EFFICIENT FLIGHT CONTROL BY USE OF EJ200 THRUST VECTORING

R. Mareca Rios*, J. Montes Barrenetxea**, X. Esquisabel Alegria*** and W. Sterr$^+$

Abstract

Thrust Vectoring can provide significant advantages at weapon system level in terms of life cycle cost reduction, agility, survivability, safety and combat effectiveness.

Extensive studies have been already conducted in the past to understand the benefits of a Thrust Vectoring Nozzle (TVN) integrated into a modern fighter aircraft. It lies in the nature of such a highly integrated engine/airframe system that benefits can not be judged either by the airframe manufacturer or the engine manufacturer on its own. Therefore emphasis is laid on engine aspects and global weapon system aspects at the same time.

The design of a 3D vectoring nozzle is a challenge which consists of a patented design featuring the so-called "Three-Ring-System", what allows all nozzle functions with a minimum number of actuators that leads to optimized mass and overall engine efficiency.

EUROJET/ITP has already successfully demonstrated full 3D Thrust Vectoring and has generic flight control system integration concepts.

This paper introduces the EJ200 engine, highlighting the specific characteristics making this engine unique in its class. The EJ200 thrust vectoring concept is discussed, including the generic benefits of TVN key elements required for optimum weapon system integration and the route to market.

Definitions and Abbreviations

3D = Thre Dimensional
ATF = Altitude Test Facility
Blisk = Integrally Bladed Disc
DECMU = Digital Engine Control and Monitoring Unit
FADEC = Full Authority Digital Engine Contro
FCS = Flight Control System
HP = High Pressure
NGV = Nozzle Guide Vane
K = Kelvin
LP = Low Pressure
SFC = Specific Fuel Consumption
SOT = Stator Outlet Temperature
TVN = Thrust Vectoring Nozzle

Introduction

It is well understood from different activities in the past that Thrust Vectoring will offer a number of valuable advantages in various fields for current and future combat aircraft. Due to its advanced design philosophy, the EJ200 engine provides an ideal basis for introduction of this future technology. For that reason, Eurojet already has taken the decision to bring forward this interesting technology coming closer to an operational application. To gain the optimum value for the overall weapon system, thrust vectoring can not be treated in an isolated approach from the engine manufacturer's perspective only. This is due to the high level of integration affecting A/C systems, A/C control, aerodynamics and propulsion system efficiency at the same time. Therefore Eurojet has conducted comprehensive thrust vectoring feasibility studies in collaboration with airframe manufacturers. In parallel, inhouse activities were carried-out leading to design and testing of a 3-D (pitch and yaw) thrust vectoring nozzle developed for the EJ200.

The validation and certification of a thrust vectoring nozzle system is a challenging task. A stepped approach

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* EJ200 Chief Engineer, ITP **EJ200 Chief Experimental Engineer, ITP *** EJ200 Chief Design Engineer, ITP
+ Engineering Director LCA, Eurojet Turbo GmbH, 85399 Hallbergmoos, Germany

is therefore proposed leading to a low risk and cost effective route to market.

The EJ200

The EJ200 is Europe's next generation advanced military turbofan engine. It has been designed to fulfil the demanding requirements of the Euro fighter Typhoon (Fig.1). The EJ200 technologically supersedes its competitors, delivering the highest thrust-to-weight ratio with the most simple engine architecture. The EJ200 philosophy is to deliver the highest levels of all-round capability whilst producing an affordable cost of ownership throughout the life of the weapon system.

A superior design concept has been achieved by using Europes centres of excellence in gas turbine subsystem design and whole engine integration. The EJ200 benefits from a completely new design that is free from the constraints of legacy product architectures found in so many of todays combat engines.

The EJ200 programme already covers over 1,400 engines for the sponsoring nations and export customers. These large sales volumes lead to economies of scale and a strong ongoing motivation to achieve cost reductions and deliver innovations in product and services to the customer. Technology insertions will ensure enhanced competitiveness of EJ200 well into the future.

The EJ200 Engine-Benchmark in its Class

The advanced design technology applied to the EJ200 makes it both smaller and simpler in layout than current military gas turbines while giving it lower fuel consumption and an unprecedented power-to-weight ratio all vital factors in enhancing the multi-mission performance and effectiveness of Euro fighter Typhoon.

The EJ200 is a two-spool turbofan with modular construction for ease of maintenance and support. The blades of its wide-chord fan features integrally bladed disks (blisks) and wide cord airfoils in all stages that are light and aerodynamically efficient, also possessing a high level of resistance to foreign object damage. The fan has no inlet guide vanes this reduces mass and complexity and improves bird strike capability without compromising operability. The EJ200 is the first military combat engine in the world to embody an all-blisk fan.

When compared with present-generation engines the EJ200 has up to four compressor stages less, up to two turbine stages less and up to one-third fewer blades. This greatly enhances the overall economic performance of the engine and the ground support system.

An integrated digital engine control and monitoring unit is standard for EJ200. This system significantly reduces pilot workload and provides a comprehensive fleet management capability.

EUROJET continues to work to provide future enhancements to the EJ200 to maintain its position as the world's leading combat engine. Thrust growth capability has been designed into the EJ200 and thrust-vectoring technology can be incorporated into the EJ200 engine as a result of a highly successful technology demonstrator programme started in 1995.

EJ200 Engine Design Description

The dimensions, component characteristics and the rotational speeds of the engine have been chosen to provide wide-chord blades with low stress levels in order to benefit component life both in terms of time at temperature and cyclic usage. It also permits achievement of the high compression ratio in only 8 stages (Fig.2). The EJ200 design is unique as no other engine of similar capabilities has such a low parts count.

The engine leading particulars and design characteristics are:

Compressors

The compressors (LP and HP) achieve an overall pressure ratio of 26:1 in 8 stages and have demonstrated both surge free handling and high efficiency throughout the flight envelope. The LP compressor (fan) is of a wide-chord blade design with an overhung bearing arrangement without inlet guide vanes thus providing excellent resistance to bird strike and foreign object damage. The performance loss associated with inlet guide vanes and the requirement for anti-icing is avoided.

Integrally bladed disks (Blisks) are incorporated in the fan and stages one to three of the HP compressor. Blisks offer benefits in both performance and weight. The HP compressor features only a single stage of variable guide vanes to provide satisfactory part load performance and handling. The compressor design ensures that carcasebending loads are isolated from the gas path, improving tip clearance control and performance retention.

Combustor

The combustion chamber is an advanced single annular design, featuring a rear mounting system, which reduces weight and cost (Fig.3). It also eliminates sliding joints commonly found on front mounted chambers; these have a tendency to fret and become a life-limiting feature of designs subjected to high cyclic usage. The relatively short design gives excellent stiffness and rigidity to the structure and a low mass.

Fuelling is via 20 air blast injectors all of which are identical. The injectors have 3 co-swirling air streams with fuel being added between the centre and the middle stream. The arrangement produces a very wide fuel cone angle and it is essentially this that allows such a short combustor to comply with the exit temperature profile requirements and its emissions targets (zero visible smoke).

Turbines

The single stage turbines (HP and LP) feature blades manufactured from advanced single crystal alloys, which provide superior thermal and mechanical properties to conventionally cast blades. The HP turbine blade is shroud less with a unique tip clearance control system that maintains tip clearance by thermal matching of turbine components.

Tip clearance control works by controlling the gap above the blade tip by moving the liner segment which forms the hot gas annulus in and out to minimize the blade tip gap. The liner segments are mounted off control discs via the HP and LP NGVs. The tip clearance is minimized by locating these control discs in the same thermal environment as the HPT disc and optimizing their thermal response by the use of thermal barrier coating and shielding. The control discs match the thermal growth of the static structure to the thermal and CF growth of the HPT disc, in this way the tip gap is minimized. A comprehensive test programme has been undertaken to validate the system and the running tip clearance has been measured using capacitance probes.

This technology guarantees that there is no thrust-droop at any engine operation condition. The turbine incorporates an advanced multi-pass and film cooling system and is capable of sustaining turbine entry temperatures up to 200 degrees hotter than previous designs.

The LP turbine is a shrouded design chosen for its high efficiency and performance retention characteristics. As with the HP turbine, this unit represents a step change from previous designs.

Afterburner

The staged afterburner system uses radial burners and primary vaporizers in the hot stream and fuel injection in the cold stream to give very high combustion efficiency over the operational range. The three burners are independently supplied with fuel, giving continuous and smooth modulation between minimum and maximum reheat. The design achieves smooth selection, low smoke and maximum thrust boost whilst minimizing instabilities.

The design incorporates Afterburner Shut Off and Distribution Valves mounted on the jet pipe, which maintain fuel in the delivery pipes up to the radial burners avoiding the need for reverse purge of the manifolds and minimizing the length of time to re prime. This eliminates the white plume of fuel vapour often seen on other engines and hence visibility.

The above design features are critical factors in making the EJ200 a fighter engine as reheat response to throttle demand is rapid, predictable and repeatable, whilst reheat operation does not leave the tell tale white plume often seen on other engines.

Nozzle

The nozzle is a fully modulating convergent/divergent single parameter system. By scheduling the exhaust throat area mission performance it can be optimized to provide high supersonic thrust and low subsonic SFC.

Engine Control and Monitoring System

The Engine Control and Monitoring System (Fig.4) are configured as one sub-system: the DECMU (Digital Engine Control and Monitoring Unit). The DECMU is engine mounted and features a high level of integration with A/C systems.

The control part of DECMU is a twin lane fault tolerant digital control unit driving the hydro mechanical elements of the system.

In order to facilitate integration with other aircraft avionic systems, the control system provides data to and receives data from those systems in serial data format via a dual redundant data bus, flight deck engine condition demand signals input to the DECMU via this bus.

The monitoring part of DECMU comprises data collection and storage elements contained within the DECMU. Data is collected, stored and processed within the engine mounted DECMU to produce information on the status of engine Life Usage, Condition/Incident Monitoring and Testability.The data is downloaded to a Ground Support System (GSS) after flight for further detailed analysis.

EJ200 Engine Supportability

Engine supportability (reliability, maintainability and testability) and low life cycle cost has been treated with equal priority to performance and mass. The values that have been set represent new standards for fighter aircraft engines; and provide a supportable and affordable engine.

The engine monitoring system provides reliable information on individual component life usage for fracture critical parts and hot components, including HP and LP turbine blades. Continuous vibration and oil analysis gives on-line information of the mechanical status of the engine. Performance trend monitoring is carried out to enhance maintenance planning and the detection of failures. For fleet management purposes the on-board Engine Monitoring System is linked through the Ground Support System (GSS) with the operators data capture and analysis system. Additionally, repairability on-condition maintenance and minimum AGE (Aerospace Ground Equipment) requirements form a major part of the design philosophy. Careful design also ensures that the routine maintenance requirements can be carried out with minimum effort, i.e. magnetic chip detection, boroscope and oil filter inspection.

The EJ200 Thrust Vectoring Nozzle Concept

Prototype Nozzle

In 1995 Eurojet/ITP launched what is called a "Technology Demonstration Phase". This phase included the design, construction and test of a prototype Thrust Vectoring Nozzle. The first run took place in July 1998.

The purpose of the test bed campaign was triple: validation of the nozzle concept, validation of the TVN control system and validation of the whole engine-thrust vector nozzle system integration. Some major achievements to be mentioned from the test campaign are:

- More than 80 running hours, 15 with afterburner operation
- 360° vectoring at various dry and reheat settings
- Maximum vector angle of 23.5° (at partial reheat)
- Maximum slew rate of 110°
- Maximum lateral force of 20kN
- Sustained 20° vector at reheat for 5 minutes for thermal validation
- More than 100 performance points tested
- Engine slams with sustained vector
- Demonstration of thrust improvement by exit area modulation (up to 2% increase)
- Endurance tests: more than 6700 vectoring cycles at constant throat area and more than 600 throttle cycles with a sustained vector
- No mechanical failures during test campaign encountered

Simple Design: Light and efficient

The great technological innovation of the Eurojet/ITP design lies in its use of one single hydraulic actuation system to control both the convergent section (throat area) and the divergent section (vectoring and exit area). This has a strong impact on issues as weight, cost and even global engine performance, since less power needs to be extracted for the hydraulic actuation. In general the Eurojet/ITP design presents a number of advantages relative to other designs:

- Minimum number of Actuators: Lower weight and better overall engine efficiency. Where other existing systems require two sets (in total 6-9) actuators, the Eurojet/ITP Thrust Vectoring Nozzle performs all nozzle functions with just one set of 4 actuators, which consequentially means a lower total weight and better overall engine efficiency.

- Optimized divergent section for high deflection angles. Although the current nozzle prototype is limited to 23° (typical limits are 17°-20°), the divergent section concept allows for growth if required. Studies have been conducted with deflections being feasible up to 30°-35°.

- Balance-Beam effect for lower actuator loads. The Eurojet/ITP Thrust Vectoring Nozzle makes use of a "partial Balance-Beam effect". Gas stream energy is utilized to move the nozzle, hence reducing the work required from the actuators.
- Fail-Safe mode: Nozzle centred and closed. In case of total hydraulic failure, the Nozzle automatically sets to safe position, closed and centred, hence maintaining dry thrust and full aircraft control to return home safely. No additional devices are needed to close and fix the nozzle in this position.

Full 3D Eurojet/ITP Thrust Vectoring Nozzle: Main Features

Many different configurations have been studied at Eurojet/ITP for a TVN. As a result of this exercise the selected solution is a convergent-divergent axisymmetric nozzle with multi-directional Thrust Vectoring. The nozzle is mechanically actuated and vectoring of the gas flow is achieved by deflection of the divergent section only. By this concept moving masses are minimized and disturbances to the engine turbo-machinery upstream of the nozzle are negligible. The Nozzle allows four degrees of freedom (4DOFs) movement, namely: Throat area (A8), Exit area (A9), Pitch vectoring and Yaw vectoring. Any oblique vectoring is made by a combination of pitch and yaw.

This system consists of three concentric rings (Fig.5) which are linked by pins forming a universal (or "cardan") joint. The inner ring is linked to the convergent section of the nozzle, the outer ring, split into two halves, is linked to the divergent section through the reaction bars and the intermediate ring acts as the crossbar between the inner and outer rings. The 4 actuators are linked to the outer ring only. The design of the rings and reaction bars is such that a small tilt angle on the ring is amplified to a large deflection angle on the divergent section.

For pure throat area adjustment all actuators move in parallel, hence all three rings follow axial movement and A8 is set to the appropriate value (Fig.6a).

For Pitch and/or Yaw vectoring, the four actuators move differently, hence defining a tilt plane of the outer ring. The divergent section will deflect in the direction of that plane. Throat area (A8) is not affected unless this movement is combined with a throat area movement (Fig.6b, 6c). Additionally, pure A9 control is performed by moving top and bottom actuators in parallel while the other two stay static, hence "hinging" the outer ring open or close (Fig.6d). The divergent section opens or closes relative to the nominal position, acquiring an "oval" shape. Hence this movement is sometimes referred to as "ovalization". Of course, A9 movements can be combined with A8 movements and/or vectoring movements.

Apart of the characteristics above described the Eurojet/ITP TVN design also presents other two important additional features: "Hinged" Reaction Bars and Balance Beam concept.

"Hinged" Reaction Bars

The design of the reaction bars presents "Hinged Struts" which allow an optimized smooth movement of petals (Fig.7). Where other designs are limited to about 20° geometric deflection by the disengagement and/or interference between petals, the Eurojet/ITP design allows for further growth and studies have been carried out for deflections up to 30°-35°.

Balance Beam Concept

The Eurojet/ITP TVN makes use of a partial balance-beam effect, which consists of taking advantage of the energy of the gas stream to help closing the nozzle in high pressure conditions (Fig.8).

The closing movement of the nozzle is accomplished by an axial displacement of the throat so that the volume swept against the gas pressure is modified; in particular, more volume is swept in the low pressure region of the nozzle and less volume in the high pressure region.

This has two beneficial effects:

- On one hand, in high pressure conditions, the total work performed by the actuation system acting against the gas stream is reduced by about 15%, which results in smaller actuator dimensions and better engine efficiency.
- On the other hand, in case of hydraulic loss in low pressure conditions, the nozzle self-closes, which is useful to retain thrust and makes it particularly interesting for Single Engine Applications (minimum thrust requirement for get-you-home feature).

Simplified Two Ring System for Pitch-Vectoring only

There is a simplified version of the Full 3D Vectoring Nozzle feasible, where the intermediate Ring is deleted, hence reducing some weight and complexity (Fig. 9). The outer Ring is split into two parts as in the previous presented version. This nozzle is equipped with four actuators as well and has got 3 DOFs (A8, A9, and Pitch Vectoring). It is suitable for application in aircraft with no Post-Stall capability, but making use of important benefits in the conventional flight envelope by pitch-vectoring only.

TVN Technology - Overall Airframe Aspects and Benefits

Introduction of TVN into existing and future combat A/C is a complex integration task affecting various A/C and engine systems at the same time:

- Airframe: general systems, flight control system, aerodynamics, loads
- Engine: nozzle design, engine control system, engine hydraulics system
- Engine/airframe interfaces: FCS/FADEC, after-body aerodynamics, introduced side forces

Consequentially, an optimized overall solution can be found and understood only by an integrated approach between airframe and engine manufacturer. The benefits of a TVN system were investigated between Eurojet and its partners in the past quite extensively considering all those aspects. An optimized thrust vectoring system addresses the following overall weapon system aspects:

- Life Cycle Cost Reduction
- Improvement of Safety
- Improvement of Weapon System Performance and Handling

Life Cycle Cost Reduction : Will be mainly achieved by optimized A9/A8 control. In mono-parametric Con-Di nozzles the divergent section (A9) follows a pre-defined relationship to the convergent section (A8). This relationship is optimized for an average of all missions, which normally means low A9/A8 Ratio for dry operations (without reheat) and high A9/A8 Ratio for operation with reheat.

The use of an independently controlled divergent section allows A9 to be optimized for any engine running-/flight-condition and has an improvement especially in those conditions where a mono-parametric A9/A8 Ratio is not optimized (take-off and supersonic cruise). For example the installed net thrust improvement is up to 7% for supersonic cruise and 2% for take-off condition at Max Reheat (Fig.10).

Optimum A9/A8 ratio at each operating condition is driven by two aspects: the internal performance of the nozzle which is maximum when the nozzle throat is chocked and exit static pressure is equal to ambient pressure and the external after-body drags which increases with reduction of nozzle exit area.

Figure 11 gives an overview of potential improvements in SFC for Part Dry and Part Reheat operation for various mission points (point performance). SFC can be reduced up to 11% in the subsonic and up to 7% in supersonic regime during Part Reheat cruise.

Cost benefits are also gained by reduction of SOT during cruise and loiter leading to increased life of hot gas path parts.

At part power operation mainly in the dry operation range, optimized A9/A8 control also leads to reduced temperatures and spool speeds at constant net-thrust increasing notably the hot gas path parts life and potentially achieving improved TBO values compared to a conventional nozzle.

A performance simulation of EJ200 typical flight mission has revealed SFC reduction of 5% and significant mean-and maximum-temperature reductions as lined out in Table-1.

Improvement of Safety : This is probably one of the strongest arguments in favour of Thrust Vectoring, applicable for peace time and war time operation. Thrust Vec-

Table-1

	Mean Temp. Reduction [K]	Max. Temp. Reduction [K]
HPT rotor inlet	-8.1	-48
LPT stator inlet	-6.4	-39
Turbine diffuser inlet	-4.7	-25

toring provides additional control power at low dynamic pressures (v < 300kts), where aerodynamic control surfaces are able to generate only a reduced level of forces and moments required to control the aircraft. This is especially true for delta-wing configurations due to a reduced lever arm of control surfaces, which are located on the trailing edge of the wing. Therefore thrust vectoring is an effective measure to reduce the risk of low speed departure and therefore leads to reduced peace time and war time aircraft loss rate.

In addition, implementation of a Thrust Vectoring system leads to an improved redundancy level due to the fact that an additional control device is added to the aircraft systems. This results again in improved safety and war damage tolerance.

Considering Thrust Vectoring as a primary control device (Fig.12) for a new aircraft design, additional advantages can be considered affecting the overall layout of the configuration. Availability of a TVN will lead to a reduction or even deletion (e.g. fin for lateral stability) of aerodynamic surfaces, leading to

- Overall mass reduction
- Reduction of Radar Cross Section (RCS)

Improvement of Weapon System Performance and Handling Reduction of take-off distance : Fig.13 shows that a reduction in take-off distance up to 20% can be achieved using a TVN system. This improvement results in the fact that from a certain forward speed onwards (depending on the aircraft layout, centre of gravity, aircraft mass) sufficient lift for take-off could already be provided, however the control surfaces are not yet able to generate enough forces and moments to rotate the aero plane to the required AoA. TVN can generate these required moments for pitch control and the aerodynamic control surfaces have not to be deflected for this reason providing the full deflection range for roll control.

Reduced Supersonic Trim Drag

Even if an unstable design of the airframe in the subsonic regime is realized, shift of aerodynamic forces in the supersonics lead to a stable configuration concerning the pitch-axis. This results in the fact that the aerodynamic surfaces have to conduct a negative (i.e. upwards) deflection to trim the aircraft. This trim setting increases drag, generates negative lift and reduces the available range of ailerons (delta wing) for roll control. This mechanism is illustrated in Fig.14.

TVN can be used to generate the required forces and moments to trim the aircraft and therefore to unload the aerodynamic control surfaces and to minimize the drag.

This mechanism is also valid and even amplified for manoeuvre performance (sustained and instantaneous turn rates) in the supersonic regime leading to even higher improvements. The level of improvement is very much dependant on the configuration and the aerodynamic lay-out of the aircraft.

Improved Handling for Configurations with Heavy Stores

For an operational aircraft various store configurations have to be considered and cleared for peace time training and war time scenarios. Such heavy configurations may lead to a C.G. shift, which has to be balanced (i.e. trimmed) by aerodynamic control surface deflection accordingly. This may - depending on the lay-out of the configuration and C.G. shift-lead to reduced margins for control surface deflection available for roll control. In addition, configurations with heavy stores lead to high inertias and therefore reduced handling qualities especially at low dynamic pressures. A TVN system will be able to recover the handling qualities by unloading the aerodynamic control surfaces and by adding additional control power in the pitch and yaw axis.

Extension of Flight Envelope (Increased AoA Capability and Low Speed Agility)

It is an obvious fact that the control power generated from aerodynamic control surfaces is reduced with decreasing dynamic pressure. Surface deflections have to be increased to compensate the lack of dynamic pressure and the control surfaces soon run into saturation. The consequence is reduced handling qualities and finally a limitation to fly in specific parts of the envelope. A further aspect to be considered for very high incidences (which by the way can only be achieved in the low speed/low dynamic pressure regime) is the fact that directional basic stability and rudder control power of the aircraft may be detrimentally affected resulting from shading of the fin by thefuselage/canopy and by detached flow/vortices emanating from the main wing, respectively.

The main advantage of a TVN system is - compared to aerodynamic control surfaces- the ability to generate control power independent from aircraft incidence and dynamic pressure and therefore is the ideal measure to open-up this regime of the envelope. Therefore TVN also provides excellent pointing capability needed for low speed close-in combat manoeuvres. The big tactical advantages provided by TVN in this part of the envelope were successfully demonstrated by flight trials conducted in the mid 90s during the X-31 Enhanced Fighter Maneuverability Programme.

Figure 15 concludes and illustrates which parts of the flight envelope can be exploited and improved by TVN technology.

Route to Market - Stepped Low Risk Approach

As already mentioned, EUROJET has successfully tested the TVN nozzle with the EJ200 engine on bench and ATF (altitude test facility). This test was conducted to validate the TVN nozzle design and the effectiveness of nozzle deflection under realistic engine operation conditions. For that reason, the nozzle was heavily instrumented and was not considered to be cleared for flight test. Also the functionality for thrust deflection control was not yet integrated into the engine control system. This first step approach was taken to gain useful information at minimum cost and low risk.

The EUROJET target is to continue with this successful strategy, i.e. to carefully consider the level of integration effort required for each step ahead. In joined theoretical studies with the airframe manufacturers, an overarching concept for a TVN system was defined. The important result of this exercise was to nail down design criteria and boundary conditions as maximum side-forces generated by the TVN system, slew rates, redundancy concept etc. from an overall weapon system perspective. On the basis of this work a TVN model was delivered to the airframe manufacturer, which was used to design a Flight Control System included with TVN functionality. An aircraft model with the TVN model will be operated in a manned simulation exercise to finally validate the TVN concept to understand machine-man interfaces and to get a feedback from pilot’s perspective.

After completion of this task, the next step could be to start flight testing with a flight worthy thrust vectoring nozzle. It is proposed to use a twin engine configuration (e.g. Typhoon) with only one engine equipped with the new thrust vectoring system. Considerations were conducted together with the airframe manufacturer about the integration concept of this TVN engine: The conclusion was that extremely useful information can be gained without any changes to the Flight Control System or other A/C systems. Clearance work has to be conducted utilizing the ability of the A/C to counter act against "asymmetries" generated by the introduced TVN side-forces. The airframe reaction due to this force build-up will be used to establish the behaviour and effectiveness of the TVN system in flight. Thrust deflection can be initiated by an already existing signal (no interface change) by the pilot and the nozzle will move according to a predefined schedule. The advantages of this proposal are:

- Validation of essential TVN models possible (control power, loads model, A8/A9 control, side-force build-up, structural coupling)
- Initial validation of a TVN system in flight possible (however not yet covering the full deflection range)
- Cost effective: No interface changes between A/C and engine required
- Flight clearance and safety: There is still one unchanged propulsion system available for safe return to base leading to a safe approach and reduced effort for clearance work

After having validated the TVN system and conduction of a model update (if required), flight testing with a single engine or a twin engine platform with full integration into the Flight Control System can be pursued. With this approach, the required update of the Flight Control System can be conducted with strongly reduced risk due to the fact that the required models are already validated. This approach is illustrated in Fig.15.

Conclusions

It has been shown that the Thrust Vectoring Technology offers numerous advantages for fighter aircraft, which can be utilized for existing platforms as well as for future aircraft concepts.

Extensive joint studies have already been conducted between Eurojet and airframe manufacturers to understand the global benefits of a TVN system considering all integration aspects and other affected disciplines and systems beyond the propulsion system at the same time.

In parallel, Eurojet/ITP on its own has already developed a concept for an EJ200 TVN nozzle, which allows pitch/yaw and independent A9/A8 control at the same time. This nozzle was already tested during a bench and ATF test programme leading to a profound maturity level concerning this technology within Eurojet. Therefore and due to fact that the recent production standard of the DECMU (Digital Engine Control and Monitoring Unit) includes hardware provisions to implement a TVN, the EJ200 is an ideal platform to bring this technology into operational service.

Detailed considerations were already made about the next steps required to bring a TVN into a flying test-bed. The strategy is to use a stepped approach with respect to the level of integration of the TVN system into aircraft systems (FCS). This guarantees a low cost/low risk approach and provides very useful information at the same time.

Fig.1 Typhoon in formation flight

Typical mass flow	**76 kg/s**
Bypass ratio	**0.4**
Fan pressure ratio	**4.2**
Overall pressure ratio	**26**
Max Reheat thrust class	**90 kN**
Max dry thrust class	**60 kN**
Typical SFC Max Dry	**22 g/kNs**
Typical SFC Reheat	**48 g/kNs**

Fig.2 EJ200 cutaway schematic

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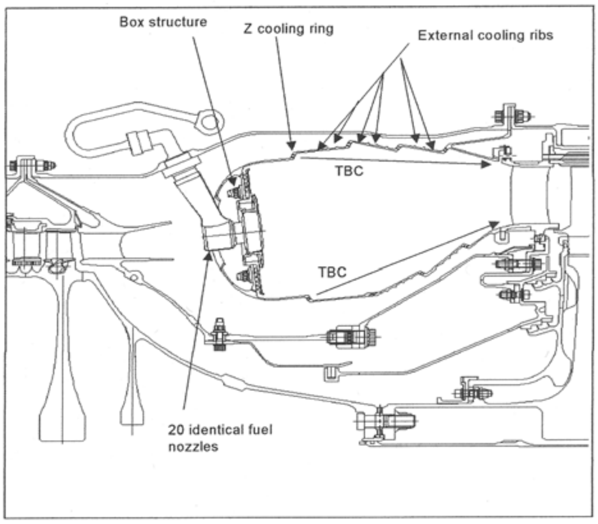

Fig.3 EJ200 combustor chamber

Fig.4 Integrated engine control and monitoring system

Fig.5 Full 3D Eurojet/ITP TVN : Three ring system concept

Fig.6 Ring movement for a) A8 control; b) Pitch deflection , c) Yaw deflection and d) A9/A8

Fig.7 Vectoring with simple and "hinged" rection bars

Fig.8 Balance beam effect

Fig.9 Comparative full 3D TVN vs pitch-only nozzle

Fig.10 SFC improvement in various parts of the flight envelope for max dry and max reheat including after-body drag effects

Fig.11 SFC improvement by independent A9/A8 control for various mission points

Fig.12

Fig.13 Reduction in take-off distance

Fig.14 Trim forces in the supersonic regime with and without TVN

Fig.15 Envelope expansion and TVN effectiveness in the flight envelope

Fig.16 Stepped low risk approach