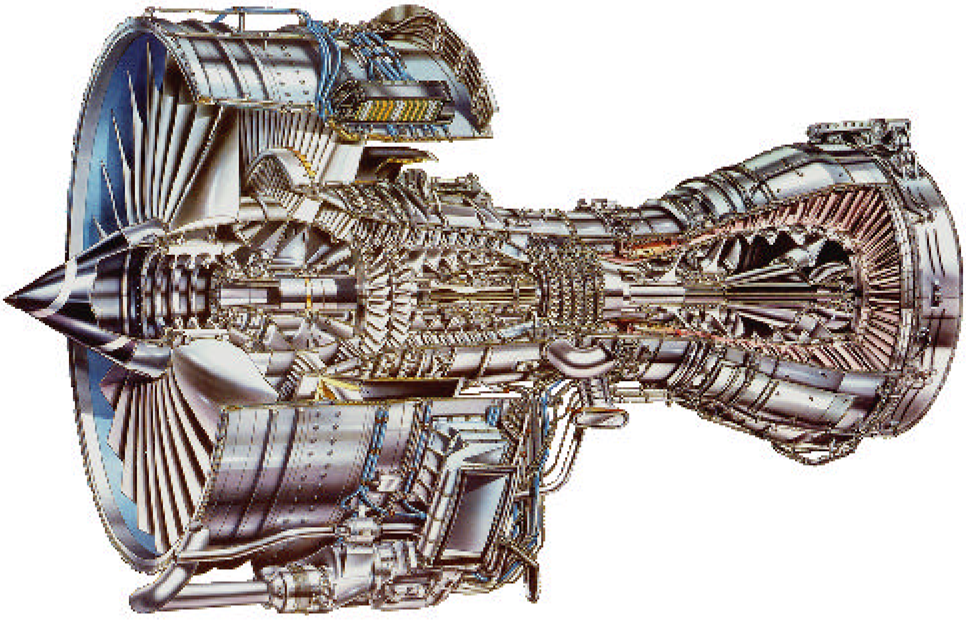

Figure 2. Trent 500

The design philosophy chosen for the engine to achieve the target fuel consumption was to improve the propulsive efficiency, which was the surest way of achieving the target, with a small contribution from increased TET, increased OAPR and component efficiency. This also helped to reduce noise generation and combined with suitable noise attenuation ensured that the engine would meet the noise targets. Improved modelling techniques and integrated working with manufacturing engineers and major suppliers were used to address the issue of cost and weight.

The engine was a three-shaft architecture, see figure 2, which is a feature of all Rolls-Royce large engines. The 97.5in diameter fan is super plastically diffusion bonded similar to the Trent 700 but with revised fan aerodynamics for lower noise and higher efficiency.

The core compressors were scaled from the Trent 800 but with additional aerodynamic technology again for improved efficiency. The combustor was a departure from previous Rolls-Royce designs incorporating a tiled construction designed to reduce the amount of necessary cooling air for the combustor walls. This enabled more air to be directed to the combustion process helping to reduce nitrous oxide emissions.

The high and intermediate pressure turbines were scaled from the Trent 800 and incorporated new cooling technology whilst the low-pressure turbine was designed specifically for the Trent 500.

In order to gain its certificate of airworthiness, the Trent 500 had to demonstrate it had met all the requirements and was ready for service, the engine had to undergo a stringent programme of ground based tests. This was followed by a series of flight tests on the A340-600 aircraft, see figure 3. All tests were successfully completed on time.

Figure 3. Trent 500 on Airbus A340

Key milestones for the project

- June 1997, the Trent 500 was selected as the sole engine for the A340.
- May 1999, the first engine run, was achieved ahead of schedule.
- March 2000, the first production engine left the factory.
- December 2000, the engine was certified ahead of schedule.
- April 2001, the A340-600 first flight.
- May 2002, the aircraft achieved certification.
- August 2002, the aircraft successfully entered into service with Virgin Atlantic.

5 Some Key Design Tools

Creativity in Teams

The design process in aerospace demands strict adherence to quality procedures to ensure product integrity and traceability, this could stifle creativity. This is addressed in a number of ways, the most important being a management culture that fosters innovation and creativity. Creativity is recognised at the highest level within the company by the Chairman’s awards for innovation to individuals and teams, in addition there are awards for successful patents. There is training for individuals and teams in techniques such as the well established structured brainstorming and the newer TRIZ method, ref 1, 2 and 3.

Risk Management

A project must demonstrate that there are a clear set of attribute targets established and that there is a risk assessed programme capable of delivering those attributes. A well-known model for risk assessment is shown in figure 4.

Risk assessment can help solve the perennial design issue of whether an attribute target is realistic and achievable. If the target is conservative but achievable then the product may not be competitive, if the target is aggressive and not achieved the consequence could be the product failing to meet guarantees and incurring financial penalties. This is particularly difficult where the attribute is the summation of a number of constituent parts, or sub-systems, for example the weight of a complex system, the performance of a machine or the cost of a large project.

Risk	=	Likelihood	X	Consequences
posed by a hazard occurring		of the hazard occurring		of the hazard occurring

Figure 4. The Risk Model

The process adopted on the Trent 500 for all attributes was a system of three bids for each sub-system, an unlikely to be worse than (ULWT), a most likely (ML) and an unlikely to be better than (ULBT), with a confidence distribution between them, figure 5. The constituents can be integrated using techniques such as Monte Carlo simulation. This technique selects values at random for the constituents and computes the overall product attribute, repeating this many times and generating a statistical plot.

This approach had the benefit of quantifying the inter-relationship between constituents on the total product and providing the basis for assessing the likelihood of attribute achievement and hence the confidence of commercial guarantees.

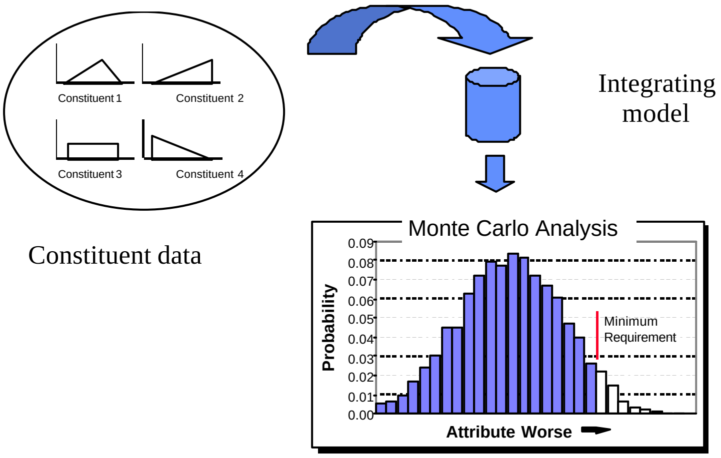

Figure 5. The Three Bid System

A second use of the risk management process, the more normal one, was conducted on the product and plan to identify major risks and mitigation action. The technique used was to identify potential hazards based on experience from previous projects and brainstorming the new features.

A rating of High (H), Medium (M), or Low (L), based on predetermined criteria, was given to the likelihood and consequence for each risk. For example the consequence of exceeding the weight target would be (L) if 0-0.01% but (H) if greater than 0.5%. Mitigation action plans were created and progressed until the risks were eliminated. The level of management visibility and effort was commensurate with the level of risk. Dta to support the risk management process came from the multitude of engine and rig tests embodied within the engine certification programme.

Technical Accounts

Once the requirements had been set the status on every attribute was tracked and reported on a monthly basis, through a series of technical accounts. This provided a history and a forward look for each attribute, recognising hazards and opportunities. As well as providing an invaluable management tool it provided good and relevant communication for the project team, suppliers and customers.

Visualisation

The financial considerations of developing a new engine are large. In order to spread this burden an industry practice is to join with risk and revenue sharing partners who buy into work packages and then share the risk and the rewards of the project. Unfortunately this involves dispersed team working where major components may be designed on different sites or in different countries with the attendant problems of time zones, culture and communication.

Visualisation played a significant part in smoothing communication and being able to do rapid design iterations. In the case of the Trent 500 visualisation took the form of an electronic representation of the engine, see figure 6, where both physical and functional interfaces were defined and agreed between partners.

The externals of the engine consist of numerous systems; oil, air, electrical and fuel. There are strict rules concerning the location of units and pipework routing to ensure integrity of the engine. It must be possible to remove parts of one system without disturbing another, so ease of maintenance and access is vital. Visualisation played a vital part in verifying the design before commitment to hardware and the training of maintenance personnel.

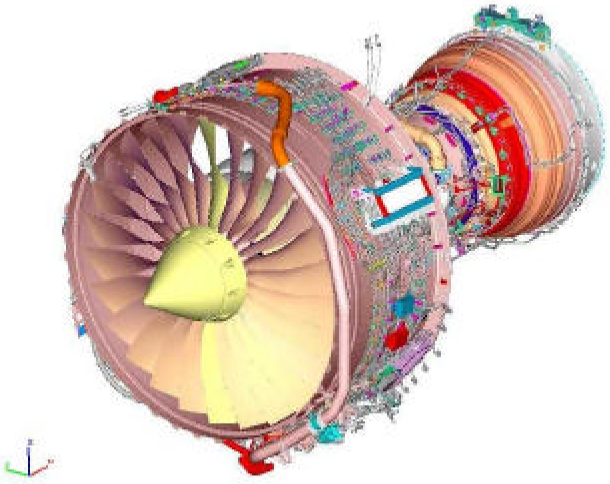

Figure 6. Trent 500 Electronic Modelling

Reliability Management

Reliability is an important attribute because of its dominant effect upon the cost of ownership. Improvements for the Trent 500 were gained by the early implementation of reliability driven design and measurement of the reliability as verification progressed. The plan had three phases, design, evaluate and monitor for reliability.

Design for Reliability

This ensures that all requirements are understood and that the designs are preferably based on the best heritage with controlled evolution. There is also an attempt to reduce parts count and complexity. The most important factor is that the performance of the design is predictable.

Evaluate for Reliability

This process attempts to evaluate and detect design weaknesses allowing corrective actions to be taken to address any necessary redesign at the earliest possible opportunity. The main tools being:

- Failure Modes, Effects and Criticality Assessment (FMECA), an assessment of how designs might fail. This is linked to a risk mitigation process to highlight where design changes are necessary or alternatively what testing might be required to underwrite the design.
- Testing is aimed at proving design intent under representative test conditions.

Monitor for Reliability

The approach taken was to implement an engine health monitoring and diagnostics system that learnt normal engine behaviour and was therefore capable of detecting disparity with normality as indication of potential failures. The Engine Health Monitoring System captured data from every engine run throughout the Trent 500 programme and flight test. It was able to detect engine anomalies that were subsequently investigated and ensured one of the most successful verification programmes ever undertaken.

6 The Role of Academia

From 1987 Rolls-Royce has engaged in a 'Centre of Excellence' approach to its academic research and a number of University Technology Centres (UTC) conduct relevant research on a long-term basis, ref 4. These centres contribute significantly to the basic design capability of the company. In particular there were specific contributions to the Trent 500 engine design, ultra-high lift LP turbine technology, CFD codes, 3D compressor design technology, compressor bleed slot geometry, secondary air system technology, spline wear modelling, heat to oil calculations, optical flow measurement and material technology - a diverse range of technical contributions.

7 Summary and Conclusions

The benefit of a robust product strategy and a related capability acquisition programme was clearly demonstrated by the Trent 500.

The use of sound design heritage and the use of modern design tools enabled:

- the Trent 500 to meet or exceed the design requirements
- the certification programme to be accomplished ahead of schedule and meet all its major milestones

The engine and airframe have demonstrated excellent reliability in the first few months of service since August 2002.

This engine is further progress in the large engine strategy and provides an excellent base from which to design the next products.

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