TITLE: Integrated Thrust Vectored Engine Control

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Thrust vectoring has the potential to provide significant improvements in combat aircraft performance and flexibility. As Eurofighter Typhoon moves into the production phase, Industria de Turbo Propulsores (ITP) and Motoren- und Turbinen-Union München GmbH (MTU) are pursuing a research and technology acquisition project to investigate the design of a thrust vectoring nozzle system suitable for future applications of the EJ200 engine. This paper describes the work related to the engine control system carried out thus far by MTU within the ITP/MTU thrust vectoring technology programme.

Abstract

Thrust vectoring is a key technology for future combat aircraft. Together with an advanced thrust vectored engine control system, the ITP thrust vectoring nozzle concept with a common actuation system for all nozzle functions (throat area, exit area and all axis vectoring) is an appropriate solution to meet the stringent requirements concerning performance, reliability and safety resulting from the intended use of thrust vectoring for flight control. An enhanced link between the flight control system and the engine control system will be necessary and the combined engine and nozzle control will have to meet new functional requirements. These requirements are on one hand related to the nozzle itself and on the other hand to the interactions between the nozzle and the engine.

Compared to present jet engine control, e. g. the Eurofighter "Typhoon" engine EJ200, the main differences concerning the control system hardware arise due to the additional actuators for the vectoring nozzle and the corresponding drive and sensing equipment. This results in a higher number of external interfaces for the FADEC (Full Authority Digital Engine Control) and hence a further step of hardware miniaturization and increases in computing power are necessary to maintain / reduce the volume and mass of the engine control unit. The main task of the vectoring nozzle control is to drive the nozzle actuators according to demanded side forces and demanded effective throat and possibly exit areas. This involves both computation of nozzle kinematics and resultant gas flow, i. e. effective areas and thrust components. A key item of the nozzle control is to keep the nozzle during all steady-state and transient conditions within its allowed operating range, which is defined by geometrical limits and maximum allowable forces. Besides response time and accuracy requirements have to be met.

Interactions between nozzle and engine are numerous – not only because of the coupling of the different nozzle functions due to the unified actuation system. During vectoring resulting side forces are determined not only by the nozzle but also by the engine thrust. On the other hand vectoring may have an influence on the effective throat area and thus on engine operation – especially in reheat conditions. Additional dependencies are related to failures and abnormal operation of the nozzle and the engine itself. A common supervisory logic ensures optimum detectability and advanced reversionary modes include coordinated actions upon engine and nozzle control.

This paper describes the work related to the engine control system done at MTU within the ITP/MTU thrust vectoring technology program. Starting from the current Eurofighter "Typhoon" EJ200 FADEC, the modifications to operate the thrust vectored engine demonstrator (EJ200 + ITP 3D vectoring nozzle + MTU control system) are described. All control functionality needed for safe and flexible bench testing of the complete thrust vectored engine has been developed.

Finally a closer look to a production solution is given. The modern thrust vectored jet engine will be controlled by a single FADEC providing thrust and side forces as commanded by the flight control system. Also extensive monitoring functions will be included within the FADEC. A clear and simple interface will provide a suitable interaction between the flight control system and the engine control system, which becomes essential for future thrust vector application.

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Nomenclature

AFCS	Air Flow Control System
ATF	Altitude Test Facility
A8	Convergent Nozzle Area
A9	Nozzle Exit Area
CFD	Computational Fluid Dynamics
DAS	Data Acquisition System
DEAR	DECU EMU Acceptance Rig
DECU	Digital Electronic Control Unit
DMSU	DECU Monitoring and Setting Up Unit
DPR	Dual Port RAM
EJ200	Jet Engine of Eurofighter Typhoon
EMU	Engine Monitoring Unit
FADEC	Full Authority Digital Engine Control
FCS	Flight Control System
FPGA	Field Programmable Gate Array
HPC	High Pressure Compressor
IO	Input / Output
LP	Low Pressure
MSU	Mil-bus 1553 Simulation Unit
PBAY	Pressure Engine Bay
PC	Personal Computer
PL	Power Lever
PLD	Power Lever Demand
PWM	Puls Width Modulation
RAM	Random Access Memory
TV	Thrust Vector
TVCU	Thrust Vector Control Unit
TVN	Thrust Vectoring Nozzle
TVDAU	Thrust Vector Data Acquisition Unit
T2	Engine Intake Temperature
VIGV	Variable Inlet Guide Vanes
VMSU	Vector Monitoring and Setting Up Unit
WDT	Watch Dog Timer

The current Eurofighter "Typhoon" EJ200 FADEC

A full authority digital engine control has been developed for the Eurofighter "Typhoon" EJ200 engine. The EJ200 control system plays an important role in the overall objectives of achieving both the high performance and the low life cycle cost objectives of the EJ200 programme.

The system comprises of

- Digital Electronic Control Unit (DECU)
- Ignition System
- Fuel Control System
- Air Flow Control System (AFCS)
- Sensors

It does not employ any hydro-mechanical computational elements or mechanical back-ups.

The main functions performed or supported by the Control System are:

- To control the engine dry and afterburner fuel flow, exhaust nozzle area and HPC Variable Inlet Guide Vanes (VIGV) position in response to thrust demands and to ensure that the engine functions throughout its operating range within the permissible flight envelope without exceeding any limitations
- To detect and compensate for control system defects and to automatically accommodate faults
- To provide the communication with aircraft and ground support systems
- To provide engine and monitoring data to the aircraft mounted Engine Monitoring Unit (EMU)

The DECU (Digital Electronic Control Unit) developed by MTU, shown in figure 1, is a key element of the EJ200 control system. It is fuel cooled and mounted via anti-vibration isolators on the underside of the LP casing. Although airframe mounted would provide a more benign environment for the DECU, engine mounted offers significant technical advantages in particular with respect to reduced harness length and consequently weight and reduced electrical interference.

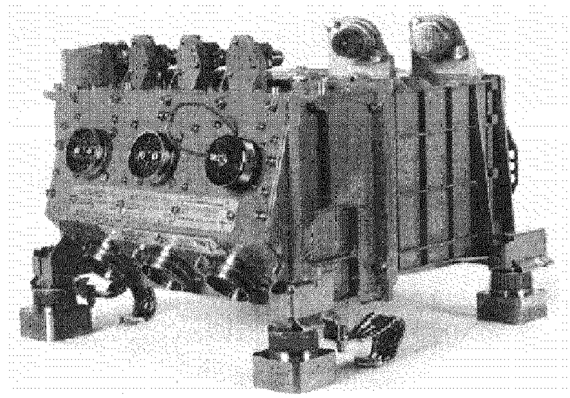

Figure 1: DECU (Digital Electronic Control Unit)

The DECU consists of two functionally identical lanes in a common chassis. Each of the DECU lanes incorporates two Motorola microprocessors communicating via intercomputer and interlane high speed serial links and having access independently to all sensors, actuators and data links.

There exist 7 actuator control loops (five fuel system, one VIGV and one nozzle) for controlling the engine.

Each of the two DECU lanes is fitted with two Mil-Bus 1553 interfaces. Two bus interfaces (one of each lane) are used to communicate with the flight control system computer, the remaining interface at lane 1 communicates with the Engine Monitoring Unit EMU. One Mil-Bus 1553 interface (lane 2) is a spare interface.

This configuration is basis to support the technology demonstration programme "Thrust Vectored Engine Control".

The Thrust Vector Demonstrator Control System

ITP is performing a R&D programme on thrust vectoring technology since 1991. In 1995 a "Technology Demonstration Phase" was launched with the aim to design, construct and test a prototype thrust vectoring nozzle for the EJ200 engine. The concept of the vectoring nozzle developed by ITP so far is very promising for future aircraft application e.g. in the Eurofighter as it provides a large 4 degree of freedom operating range combined with minimum extra weight and minimum changes to engine and aircraft.

MTU's participation in this programme began in 1995 being responsible for the engine and nozzle control system. The system presented in the following sections describes the first achievements on the way to an integrated thrust vectored engine control for future aircraft application. It addresses all requirements to support bench testing of the thrust vectored EJ200 engine.

New System Requirements for Vectoring Nozzle Control

The main functional requirements were to ensure safe operation both of the vectoring nozzle and the engine whilst providing the necessary flexibility to carry out all development tests. In addition to normal engine control the following vectoring nozzle functionality is required:

- Calculation of Nozzle Kinematics
- Geometrical Limitation of Nozzle Operation
- Vectoring Rate Limitation
- Nozzle Actuator Control
- Nozzle Actuator Supervisory
- Recovery Actions on Engine and Nozzle in Failure Cases
- Emergency Deactivation of Nozzle Actuation
- Extensive Test Features (related to the vectoring nozzle)

System Overview

In order to avoid hardware modifications to the DECU a separate control box, the Thrust Vector Control Unit (TVCU), was designed and developed to control the thrust vectoring nozzle. This was necessary, since the vectoring nozzle is controlled by four independent actuators thus requiring four independent actuator control loops. The standard convergent-divergent EJ200 nozzle is controlled by a single electronic actuation control loop and four hydraulically synchronised actuators. The next figure shows the basic structure of the system used within the present technology demonstrator programme.

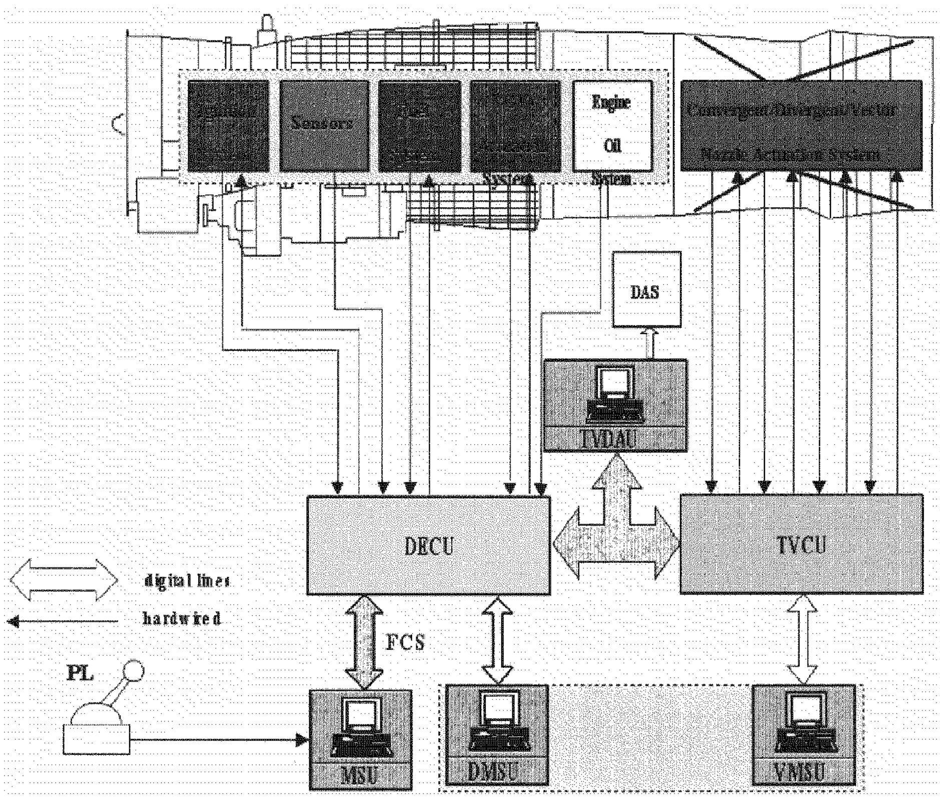

Figure 2: Thrust Vectored Engine Control System, Technology Demonstrator

The thrust vectored engine is controlled by two units,

- The DECU responsible for

  Fuel Metering System (dry and reheat), variable guide vanes, all valves and sensors except those fitted on the thrust vectoring nozzle

- The TVCU responsible for

  the complete convergent-divergent thrust vectoring nozzle including the nozzle control and area limitation, the actuator control, the safety and supervisory functions and the extensive test features for the system development.

These two units are connected by a Mil-Bus 1553. There is an additional unit in the digital bus connection between the DECU and the TVCU, the Thrust Vector Data Acquisition Unit (TVDAU) monitoring the bus transfers, which includes the TVCU control data and engine data. The DAS is a data acquisition system where the recorded data are stored on a mass media.

The Mil-Bus Simulation Unit (MSU) is a PC-based simulation of the FCS Mil-Bus 1553 Interface, providing the FCS demands (PL, nozzle vectoring), air data input and visual display of the DECU and TVCU control parameters. With this configuration bench testing of the thrust vectored engine is performed as follows:

- Throttle and geometrical vectoring demands are introduced via MSU
- Changing of engine control parameters and configuration is possible via DMSU
- Changing of nozzle control parameters and configuration including open loop modes is performed via VMSU (Vector Monitoring and Setting Up Unit)

The Thrust Vector Control Unit

The TVCU consists of two functionally identical lanes in a common chassis.

The following figure shows the hardware architecture:

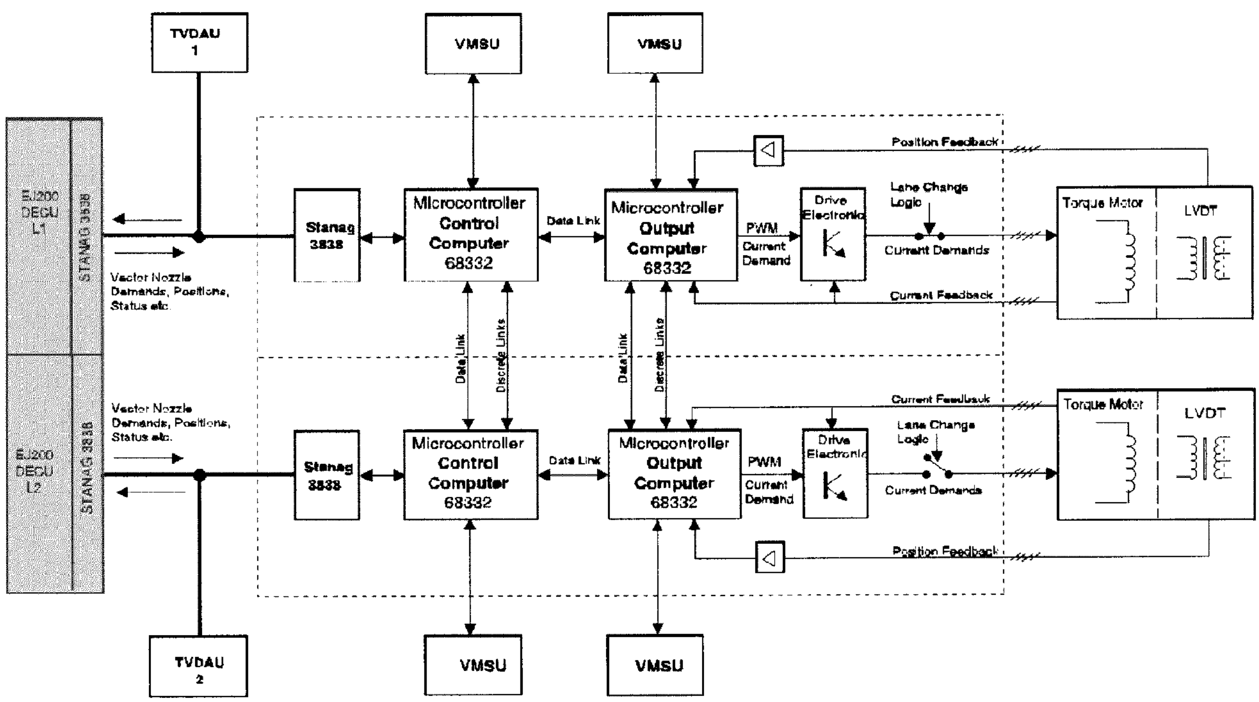

Figure 3: TVCU Hardware Architecture

Each of the two identical TVCU channels consists basically of a digital Mil-Bus 1553 interface to communicate with the DECU and the TVDAU, two microcontrollers Motorola MC68332 and the drive and sensing electronic necessary to operate the nozzle via four independent electro-hydraulic servovalves.

The two processors of one lane, i.e. the Control Computer and the Output Computer, are synchronised and communicate via a Dual Port RAM (DPR). In addition each of the processors of one lane communicates via a serial data link with the related processor of the neighbour lane. Also both TVCU channels are synchronised.

The tasks performed by each lane are distributed to the two microcontrollers which operate with different cycle times:

- Control Computer (10 ms cycle time)

  Mil-bus 1553 communication, nozzle kinematic calculation, nozzle operation geometrical limitation, vectoring rate limitation, nozzle actuator supervisory, emergency deactivation of nozzle actuation, extensive test features.

- Output Computer (2.5 ms cycle time)

  Nozzle actuator control, actuator drive current check, extensive test features (related to the actuator control only)

Functions such as the communication with the VMSU, the standard computer safety (memory check, address line checks, WDT supervisory, communication link checks) are performed on each of the processors.

This configuration enables a new approach with respect to EJ200 actuator control to be introduced, namely fully digital. A pulse-width modulated (PWM) signal with a basic frequency of 9.6 kHz is applied to the torque motors of the electro hydraulic nozzle actuators. The current / position control algorithms are implemented as microcontroller software. The following figure shows the basic architecture of the digital position controller.

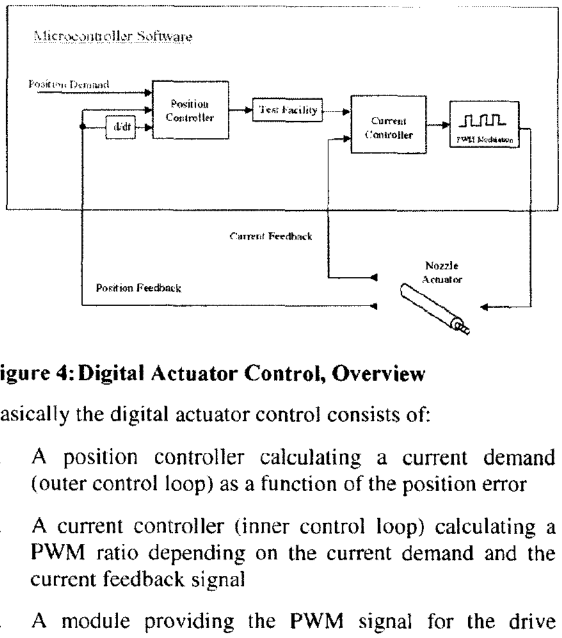

Figure 4: Digital Actuator Control, Overview

Basically the digital actuator control consists of:

1. A position controller calculating a current demand (outer control loop) as a function of the position error
2. A current controller (inner control loop) calculating a PWM ratio depending on the current demand and the current feedback signal
3. A module providing the PWM signal for the drive electronic
4. An open loop test facility which allows to apply defined currents to the nozzle actuators for test purposes

In addition to the digital actuator control the output computer performs also the supervisory of the drive currents. A model of the torque motor is introduced for this purpose and the "model current" is compared with the measured current taking into consideration state dependent limits. The reason to implement the drive current supervisory on the output computer is that the cycle time of 2.5 ms allows an appropriate modelling of the fast varying current.

The model of the actuator (piston position) and the supervisory of the sensing electronics are implemented on the control computer since the cycle time of 10 ms is sufficient to perform an accurate modelling.

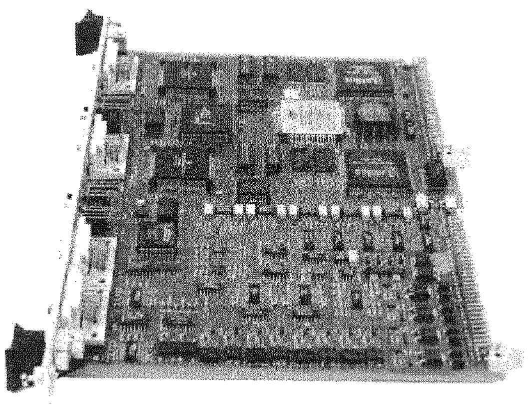

Figure 5: TVCU Board Containing One Lane

This figure shows one complete TVCU lane. The upper half of the board represents the computer part (control and output computers, memory, Mil-Bus 1553 interface), the lower half represents the drive current and the position sensing electronics.

Two boards are mounted, together with two off the shelf power supplies, in a standard rack system. The unit is designed to be operated at environmental temperatures from 0 deg Celsius to 40 deg Celsius, i.e. in laboratory type environment. The technological innovations of the TVCU are the introduction of fully digital actuator control loops implemented in the output computer and the implementation of new more accurate digital models for the actuator supervisory. The improved supervisory functions are essential when the thrust vectoring nozzle becomes an active aircraft control surface in future flight programmes.

The use of a Motorola MC68332 microcontroller for the purpose of digital actuator control allowed the introduction of four (4) control loops into one processor (taking into account the control cycle time of 2.5 ms). Further development work performed at MTU lead to the introduction of a special processor core optimised for the purpose together with the proven control algorithms into a FPGA of the XILINX XC4000XLA family (4085). This approach allows, together with the related sensing and drive electronics, the control of 15 actuators using one single chip. A big step in direction of highly miniaturised IO and improved actuator supervisory has been performed.

Development and Verification

Within the development of the control functions and the control system integration and verification simulation plays an important role, both in off-line and real-time environment. Simulation models are developed in off-line environment, adjusted and validated by analysis of real test data as far as available and can then be used for the different purposes in off-line and real-time simulation environments.

Simulation Models

For the purposes of the demonstrator programme the following models were developed:

1. Nozzle Kinematic Relations

   The thrust vectoring nozzle is characterised by its kinematic relations between the four actuator positions and the geometrical state of the nozzle, i.e. vectoring in two directions and throat and exit area.

2. Nozzle Actuator Loads

   The loads on the actuators vary strongly during vectoring. The data for the correlation between nozzle deflection and resulting actuator forces for various engine settings were obtained from CFD calculations performed at ITP.

3. Nozzle Actuators

   The actuation system consists of four identical hydraulic actuators. Dynamical models of the actuators were derived from the physical description of the actuator components.

Effects not modelled are related to the flow characteristics of the vectoring nozzle. Thrust deflection needed not to be modelled as there is no feedback to the control system. Vectoring influence on effective throat area was neglected and instead covered by the introduction of an increased A8-schedule within the engine control (increased surge margin).

Actuation System Tests on Hydraulic Rig

A hydraulic test facility was built which allowed to test and operate the real actuators under varying operating conditions, especially applying high tension and compression forces.

Extensive testing was performed with respect to the following purposes:

- Verification of actuators
- Validation of actuator models
- Determination of uncertain model parameters
- Test and validation of actuator control in closed loop mode

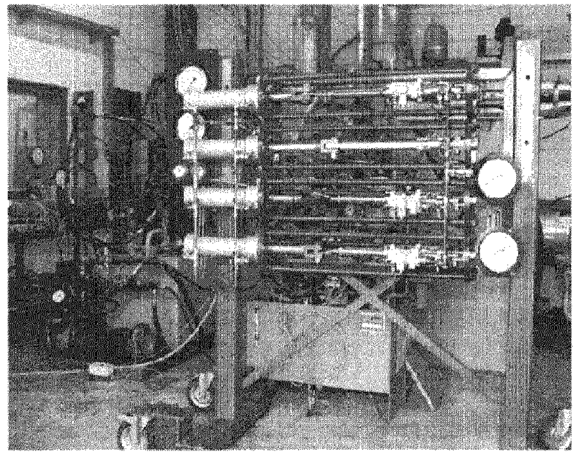

Figure 6: Nozzle Actuators on the All-Can-Do-Rig

Real-Time Testrig

For DECU development, testing and qualification MTU uses test facilities (DEAR = DECU EMU Acceptance Rig) incorporating real-time simulation of engine, actuators, sensors and aircraft signals. Thus the DECU can be operated in closed loop mode under realistic conditions enabling for example extensive testing of failure cases without the risk to damage real engine components. The standard test rig for the EJ200 DECU incorporates detailed dynamical models of the engine and the standard actuators as the DECU covers both engine control and control of subsidiary actuation systems.

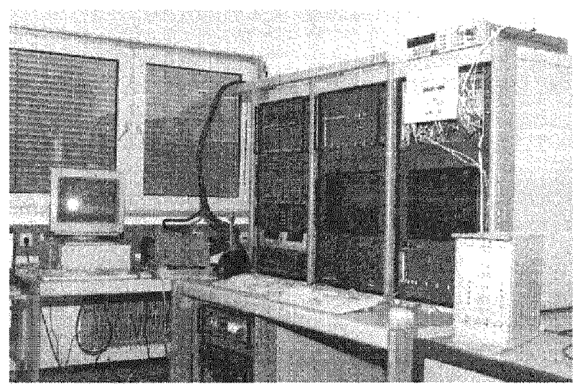

Figure 7: The thrust vectored engine DEAR

For vectoring nozzle control system integration and test a thrust vectored engine DEAR (TV-DEAR) was built. The TV-DEAR enables comprehensive simulation of the complete thrust vectored engine control system. The movements of the simulated nozzle actuators are controlled by the TVCU and are influenced by the varying loads, which in turn depend on nozzle vectoring and engine operating condition. The geometrical state of the simulated vectoring nozzle is determined by the four actuator positions. The computed exit area A8 influences in turn engine simulation and DECU control reaction.

The TV-DEAR was mainly used for the following purposes:

- Thrust vectored engine control system integration
- Robustness checks of actuator control (excessive variation of actuator forces due to vectoring and unknown friction forces)
- Failure simulations for development and testing of supervisory and recovery logic
- Acceptance testing of the complete control system

Results of Thrust Vectored Engine Bench Testing

The control and data acquisition system was integrated at the engine test bed at Ajalvir near Madrid in the week before the first West-European thrust vectored engine run on the 30. July 1998. The test results obtained during the running of the prototype include the following achievements:

- 80 running hours, including 15 with reheat
- Vectoring in all 360° directions, both dry and reheat
- 23,5° maximum vector angle
- 110°/sec maximum slew rate
- 20 kN maximum lateral force
- Thermal case: sustained 20° vector in reheat for 5 minutes
- Rapid transients Idle-Dry-Reheat while vectoring
- 100+ performance points run
- Exit area control: 2% thrust improvement
- Endurance: 6700+ vectoring cycles
- Endurance: 600+ throttle cycles

The fully digital control of the nozzle actuators was successfully tested. The control quality (transient and steady state) was excellent in all load conditions. The next figure shows an actuator movement at high load condition.

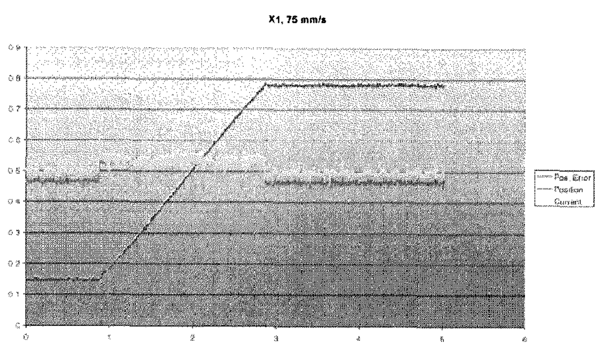

Figure 8: Actuator movement in max. Reheat

The blue line represents the position error (demanded position – measured position) which is 0.5 mm during the whole movement. There is no position overshoot at the end of the movement.

Also the new digital actuator modelling led to excellent results. Despite the fact that the nozzle actuators were supervised with significantly lower tolerances compared with the DECU, no false failure indication was noted during the tests. On the other hand, a loss of an external pump supplying the hydraulic power to the nozzle was immediately detected.

The conclusion of the ground tests in Ajalvir represents the successful conduction of the Technology Demonstration Phase 1. From this point onwards, the next steps taken include a continuation of the development work related to the FADEC, the control system integration taking into account safety aspects and the continuation of the feasibility study with DASA Military Aircraft and ITP.

Additionally, altitude tests with the prototype nozzle are scheduled for mid of 2000 at the Altitude Test Facility (ATF) in Stuttgart.

The next major milestone in the thrust vectoring programme will necessarily be a flight programme, in order to validate the TVN in actual flight.

The Future Modern Thrust Vectored Engine Control

The integration of the thrust vectored engine control with the flight control system is a major issue because the vectoring nozzle – as part of the engine – becomes an active control surface of the aircraft. A suitable interface between the flight control system and the engine control system becomes essential.

The redundant Mil-Bus 1553 between engine and aircraft control units is an excellent prerequisite for this integration.

The ITP thrust vectoring nozzle concept with a common actuation system for all nozzle functions (throat area, exit area and all axis vectoring) is an appropriate solution to meet the stringent requirements concerning performance, reliability and safety resulting from the intended use of thrust vectoring for flight control. The common actuation system means that for example the parameter nozzle area can NOT be controlled independently from the parameter vector deflection. This leads, together with other reasons as described below, to a system configuration as detailed within this section.

The baseline of the control system architecture is shown on the next figure. Principally the system is characterised by the following two major facts:

- The engine is controlled by a single FADEC providing all engine control (including thrust vectoring)
- The FADEC controls thrust and side forces as commanded by the flight control system

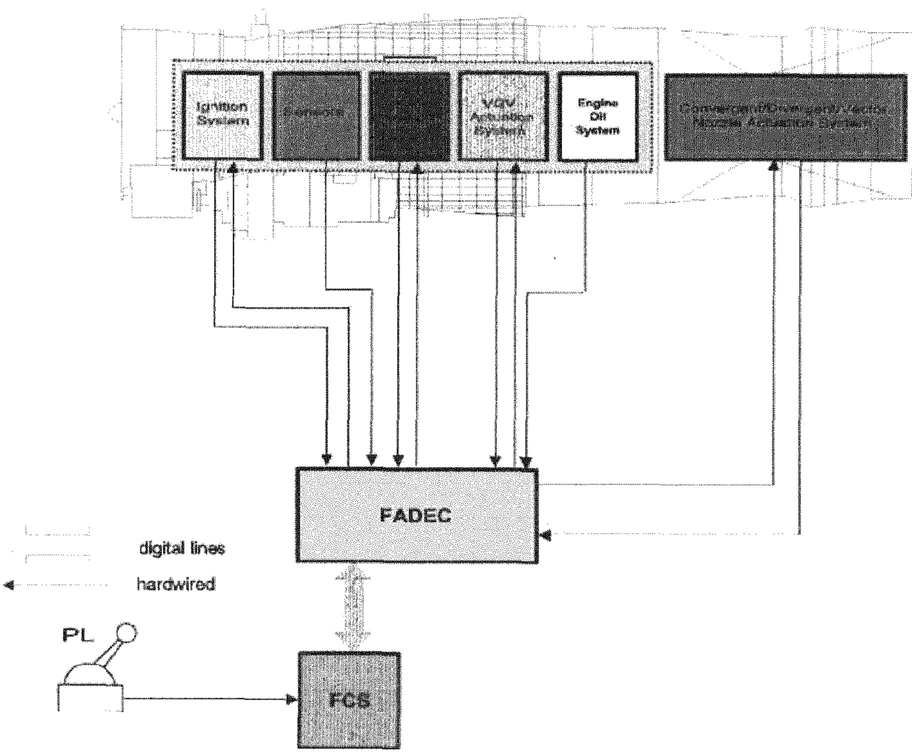

Figure 9: Thrust Vectored Engine Control System, Production System Configuration

The configuration as defined above has a number of advantages:

- Autonomous Engine Configuration
- Simple Interface
- Minimum Interaction FCS – FADEC
- Minimal Weight (minimised cabling, no additional control box)
- Optimum Architecture for Engine and Nozzle Supervisory
- Optimum Architecture for Reaction in Failure Cases (recovery actions)

Interface Flight Control System – Engine Control System

The basic intention is to keep the interface between the flight control system and the engine control system as clear and simple as possible (minimised system interdependency). Engine throttling will be determined by a power lever demand exclusively. Concerning thrust deflection the relevant variables for the aircraft and thus for the FCS are the lateral components (pitch and yaw) of the engine thrust, called side forces, together with their resultant point of attack. The most detailed information about engine and nozzle operating conditions which determine the side forces are available within the FADEC. This leads to the following basic concept for the interface:

FCS -> FADEC

- Power lever demand (PLD) to define engine throttling
- Side forces demand to define nozzle vectoring

FADEC -> FCS

- Current side forces, including point of attack, and thrust
- Maximum possible side forces, taking into account current engine power level, flight condition, nozzle limitations etc.
- Warnings in case of inability to provide required side forces, failure indications

The control loop of the vectoring nozzle system is required to have similar response characteristics as those of the aircraft control surfaces. A frequency response analysis has been performed and showed that the nozzle control system is inline with these aircraft requirements. Two major areas of influence have been identified with this analysis:

- The design of the nozzle control valves
- The synchronisation of the FCS and the FADEC

In case of independent cycle rates of the FCS and the FADEC an undeterministic time delay would be introduced into the thrust vectoring aircraft control with adverse effects on control performance and stability margins.

New Functional Requirements

For a flightworthy thrust vectored engine control additional and enhanced functionality is required compared to the basic functionality of the thrust vector demonstrator with respect to:

- Calculation of thrust and side-forces
- Operational limitations
- Recovery actions for failure cases

On-Board Calculation of side-forces and thrust

The requirement for the integrated thrust vectored engine control, to follow demanded side forces with an accuracy suited for flight control purposes (5% of possible maximum side forces are envisaged) makes the development of an on-board thrust and deflection model necessary.

For non-deflected nozzle the thrust can be calculated with sufficient accuracy from the performance model of the engine and nozzle which reflects the thermodynamic cycle of the engine. The deviation of the real convergent/divergent nozzle in comparison to an ideal nozzle is taken into account by introduction of correction factors for the discharge coefficient and the thrust coefficient.

For deflected nozzle flow phenomena are more complex and thus a simple physical description is not available. A model providing side forces and thrust has therefore to be derived from CFD calculations calibrated by test data. Extensive testing will be necessary to cover all non-linear effects occurring within the operating range of the engine and the multiple-degree-of-freedom vectoring nozzle.

Operational Limitations

Depending on engine operating condition, flight condition and available hydraulic power various limitations for vectoring ranges and rates of the nozzle have to be taken into account keeping forces and temperatures within safe limits. Transient control errors of the actuator control have to be avoided even during high deflection rate vectoring and during simultaneous performing of different nozzle operations.

Recovery Actions for Failure Cases

The most important task of the recovery logic is to avoid any unintended side forces due to failures of the control system. Furthermore limitations of the thrust modulation range should be kept to a minimum.

Accommodation of actuation system failures both involves changes to engine and nozzle control. For most of the flight conditions a centered nozzle is the appropriate reaction in order to maintain engine thrust as far as possible. Nozzle centering in failure cases will have to be initiated by the thrust vectored engine control possibly via some emergency actuation device but A8 control is also effected with significant influence on engine control, as e.g. loss of reheat and limited thrust range.

Further Impacts on the Control System

Thermal Management

Typically fuel cooling is the preferred method for optimum engine thermal management systems. The current EJ200 cooling concept has optimised to the extreme whereby only the fuel consumed by the engine is used, i.e. no recirculation is necessary. The introduction of thrust vectoring introduces additional heat rejection requirements into the system and consequently a different approach to the engine thermal management. This could be, for example, handled by the engine FADEC in controlling the fuel to be returned to the aircraft tank. The temperature of the fuel flow to the burner could be maintained to the maximum possible value to minimise the recirculation flow to the aircraft.

Hydraulic System

The introduction of thrust vectoring can double or triple the requirements for the hydraulic power. The maximum transient requirements, combined with the nozzle actuator loads, cause this significant increase for hydraulic power supply and electrohydraulic servovalve capability. Development work to define an appropriate system architecture (combination of gear and centrifugal pumps, FADEC controlled pressurizing valves) and advances in component technology are necessary to meet the requirements of the hydraulic system.

Conclusions

Successful ground runs with a thrust vectored EJ200 engine have been conducted. The engine control system was enhanced to support this ITP / MTU technology research and acquisition project. The proof of concept for the MTU control system is achieved.

Some of the challenges for a flightworthy solution are already addressed:

- Highly integrated actuator control
- Enhanced actuator supervisory

The ongoing activities are concentrated in

- Supporting engine tests on the altitude test facility in Stuttgart scheduled in mid 2000 and
- The continuation of the feasibility study with DASA Military Aircraft and ITP

The introduction of a thrust vectoring system in Eurofighter Typhoon is currently considered as part of future updates depending on Customer prioritisation of requirements and would take place in accordance with the Eurofighter and Eurojet Partner Companies.

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