Development of the turbines for the Vulcain 2 turbopumps

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Abstract

The Vulcain 2 is a new version of the main engine for the European launcher Ariane 5. As one of the partners in the engine program, Volvo Aero is developing the turbines for the turbopumps. This involves a totally new, powerful two-stage turbine for the oxygen turbopump, and the existing turbine definition of the Vulcain fuel turbopump is to be qualified for a new operating envelope.

New working methodology has been successfully applied, based on our experience of Vulcain turbine development. The result is considerably shorter lead-times and reduced manufacturing costs. Testing at turbopump level has been successful, demonstrating the function of the turbine. Engine testing, which begins this summer, will provide final qualification of the turbines.

Conclusion

- **The present Vulcain fuel-turbopump turbine will be qualified for a new operating envelope with a 25% increase in power output.**
- **To reduce development lead-time and manufacturing costs, new working methodology, based on the lessons learnt from the development of the turbines for the Vulcain engine, has been successfully applied.**
- **Testing at turbopump level has been successful and has demonstrated the function of the turbine. Engine testing will start this summer and will provide final qualification of the turbines.**

Introduction

The Vulcain 2 is an upgraded first-stage engine for the European launcher Ariane 5. The main objective of its development program is to increase thrust and ISP, and decrease production cost in comparison with its predecessor.

An increase in the overall O/F mixture ratio specified for the combustion chamber requires a higher oxidizer-pump flow rate and, consequently, a higher turbine power output. When it comes to the fuel turbopump, the same definition as for the Vulcain will be kept, and both the turbine and the turbopump are to be qualified for the new envelope.

The Vulcain 2 program is being carried out within the framework of an ESA contract under the leadership of the French space agency CNES. The program began in 1995 and engine qualification will take place in 2001.

The main contractor for the Vulcain 2 engine and the hydrogen turbopump is SNECMA's SEP Division. Fiat Avio is responsible for the oxygen turbopump. The development of the turbines for the two turbopumps, and the nozzle extension, has been subcontracted to Volvo Aero Corporation.

Turbine requirements

Oxygen Turbopump

The flow rate increase of the pump requires approximately 50% higher turbine power in comparison with that of the pump for the original Vulcain engine. During the concept phase of the oxidizer turbopump, a decision was made together with FA and SEP to develop a two-stage turbine (a

single-stage turbine was used for the Vulcain) in order to increase the efficiency and ISP of the new engine version. The decision meant that an entirely new turbine design was required which, nonetheless, was to be based on the existing Vulcain turbines.
The main design input data for this new two-stage turbine were:

Inlet pressure, 72 bar
Inlet temperature, 873 K
Pressure ratio, 12
Shaft speed, 12660 rpm
Power output, 5130 kW

At the same time, all the geometrical interfaces of the original Vulcain engine were to be kept.

Fuel Turbopump

For the fuel turbopump, the definition for the original Vulcain was to be used. Since the operating envelope had to be changed in order to meet the engine's requirements in terms of hydrogen flow rate and outlet pressure, the turbopump had to be qualified for the new envelope. The following design data were changed:

Inlet pressure, from 78 to 91 bar
Inlet temperature, 873 K unchanged
Pressure ratio, from 17.4 to 15.5
Shaft speed, from 34070 to 35680 rpm
Power output, from 11410 to 14290 kW

Development Objectives

The following objectives for turbine development were defined:

- Reduction of manufacturing cost in comparison with the Vulcain.
- Reduction of development lead-time in comparison with the Vulcain.
- Minimized testing of prototype hard-ware during aero design/development
- Increased robustness of the design by minimization of sensitivity to variations in tolerances and processes

Development Strategies

In order to attain the defined objectives, the following strategies were adopted:

Manufacturing cost was to be reduced by less welding, less advanced material, fewer components and the use of a design definition more adapted to an efficient manufacturing environment.

Lead-time was reduced by having more concurrent engineering with both the customer and the suppliers. At Volvo, more efficient working methods were developed in which the design team and manufacturing engineers worked more closely together in the early stage of the project than had been done in previous projects. This afforded the release of the manufacturing definition on a step-by-step basis. Work on tooling and manufacturing drawings could then be started earlier and lead-time could be shortened.

All available experience of the suppliers in the Vulcain program was also utilized in the early conceptual phase to ensure that the lessons learnt there were fully taken into account.

Design-To-Cost methods were used in the conceptual and design phases to ensure that the cost target was reached. It is a well known fact today that the cost of any product is, to a large extent, set by the decisions made in the earliest phases.

In order to *reduce the number of performance tests* on simulated hardware using air, multistage CFD was to be used in the design phase to increase understanding of different flow phenomena and to decrease levels of uncertainty.

Turbine Configuration

Oxygen TP

The turbine is of impulse type as its pressure ratio is high, around 12. Furthermore, it was decided to use an aerodynamic concept similar to the existing two-stage Vulcain turbine (Fuel TP turbine) which had proven to work very well (in the Vulcain program). This meant that almost all expansion takes place in the first stator (nozzle), which is of Laval type. In the second stator, only limited expansion takes place. In other words, the turbine is basically of velocity compound type.

The concept chosen for the Oxygen TP turbine is illustrated in Figure 1. The turbine concept is based on two rotors with disks and separate blades. The turbine components are basically the following: inlet manifold, first nozzle section, first rotor blades, second stator, second rotor blades, outlet guide vane and diffuser.

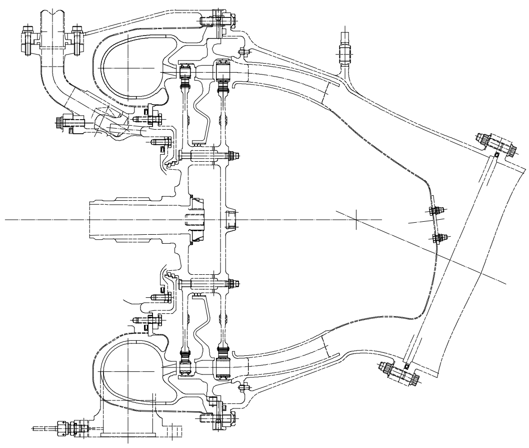

Figure 1: Oxygen TP turbine layout.

Oxygen TP turbine overall data:

Mean diameter 323 mm
37 nozzles in the first nozzle section
133 blades in the first rotor
89 nozzles in the second stator
103 blades in the second rotor
31 outlet guide vanes

It is well known that blade vibration is a critical failure mode, especially for turbines of impulse type. The most important preventive action to be taken to avoid blade resonances is to keep all blade resonances outside the operating speed envelope. However, in practice this is not entirely possible and, for the Vulcain, loose dampers were used on the rotor blades of both turbines to reduce the risk of blade vibration.

For the Vulcain 2, further analysis and a dedicated blade vibration test, using slip-ring and strain-gauged blades, were carried out to measure the blade resonances, response and effect of loose dampers. The conclusion drawn from the test was that stresses were reduced by the introduction of loose dampers, especially in some modes. It was, however, decided to keep loose dampers only as a backup solution since an acceptable margin for blade vibration could be attained by keeping the high-response resonances outside the operating speed envelope.

Material

The choice of material for the turbine was basically the same as for the Vulcain turbines, which means that IN 718 was used for all parts except for the blades where Super Waspaloy was chosen. Material testing was performed in the early phase to investigate the possibility of using IN 718 for the blades as well. The choice of Super Waspaloy for the Vulcain was based on the need for high strength at high temperatures, especially for the Fuel TP turbine which has relatively high peripheral speed.

This choice was successful in terms of functionality, but it also proved to be expensive. The requirement on LCF life was identified as the critical area for the choice of blade material for this turbine.

LCF material testing was carried out at 100 bar hydrogen and 1100 K to compare IN 718 and Super Waspaloy, which showed only a small reduction in LCF capability for IN 718 in this application.

Consequently, it was decided to use IN 718 for the blades, too, in consideration of cost reduction and the fact that the risk associated to this change was regarded to be very small. It should also be pointed out that the pressure level for the turbine is only 100 bar and that IN 718, according to several tests in hydrogen environment, does not show any significant hydrogen embrittlement.

Fuel TP

The turbine used for the Vulcain 2 is identical to the Vulcain configuration except for some minor changes regarding manufacturing cost and lead-time reductions. The configuration is shown in Figure 2.

Fuel TP turbine overall data:

Mean diameter 240 mm
23 nozzles in the first nozzle section
106 blades in the first rotor
67 vanes in the second stator
94 blades in the second rotor
13 outlet guide vanes

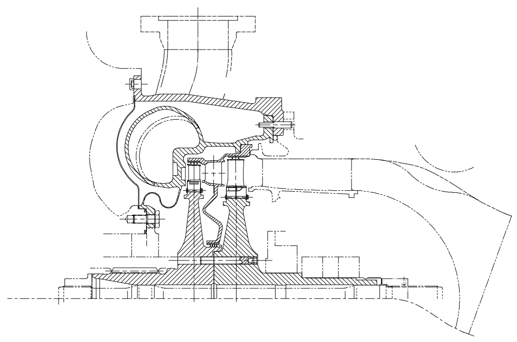

Figure 2: Fuel TP turbine layout.

Despite the operation envelopes' having been increased and extended to considerably higher pressure due to the larger power output requirement, the configuration of the Fuel TP and turbine was to be retained for Vulcain 2 operation. It is worth noting that the required power output at the extreme operating point has been increased by about 25 % for the Vulcain 2 in comparison with the Vulcain.

Minor changes have been introduced in manufacturing, some for adaptation of requirements to manufacturing outcome based on Vulcain experience, others for further reduction of manufacturing cost and lead-time.

The materials used for the turbine have not been changed from those used for the Vulcain. IN 718 is used for static parts, manifold, second stator and housing, and Super Waspaloy for rotating parts, blades and discs. The turbine is shown in Figure 3.

Figure 3: Fuel TP turbine.

Aerodynamic design and development

In the development of the aerodynamic design of the Vulcain turbines, a substantial amount of testing in air was done using simulated hardware. At that time, there were no sufficiently powerful Computational Fluid Dynamics (CFD) tools available for use in the design process. That brought about a long lead-time during the predevelopment phase and the process was also expensive.

It was therefore decided already at the beginning of the design of the new oxygen turbine that CFD tools should be used more extensively. From the early concept studies it was clear that the aerodynamic concept was going to be similar to that of the Vulcain's Fuel TP turbine.

At an early stage, it was determined that the main challenge would be to make the second stage work properly. Since this type of turbine is very sensitive when it comes to matching the two stages, it was clear that some testing activities in air were going to be required to prove the function of the turbine before tooling was released for the real development hardware, see Figure 4.

During the design and testing of the simulated hardware it was found that the CFD tool was very powerful, particularly for matching the two stages together. This approach successfully reduced the number of tests to a minimum and the CFD tool did not only prove to have a very good correlation with tests, it also provided valuable insight into the details of flow phenomena which are not possible to measure.

Figure 4: Performance demonstrator, LOX TP turbine of the Vulcain 2

Manufacture of Development Hardware

Major objectives for the development of the new turbine were to reduce both manufacturing cost and the extent of support activities such as treatment of non-conformances, etc. To accomplish this, it was necessary to reduce the number of operations in manufacturing and choose more robust concepts in terms of manufacturing to ensure fewer non-conformances.

These objectives required close cooperation between design and manufacturing engineers from the very first day of the project. The following text covers the manufacturing processes in brief, focusing on the introduction of changes for the Vulcain 2 versions.

Stator 1 is a forging that is turned and ground. The nozzles are machined by EDM (Electro Discharge Machining), which gives very precise results and is regarded to be very suitable for the quite complex and small nozzles. The inlet manifold is produced as a formed sheet metal part which is then welded to stator 1. Considerable development work has been carried out with the purpose of better optimizing the manifold part.

First of all, emphasis was placed on reducing the number of welds from four to only one in order to increase quality, lower cost and minimize inspection procedures. Second, the shape of the manifold's cross section was changed from circular to elliptical to allow for a better fit to stator 1 for the welding operation, see Figure 5.

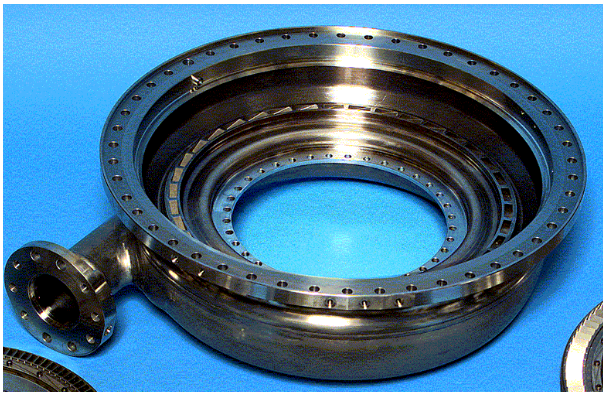

Figure 5: Inlet manifold and nozzle section

Stator 2 is a precision casting and, for the Vulcain 2 version, an integrated diaphragm has been introduced, see Figure 6. For the original Vulcain, a sheet metal diaphragm was welded to the casting, but the advantage of using a single casting is that welding is not required and both lead-time and the cost are reduced.

Figure 6: Stator 2 with integrated diaphragm

Manufacture of the rotor blades begins with bar stock. An ECM (Electro Chemical Milling) process is used to create the airfoil. The firtree, inner and outer platforms are ground to final dimensions. Through very close cooperation with the blade manufacturer and the design team, the lessons learnt from the Vulcain were taken into account and a much more optimized geometry, in terms of manufacturing efficiency, was created.

The typical difference in the complexity of the geometry is illustrated in Figures 7 and 8. These design efforts made for fewer operations, easier inspection, less non-conformances and, in the final analysis, reduced cost. The material for the rotor blades was changed and, as mentioned previously, the loose dampers were eliminated to reduce cost.

Figure 7: First-stage blade of the Fuel TP turbine (left) and the Vulcain 2 first-stage blade of the Oxygen TP turbine.

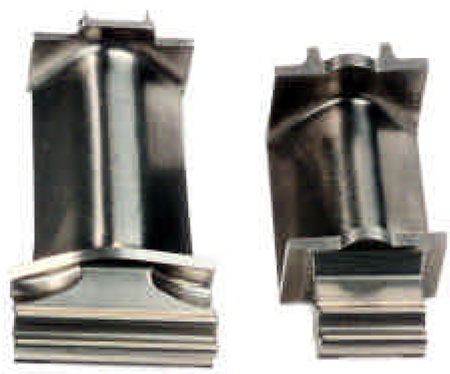

Figure 8: Second-stage blade of the Fuel TP turbine (left) and the Vulcain 2 second-stage blade of the Oxygen TP turbine.

Testing

Component Testing

A pressure burst test to check the strength of the new manifold and nozzle section was successfully performed. A dedicated test was also performed to verify rotor blade resonances. The rotor blades were fitted with strain gauges and the pressure variations applying forces to the blades were measured with pressure transducers mounted in the stage 1 and 2 blades. A slip ring device was used to transmit the necessary readings from the rotor. Different types of loose dampers were also tested. The results from the tests agreed well with the numerical predictions regarding resonance frequencies, pressure fluctuations and strain levels.

Hot Testing, oxygen TP turbine

Tests conducted on the first TP were performed in early 1999 without any problems. The objectives were to verify the performance of the turbine and the pump within the operating envelope. The performance measured in the tests correlates well to the predictions. A second developmental prototype TP is now being tested at bench level at DASA in Germany. Roughly 25 tests have now been run (see Figure 9) to investigate compliance to the pressure and temperature envelope. Further testing at bench level will be performed with the purpose of checking function, mechanically debugging the unit and verifying the cavitational behavior of the TP. The findings obtained from the first developmental prototype turbine have not shown any severe damage.

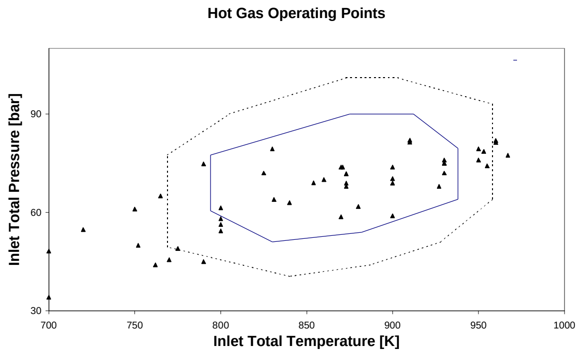

Figure 9: Tested envelope, Oxygen TP turbine

The first engine testing program will begin this summer using a test rig in Germany. A second test rig in France will also be used for later engines. The objective of this engine testing is to qualify the subsystems as well as the engine itself. The plan is to use seven engines during the development phase of the Vulcain 2.

Cold and hot testing, Fuel TP turbine

For the turbine of the hydrogen turbopump, two air driven tests have been conducted. The first was conducted to characterize the turbine for Vulcain 2 operation and verify outlet guide vane performance using dedicated instrumentation. The second was to verify turbine performance prior to testing at engine level and check that turbine manufacturing status was in line with requirements.

This turbine will be tested again in air after completion of testing at engine level to verify evolution of performance characteristics.

Only one turbopump testing campaign was planned, as the design is already sufficiently well known from extensive development testing of the Vulcain. Testing has already been performed with successful results. Envelope extremities, and beyond, were tested in regards to performance and structural integrity, and were found to be perfectly within specified requirements.

The verification and demonstration of long-duration mechanical integrity and life will be shown in future engine tests.

Acknowledgments

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Oxygen TP turbine development work was carried out under contract with Fiat Avio within the framework of Vulcain 2 engine development with SNECMA's SEP Division as the prime contractor under CNES/ESA contracts.

Fuel TP turbine development was carried out under contract with SEP, a Division of SNECMA, within the framework of Vulcain 2 engine development with SNECMA as the prime contractor under CNES/ESA contracts.