Design of a new Fighter Engine - the dream in an engine man's life

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1. INTRODUCTION

In 1984-85 a feasibility study between 5 European Nations France, Germany, Italy, Spain and United Kingdom for a common air superiority fighter was pursued which ended in 4 Nations to step into the Definition Phase in autumn 85. For us this was the beginning of an exciting experience in various roles as MTU Chief Engineers and Technical Directors of Eurojet Turbo GmbH, i.e. Chairmen of the Chief Engineers’ meeting.

Designing a brand new fighter engine at the very edge of technology is an occasion so seldom that given the opportunity to take a lead function in such a multi-billion dollar project is a dream, which only few enjoy once a life.

2. INTERNATIONAL COOPERATION

A four Nation project is a delicate task. It is however of great help if 3 of the 4 partners have known each other for a long time as in case of Eurojet where Fiat, Rolls-Royce (RR) and MTU already had a long experience in the Tornado/ RB199 engine project and could integrate the Spanish ITP Company easily. Cooperation can have 2 distinct difficulties:

- The way of cooperation
- The work share and split of responsibilities

Eurojet agreed to operate to the principle of joint working groups and unanimous decisions in groups and subgroups - a not convenient system but one which forces everybody to convince rather than to dictate and that improves the quality of a decision.

The work share and component/responsibility distribution is very important and sometimes very difficult to achieve to all partners’ satisfaction because it contains the strong element of technology transfer. In most cases, however, it is a question of the available technology background and if one looks at the work share eventually found in the EJ200 it follows this line with one big exception:

- the convergent/divergent nozzle for which no background existed was given to the newcomer SENER, later ITP, and they solved it admirably well.

As can be seen from Fig. 1, the responsibilities are split as follows along the engine:

<table>
<thead>
<tr>
<th>Company</th>
<th>Responsibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTU</td>
<td>Low pressure compressor, Heat exchanger, Fuel system,</td>
</tr>
<tr>
<td></td>
<td>Digital Control System</td>
</tr>
<tr>
<td>RR</td>
<td>Inter Duct casing, Compressor, High pressure turbine</td>
</tr>
<tr>
<td>Fiat</td>
<td>Low pressure turbine, Afterburner, Gearbox</td>
</tr>
<tr>
<td>SENER / ITP</td>
<td>Convergent - divergent nozzle, external Dressing</td>
</tr>
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To integrate four responsible companies to an overall success requires continuous preparedness to really cooperate, to accept other than own ideas, to respect and appreciate the partners efforts and to develop a feeling for the partners sensitive areas - it is likely to fail on a „shear power“ situation in an environment of the european type, namely several similarly strong partners.

3. THE TASK - REQUIREMENTS AND ASSUMPTIONS

The new engine should be:

- optimised for the fighter role
- outperform existing engines at lowest possible weight
- be designed equally well for low cost of ownership (LCC), as for high performance
- set new standards on life, maintainability and testability
- provide carefree handling everywhere in the flight envelope
- Built in 15% thrust growth potential

Fig. 2 summarises is in short the task given to the engine companies. It is written down in a document called the European Staff Requirement ESR-D in which the Joint Air Staffs described what the four Air Forces expect the new Weapon System and as part of it - the engine - should provide. Europe may look small - nevertheless the requirements of the 4 Air Forces were different enough that Eurofighter and Eurofighter had to design the aircraft for 11 different missions
8 performance guarantee points
Out of the 11 missions 2 were design driving namely the:
- Air superiority mission
- Supersonic minimum time intercept mission
which each burns about 75% of the fuel either at subsonic speed in dry engine mode or at high supersonic speed in afterburning operation. It is obvious that these 2 conditions are the sheer opposite with regards to the dominating overall engine parameter specific thrust.

Dry specific thrust directly reflects itself in the nozzle pressure ratio and nozzle entry temperature and for an optimised mixed turbo fan cycle the nozzle pressure ratio closely correlates with the fan pressure ratio.

Therefore, the dominating engine cycle design parameter is the fan pressure ratio with the bypass ratio resulting from the available technology level as shown in Fig. 3.

Reheat specific thrust depends almost exclusively on the afterburner temperature, in particular at supersonic flight conditions. Highest possible reheat temperature gives smallest engine mass flow and engine size to achieve the demanding aircraft point performance requirements. However, due to the steep increase in specific fuel consumption, when increasing the afterburner temperature towards the stoichiometric limits the reheat temperature has been carefully selected to achieve the best compromise between high specific reheat thrust and low specific fuel consumption during aircraft combat manoeuvres at full power.

Amongst a careful cycle optimisation, high engine technology is mandatory to achieve the weapon system requirements.

Highest engine technology for a given optimum specific thrust results in:
- the smallest core and hence the lightest engine
- the lowest specific fuel consumption and hence lowest fuel tank size and mass.

The task of the Eurofighter engine design was to optimise the engine specific thrust and to provide the adequate engine technology to achieve the partially conflicting aircraft performance and mission requirements with lowest possible procurement and operating costs.

4. THE OPTIMISATION PROCESS OF THE ENGINE CYCLE

4.1 General Approach
As stated above the customer required a Weapon System with lowest possible investment and operating cost, which fully achieves the mission and performance requirements. In general - not in every detail - aircraft cost does correlate well with its basic mass. Aircraft design experience shows that a multitude of requirements can usually be fulfilled at a given level of technology by increasing the size of the aircraft - resulting in higher overall cost and cost of ownership and that was the strictly forbidden way forward. „Mass“ was the undoubtedly most quoted word during the first phase of the project and remained there most of the time.

Starting from this hard condition with the basic thermodynamics, shown on Fig. 3, the engine design proceeded in closest possible co-operation with the aircraft companies over several iterative steps which are sketched in Fig. 4.

The iterative process of cycle selection
The following approach was used:
- Fixing of a nominal thrust size (90 kN)
- Variation of fan pressure ratio and turbine rotor inlet temperature within a sensible range
- Selection, decision and proof of feasibility of the engine architecture - the most challenging part
- Evaluation of outer dimensions, mass and performance data for all variants
- Scaling factors for different thrust size engines
- Final optimisation process out of the most promising variants

How engine design affects the required minimum aircraft basic mass empty is sketched on Fig. 5 as a function of fan pressure ratio (i.e. dry specific thrust) as the governing parameter and engine technology level.
4.2 Definition of Optimum Specific Thrust
The optimum specific thrust i.e. the optimum fan pressure ratio was investigated in the initial part of the definition phase.

The optimum fan pressure ratio is the intersection of two mirror image functions which result either from the Air Superiority or the Minimum Time Intercept missions.

The optimum fan pressure ratio for the air superiority mission is well below 4. The optimum fan pressure ratio for the supersonic min time intercept mission is above 4.5.

The minimum aircraft mass in case of the conflicting Eurofighter requirements resulted at a fan pressure ratio of 4.2. The absolute level of aircraft mass required can then only be influenced by the engine technology level applied. The really interesting result is that the optimum fan pressure ratio does actually change very little with technology level.

4.3 Selection of Technology Level
The technology level to be applied was the highest available or achievable in time within the four partner nations based on existing technology or demonstrator programs.

The design philosophy followed the principle:
- Simple rugged design with a minimum number of turbomachinery stages and parts
  - high component efficiencies by advanced 3-D design and high rotational speeds
  - Acceptable risk level, no new exotic materials
  - Optimised performance to fulfil all missions/guarantees
  - Lowest Cost of Ownership

Engine design technology level expresses itself essentially in 2 parameters:
- compressor exit temperature
- turbine rotor inlet temperature

The excellent supersonic performance capability of the Eurofighter resulted in the need of unrestricted engine operation at high compressor inlet temperatures. The overall compression ratio was selected such that material property limits in the HP spool were not exceeded. Fig. 6 illustrates that within the temperature limit optimum dry specific thrust at minimum dry specific fuel consumption is achieved.

The choice of turbine inlet temperature is illustrated in Fig. 7, which shows a number of limits to be considered in a plot of bypass ratio vs fan pressure ratio:
- 4.8 maximum fan pressure ratio for a growth version
- Maximum RIT level for life requirement

4.4 Selection of Nozzle Concept
The optimised cycle did not fulfil the minimum time intercept missions. So far a simple convergent nozzle was used in the design process. In order to reduce the fuel consumption during the supersonic cruise phase the effect of a convergent/divergent nozzle was studied.

The application of the supersonic nozzle was at the time a fiercely fought decision as no real data base existed in Europe. However the additional mass at the back end - and this was the main mental block under the overall mass limit - is a very good investment as it brought the break through in a stalled situation by improving the available combat time by 25% to a satisfactory level (see Fig.). In fact the reduced back end drag even slightly improved the Air superiority mission as well.

4.5 Final Cycle Choice
The best cycle design solution was an engine with the following overall parameters:
- FAN PR 4.2
- BPR 0.4
- Overall PR 25.6
- Con/di nozzle, single parameter control

5. FIXING THE ENGINE ARCHITECTURE
In parallel to the consecutive cycle selection process the engine companies went through the core process of engine design:
**Design rationale and decision on the engine architecture**

It is the most challenging step as it requires a systematic decision process on very fundamental elements in a floating environment and it requires partially very deep investigations, which take a certain time to achieve conclusive results. It is this phase where the Chief Engineer's capability to judge the directions without having everything in black and white is required most. He must be able to go forward and keep enough flexibility to react to outside changes or look for solutions which allow correction without changing the basic decisions. This is what we call the „Art of Engineering“.

The basic decisions in the EJ200 design were:

- Fan with or without variable inlet guide vanes
- Fan bearing arrangement - overhung or straddle mounted design
- Rear bearing arrangement - hot interturbine duct or turbine exit case strut/intershaf beaning
- Co- or contra rotating spools
- Convergent or convergent/divergent nozzle

**Decision Rationale**

Fig. 9 sketches schematically the basic options with respect to bearing arrangement and fan design.

**5.1 Variable IGV's or no IGV's**

This question actually remained open for some time as it was very difficult to answer. The attraction of not having a complicated, expensive and bird strike sensitive element as a variable inlet guide vane is very high with respect to life cycle cost and mass. This is specifically true against the very demanding bird strike resistance requirements imposed on to the EJ200, which are drastically above comparable engines. However elimination of the variable IGV's implies the problem of aerodynamic matching over the whole speed range and avoidance of dangerous mechanical resonances over the large range of fan speeds as the required flow range can only be covered by fan speed. The fan is the component in an engine which operates over the by far widest speed and flow range between idle and transonic flight, i.e. something between 35 % and 105 % speed. The whole range of the characteristics is covered with performance guarantee points due to the different missions and point performance requirements written down in the ESR-D document. It was not really known whether or not all these conditions can be met with a wide chord 3-stage fan of fixed geometry at 4.2 pressure ratio until additional test data became available from a very similar 3-stage rig. The solution was to strive for a design which could eventually apply variable IGV's without changing the bearing arrangement but leave the way open for a very simple design.

**5.2 Fan bearing arrangement - overhung vs straddle mounted design**

This decision was probably the most difficult to make as it implies a limitation on the maximum fan tip speed. The investigations covered:

- general shaft dynamics
- manoeuvre loads
- unbalance forces and shaft deflections in case of blade loss
- mass trade off

It was concluded that an overhung fan can be designed with the wide chord aerodynamics required for the 4.2 pressure ratio at a certain tip speed limit. This actually paved the way for the simplest possible design of a top performance supersonic fighter engine of unprecedented appearance. The EJ200 design is unique as no other engine of similar capability has such a low number of parts.

**5.3 Rear bearing arrangement**

The design logic for the interturbine strut vs turbine exit strut/intershaf bearing was a minimal shaft dynamic interference between low and high pressure system, both being directly supported against the casing via the hot strut structure.

- lower mass
- no intershaft seals
- lower life cycle costs

**5.4 Co- or Contra rotating shafts**

There are 4 arguments for the contra-rotating arrangement:

- reduced gyroscopic forces under manoeuvres
- minimal tip clearances under manoeuvre loads in conjunction with inter turbine duct arrangement
- reduced aerodynamic loading on the low pressure turbine stator vanes
- reduced aerodynamic sensitivity of the high pressure compressor against rotating stall cell distortions emanating from the fan.

**5.5 Number of HP-Compressor stages**

With the choice of a 4.2 fan pressure ratio a 5-stage HPC appeared compatible with the available data base.

Figs. 10 and 11 recall the engine architecture decision which in case of the fan bearing arrangement is driven on simplicity reasons.
6. DESIGN TO LIFE CYCLE COSTS

Minimum Life cycle cost was a basic requirement in the ESR-D. The evaluation and comparison of the various options showed that the basic elements where the EJ200 differs from comparable high performance fighter engines is the NON IGV and the turbine interduct bearing support. These 2 elements reduce life cycle cost by about 2.4 % - which may sound small. It is, however, a very big sum of money for the airforces.

Fig. 12 shows the essential summary of the life cycle cost study.

7. BASIC PROGRAMME PHILOSOPHY, DEVELOPMENT PROCESS AND RESULTS

"The engine program must be of an acceptable risk level and the design principle is to be demonstrated in a Design Verification Program". From this philosophy an overall program was defined which followed the phases shown on Fig. 13.

The engine development process followed the prescribed procedure to build 3 Design Verification Engines, which actually were designed and built parallel to the Definition Phase and DVE 01 did run only 2 weeks after signature of the Main Development Contract without fan IGV's and achieved within 2 test hours 95 % of the dry design thrust. After a deep investigation into the design principles and overall engine architecture the "Full Scale Development Engine" design started and run first in October 90. The contract asked for continuous thrust increase and flight envelope expansions over a 3 years period and Eurojet reacted to this requirement with 2 basic engine standards, the 01 and the 03 line, which started with 80 % nominal thrust followed by 100 % thrust for the 03 standard engines.

The engine up to now has undergone an extensive test program with

- 5.600 hours bench testing
- 3.100 hours in altitude test facility
- 500 hours in the aircraft

The engine has been exposed to most severe intake distortion testing with different types of distortion gauzes simulating distortion levels up to DC 60 ~ 1.0. The engine is highly responsive and has achieved all the specification handling times. During its total flight testing the engine never experienced a surge in flight. The engine does have a very good track record and the pilots like it as reliable, responsive and powerful.

Fig. 14 shows the experience gained in altitude test facilities all over the flight envelope.

8. NEW ELEMENTS

Parallel to the main program Eurojet developed advanced elements for the engine and will introduce these into the production engine standard.

The most obvious changes are the so called "All Blisk Fan" and the new advanced Digital Control Unit although there are advanced features like better material turbines for even longer life and the change of the vaporiser combustor to an airspray design in the 03 Standard.

The blisk fan became a viable solution when the linear friction welding technique developed into a stable process allowing the repair of big diameter blisks and hence make them cost effective for the combustor.

MTU started development of the linear friction welding process together with Rolls-Royce and eventually brought it to a standard that now blisk fans can be introduced into the latest 03 Standard engines. The engine does achieve its specification mass and performance and it is undoubtedly one of the "hottest" and highest performance engines anywhere in the world - it is a European Success Story.

9. CONCLUDING REMARKS

The design of a new fighter engine is a personal experience one will never forget. It is an effort full of technical excitement and interesting interaction. In a phase where there are unknowns which by no means can be answered in all and every detail it always happens that some decisions must eventually be taken by engineering judgement after intense debates with good friends and colleagues. One of the deepest experiences I enjoyed during my activities in this project was the friendship and continuous assistance of the late Rolls-Royce EJ200 Chief Engineer R. J. Lane who is no longer amongst us. The fact that we can present this paper on a successful engine program is much to his credit.

Acknowledgement

The authors wish to express their thanks for permission to publish this paper to NETMA, EUROJET and the Management of MTU.
Figure 1
EJ200 - Production Workshare

Figure 2
EJ200 - Engine Requirement (ESR-D)

Figure 3
EJ200 Effect of Fan Pressure Ratio and Turbine Inlet Temperature on Engine Performance

Figure 4
EJ200 - Definition

Figure 5
EJ200 - Selection of Fan Pressure Ratio

Figure 6
EJ200 - Cycle Selection

Figure 7
EJ200 - Cycle Selection

Figure 8
EJ200 - Effect of Convergent/Divergent Nozzle on Aircraft performance
**EJ200 Design Rationale on Engine Architecture**

<table>
<thead>
<tr>
<th>TOPIC</th>
<th>Arguments</th>
<th>Weighting</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rear bearing arrangement</td>
<td>shaft coupling</td>
<td>++</td>
<td>Keep decision open until aero results available</td>
</tr>
<tr>
<td>Inter Turbine Strut vs Intershaft bearing</td>
<td>minimum tip clearance change</td>
<td>-</td>
<td>Consider non IGV solution for mass reasons</td>
</tr>
<tr>
<td>Co-Contra-Rotation</td>
<td>Life cycle cost</td>
<td>+</td>
<td>Co/Con single parameter for mass reasons</td>
</tr>
<tr>
<td></td>
<td>Reduced gyroscopic loads</td>
<td>+</td>
<td>Con/Con single parameter for mass reasons</td>
</tr>
<tr>
<td>Con-/divergent nozzle</td>
<td>Supersonic performance</td>
<td>++</td>
<td>Con/Con single parameter for mass reasons</td>
</tr>
<tr>
<td></td>
<td>single control parameter</td>
<td>-</td>
<td>Con/Con single parameter for mass reasons</td>
</tr>
<tr>
<td></td>
<td>two control parameters</td>
<td>-</td>
<td>Con/Con single parameter for mass reasons</td>
</tr>
</tbody>
</table>

**EJ200 - Design to Life Cycle Cost**

![Graph showing life cycle cost comparison between different configurations](image14.png)

**EJ200 - Programme Phases**

- **Phase 0**: Engine definition
- **Phase 1**: Technology acquisition
- **Phase 2**: Design verification
- **Phase 3**: Full scale development
- **Phase 4**: Production

**ATF Experience with F3D Engines**

![Graph showing test results](image14.png)