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FLIGHT EVALUATION OF THE ATTAS DIGITAL FLY-BY-WIRE/LIGHT FLIGHT CONTROL SYSTEM

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Abstract

An overview of recent development and flight test experiences of the DFVLR's flight test vehicle ATTAS (Advanced Technologies Testing Aircraft System) equipped with a digital fly-by-wire/light flight control system is presented. System design, multiprocessor communication management, parallel data processing, redundancy management as well as software development and validation are summarized.

Further, the role of ground based system simulation for development and testing, flight test procedures and some interesting flight test results are dealt with.

1. Introduction

In the last six years a modern flying simulator and demonstrator aircraft called ATTAS (Advanced Technologies Testing Aircraft System) has been developed by DFVLR and MBB supported by the Ministry of Research and Technology of Germany [1]. ATTAS is based on a MBB developed twin-turbofan, short haul passenger aircraft VFW 614 (figure 1), which is ideally suited for this purpose due to it spacious cabin, test equipment loading capability, flight performances and excellent handling qualities.

Over the next 15 to 20 years ATTAS will serve as the primary DFVLR flight test vehicle for research and development to demonstrate and validate new methods and technologies in the area of flight control, flight guidance, navigation, man-machine interactions and in-flight simulation (figure 2) [2].

In addition to method oriented research application ATTAS provides a wide integration and testing capability for aircraft equipment as it is summarized in figure 3.

Within the DFVLR research programs ATTAS will mainly be used as flying simulator [3] in a broad sense. In this role ATTAS is able to represent the dynamic behaviour of model aircraft or systems under real environmental conditions in total missions providing the pilot with exact visual and motion cues in an early stage of a development. To fulfil all these testing capabilities ATTAS was heavily modified and equipped with a powerful fly-by-wire/light flight control system.

This system, designed by DFVLR, fulfils also the requirements to be very easily adapted to changing flight tests and to give the experimenter clear and simple to handle software and hardware interfaces [4].

The fly-by-wire/light flight control system (FBW-system) development, integration and flight test experiences will be dealt with in this paper.

2. Aircraft Modifications and Equipment

The main aircraft modifications, test equipment and features are summarized as follows (see also figure 4):

- right hand seat safety pilot with conventional control system,
- left hand seat evaluation pilot with full axis fly-by-wire controls,
- freely programmable flight instruments/displays (CRT's) (figure 5),
- fly-by-wire controls/column or sidestick with adjustable force feel system,
- dual channel digital on board computer system with fibre optic data bus providing freely programmable control laws and flying qualities,
- duplex inertial reference and digital air data systems,
- comprehensive on board data acquisition system, recording and PCM-telemetry,
- 15 electro hydraulic self monitored actuators, partly duplex linked by MIL-BUS 1553B to the FBW-system,
- antennas installation provisions,
- dual redundant hydraulic system,

- dual redundant electrical system,

- fly-by-wire motivators for

  - o elevator,
  - o stabilizer,
  - o rudder,
  - o both ailerons (also with symmetrical deflection capability),
  - o both engines,
  - o landing flaps,
  - o six direct lift flaps,

- on board operator consoles (four places),

- nose boom with α, β - and TAS-probe.

2.1. Additional Control Capability

To give ATTAS a 5-DOF simulation capability five independent control surfaces must be available. Therefore, ATTAS was equipped with a specifically developed 'Direct Lift Control' System (DLC) for pitch/heave motion decoupling and gust/load control. For low frequency DLC operation the basic VFW 614 landing flap system can electrically be deflected between 1 to 14 degrees. The rear part of the landing flaps have been divided in six (three on each wing) fast moving flaps having about 85 deg/sec flap rate and ±35 degrees flap deflection capability for high frequency direct lift modulation. Both lift devices can simultaneously be used between 1 to 14 degrees landing flap position. Further, DLC flap pairs can be individually controlled. The total DLC heave modulation capability is $\pm 0.27\ \Delta c_L$. The permissible flight envelope is shown in figure 6 demonstrating that DLC can also be used in the high speed region up to 285 kts.

Another important feature of the ATTAS FBW-system is the superimposed symmetrical aileron actuation capability which will be used for wing bending mode control. Because the ailerons are mechanically connected in the basic aircraft's flight control system, the symmetrical aileron deflections are compensated on pilot's wheel by using a differential gear.

2.2 Data Aquisition System

The aircraft is equipped with all sensors which are necessary to measure the aircraft body rates, accelerations and attitudes as well as all control surface positions, pilot command inputs and engine data. Air data are calculated by two air data computers, inertial data by two laser gyro inertial reference units (LTN 90). Analog sensor outputs are conditioned (amplified, filtered etc.) in a DFVLR developed signal conditioning system. A very important feature of this system is that all parameters for each channel can be set, checked, and electrically calibrated from an on board master computer (figure 7).

2.3. Electro Hydraulic Actuators

The electro hydraulic actuators have been developed for ATTAS by Liebherr Aerotechnik, LAT, in Germany.

In total 15 self-monitored high bandwidth actuators are used to drive all the motivators mentioned above.

The actuators are installed in parallel to the basic aircraft control system. They are linked by integrated electro hydraulic actuated clutches which can be opened in any situation by pressing a switch on the safety pilots control wheel or by introducing a certain amount of force in safety pilot's controls.

The actuator electronic is fully digital using duo-duplex microprocessor configuration for failure detection and failure handling. The complete actuator electronic is included in four boxes. Data communication with the FBW/Light computer system is realized by a duplex MIL-BUS 1553B as it is shown in figure 8. Due to safety reasons elevator and rudder actuators are doubled providing duo-duplex failure behaviour. For DLC control surface redundancy was applied by using three independent pairs of DLC flaps which are in addition monitored by a separate device as it is shown in figure 9.

2.4. The Fly-By-Wire/Light Control System

The Fly-by-Wire/Light Flight Control System as heart of ATTAS has to provide all operational functions needed for

- normal fly-by-wire operation (control laws, mode switching),

- interfacing external devices,

- data processing and recording,

- monitoring and error detection,

- computation of experimental functions.

The performance has to meet the requirements for

- computational cycle time of less than 20 ms for all functions,

- required redundancy for flights in critical manoeuvres (take off and landing etc.),

- airborne equipment and interfacing of aircraft systems (ARINC 429, MIL BUS 1553 B, etc.),

- freely programmable capacities for user applications in a high order programming language.

To meet these requirements the system has been designed as a two channel computer network consisting of four processors in each channel with one common central processor for communications and data recording (figure 10). All on board computers are of MIL-Spec. LORAL/ROLM types (MSE/14 and Hawk/32) which are software compatible to the commercial Data General Eclipse S/140 and MV/8000 series [5].

The network in each channel is based on a ring structured serial fibre optical bus system providing actual data rate in each channel of 150 kWords/sec. The theoretical data BUS performances of the installed systems are compared in figure 11. Network redundancy is used for failure detection by comparing exchanged input and output data. In the case of exceeding given amplitudes and time thresholds the system will be passivated and enabling the safety pilot to convert to the basic aircraft control by providing smooth transients. Software is identical in both channels.

The data processing system operates A/D converters and digital input/output, interfacing the signal conditioning system, the ARINC 429 BUS connected to the air data computer, inertial reference and avionic systems, as well as MIL BUS 1553B for data exchange with the actuator electronic units (AEU). In total more than 400 input and 300 output signals are processed in each channel.

The computational power of the system is about 3.1 Mega Floating Point Operations (MFLOPS) in each channel. 1.4 MFLOPS are available for experimental functions in the Hawk/32 32-bit computer with up to 8 MB of memory.

System and software design allow an easy system integration of experimental functions and additional hardware components.

2.5. Fly-By-Wire Control Functions

Operation of ATTAS is performed in the following three principal modes, as illustrated in figure 12:

- BASIC Mode
- Fly-By-Wire Mode (FBW-Mode)
- Simulation Mode (SIM-Mode)

In the BASIC Mode ATTAS is operated using the basic mechanical controls of the safety pilot on the right hand seat in the cockpit.

In this mode of operation ATTAS is used for all the experiments in which electrical flight control is not required. Nevertheless on board computation, data aquisition and data recording capability is fully available.

In the FBW-Mode the evaluation pilot on the left hand seat has control to the FBW-system by connecting the electro hydraulic actuators to the basic aircraft control system. Flight operation will be performed identically to the basic controls (FBW 1:1 function). Figure 13 illustrates the FBW control functions installed for the elevator as an example.

In the SIM-Mode the aircraft also operates under fly-by-wire control but the functional connection between pilot inputs and actuator commands are given by user defined functions such as used for in-flight simulation control laws (IFS) where the evaluation pilot flies an aircraft model built in the computer program. Model following control laws generate commands for all the actuators to force the test aircraft to follow the on board computed equations of motion.

Primarily the fly-by-wire system provide control functions for the actuators of the primary controls

- elevator,
- ailerons and
- rudder,

and the secondary controls

- stabilizer,
- engines,
- landing flaps and
- DLC flaps.

Further, special functions for mode switching and for minimizing transient effects based on mode switching are provided.

For electro hydraulic actuator engagement a coincidence function moves the actuator piston into the relevant position before clutches are closed.

Limiter functions reduce the actuator command signals in maximum rates and amplitudes according to safety and flight conditions.

An automatic elevator trim system operates the stabilizer in such a way that the aircraft is always in trim condition. In cases where the safety pilot reconverts to the basic control system the resulting column and aircraft transients will be negligible.

Evaluation pilot's displays and instruments are controlled by the FBW-system to represent standard symbology (FBW-Mode). In the SIM-Mode display representation is freely programmable due to user purposes. For system checkout and preflight check procedures special functions are included in the FBW/Light software program.

2.6. ATTAS Simulator

Essential part of the total ATTAS is the ground based ATTAS simulator (figure 14) which was designed and developed in parallel to the aircraft. The ATTAS simulator is a complete copy of the flying system simulating all system functions in real-time on the ground. This facility is the primary tool for software and functional testing.

Further, the simulator assists the ATTAS operation by validating user applied software (experiments) and by preparing flight test procedures. The ground simulation consists of an identical ATTAS cockpit, a nearly identical computer configuration based on commercial Data General computers which are software compatible to the LORAL ROLM on board system, a hybrid computer EAI 600 and the high speed multiprocessor system AD 10. These both computers simulate the complete aircraft flight dynamics, actuator response as well as engine and sensor informations of the aircraft. All sensor data are connected to the ground based FBW-system via connector identical interfaces (A/D, D/A, ARINC 429, MIL-BUS 1553B), so that flight test hardware can be plugged into the simulation. By this all in-flight computer programs can be developed and checked out on the ground under real time conditions before they are transferred via magnetic tape on board the aircraft. Further, for 'hardware in the loop' simulation and testing purposes ATTAS can be linked with the ground simulator via fibre optic bus extension while standing on the ramp or in the hangar. This situation is illustrated in figure 15.

3. Software Development and Data Handling

According to the ATTAS equipment with a central FBW-system software development was a main project of about 60 man years at DFVLR [6]. Organization problems had to be solved while 10 developers worked on the project at the same time.

Software development was organized in a 'top down' stepwise method. System development must be considered for hardware and software together. So from the beginning of the system design software functions were analyzed and designed in parallel to the hardware design in progress. With the structure of the data processing system the functional structure of the software was defined and resulted in the Software Requirements Document (SRD).

Mainly the involved subsystems and their interfaces (ARINC, MIL BUS 1553B) specified the requirements to be fulfilled by the software. Also user requirements for minimum controller cycle time and computing power with reusable software had to be considered.

3.1. Software Structure

According to the design of the data processing system three main software functions can be identified to be embedded in the computer network:

- Input/Output Operations (Terminal Computer Functions)
- Fly-By-Wire and Experimental Functions
- Communication Functions with different subsystems

Input/Output Operations are installed in the Cockpit and Tail Terminal Computer (CTC, TTC). They include the interface drivers, data checks with the second channel, scaling and data communication to the parallel processors in the network. According to these functions the program structure is fully sequential with one interrupt level (figure 16). The interface sampling cycle time achieved defines the minimum cycle time in the total system. Therefore, optimization had to be done to reach the margin of 20 ms as maximum cycle time in program flow. Synchronization of all components is done with a Programmable Interval Timer (PIT) interrupt in the cockpit terminal computer program.

Fly-By-Wire Functions are mainly installed in the FBW Computer (FBWC) to fulfil all operations of the FBW control law. The software structure has to consider timing requirements and switching problems. Special monitoring functions take control of program flow in three priority task levels with different cycle times. A special SUPERVISOR modul is installed to control system states and failure detection in the total system.

User functions are installed in the Experimental and Control Computer (ECC) to give free space and full performance for experimental programs. With the chosen program structure user programs can be included without changes in the operating system and the runtime structure.

Communication Functions include the interfacing to the telemetry system, data recording on magnetic tape, quicklook presentation on displays, program loading and offline handling. Non-standard interfaces to experimental devices are also realized. These functions are not essential for fail passive behaviour of the FBW control system, therefore these functions are installed in the single Central Communication Computer (CCC) which communicates with all computers in both channels in the duplex data processing system (figure 10).

The program structure is sequentially designed with high speed periodical operations in the foreground and slow, time consuming operations in the background.

3.2. Software Development

Handling the ATTAS software project as a medium size project and the requirement to maintain the system for at least 10 to 15 years special procedures and tools were mandatory.

The TOP DOWN design method was used in 6 steps. Each step ended with a review on the final documents:

(1) Software Requirements Document

(2) Software Design (rough) Document

(3) Software Detailed Design Document

(4) Coding and Modul Testing Source Code

(5) Integration and Verification - Program Test Results

(6) Validation (Ground and Flight Test) - System Test Results

Test requirements had to be developed in step 1 to 3 as part of the design, giving the opportunity of checking programs in further steps against the requirements.

The ATTAS software has been built using ROLM's Advanced Real Time Operating System) (ARTS) for real-time control and high order language implementation (FORTRAN). Assembly language has been used for interface driver coding.

Software development was done on the ATTAS ground based data processing system using a super mini computer MV/6000 of Data General.

Though the development system with the Data General's Advanced Operating System / Virtual Storage (AOS/VS) is functional software compatible with real time operating system (ARTS) check out for many functions could be done offline. The fibre optic connection between the development and the target system gave the advantage of down loading developed code into the target processor from the same workstation as (illustrated in figure 15) used for offline operations.

3.3. Software Test and Validation

The test concept for ATTAS software development was applied in two phases:

- Modul Test

- Validation

Offline tests are required for any modul used in different programs. This is fulfilled with test programs to be run on the development system where also the test results are recorded. Modul tests concerning the target systems interface drivers are also used in 'stand-alone' programs on the target processor with good capability for interface system tests. Identical software modules are used in test programs during check out as well as in the real-time ATTAS software.

The design of the ATTAS ground system followed the idea of testing all software functions of the target system in the ground simulation. Besides the capability of testing interface moduls the major advantage is that validation tests can be performed on the ATTAS ground system prior to the on board system.

Test functions generating command inputs are available to be recorded with all data available as measured inputs or program outputs. Identical software test procedures are used in 'firstflight' and 'preflight' tests in the aircraft.

Operating the ground based cockpit in connection with the aircraft simulation all evaluation pilot operations can be trained and checked to obtain adequate flight test results.

3.4. Data Handling

PCM signal recording and transmission to the ground station with the telemetry system is available. Besides this data recording is done on a digital magnetic tape (800 bpi, 75 inch/sec) attached to the data processing system.

The format of data recording is the same as the data format used in the computer system. Integer format for bit and logical information and floating point format for continuous signals are used. In the magnetic tape header informations for signal identification, signal form and frequency as well as format parameters and user informations are recorded.

Based on the header information a magnetic tape with raw data can be processed in the ground system converting the data into a format to be exploit on the main frame computer system. A standard evaluation program, DIVA - a dialogue interpretation program - is used for data analysis providing time history plots and frequency correlation functions (figures 18 to 20). All the flight test results in this paper had been processed with this program package.

4. Ground and Flight Tests

Special test procedures were evaluated for ATTAS according to the basic aircraft maintenance and test instructions. The ATTAS test concept therefore devides into two phases, 'Ground' and 'In-Flight' tests.

Standardized ground tests are performed in periodical intervals or in preflight checks. In-flight tests are normally included in the evaluation program for user flight tests.

4.1. Ground Test Requirements

The ground tests are performed as so called 'Firstflight' and 'Preflight' checks.

For both special test procedures are put down as 'Ground Test Requirements' documents, GTR's. For Preflight checks the data processing system is involved in all parts needed for fly-by-wire control functions. The program functions cover all modes and switching conditions to obtain full scale of test conditions. The GTR's give detailed information how tests have to be performed and how they fit in the basic aircraft checks and operations.

Firstflight checks are also defined in GTR documents organized in different parts to check out single components of the equipment independently. The software for interface tests is used in this case to check ATTAS components including the computer interfaces, wiring, measurement equipment etc. Another advantage of using the on board computer system in check out procedures results in data recording and presentation. Quicklook functions on displays are available and of course both, hardware and identical software is checked in connection.

4.2. Flight Test Results

The FBW control system acceptance and validation flight test program carried out in 1987 covered the mode switching functions, flight control functions, switching transients, recovery procedures due to actuator hardovers, failure mode evaluation and the fly-by-wire operation in general. Switching and transient functions occuring by switching between FBW- and BASIC-mode operation have been of main interest.

Therefore, the FBW-mode was switched off during various aircraft manoeuvres such as steep turn, high roll rates, pull ups, during landing flap operations with and without the auto stabilizer trim system. An example of the resulting transients during FBW-off switching is shown in figure 18 demonstrating smooth transient response, which was very well accepted by the safety pilot.

The FBW operation was tested throughout the complete flight envelope, which is presently limited to a minimum altitude of 500 ft above ground due to safety reasons.

Aircraft control behaviour and control system response was evaluated by pilot induced high frequency inputs. A typical result is shown in figure 19 where the aileron was excited. Due to the complete measurement of different elements of the control system a detailed analysis is possible. Test results of figure 19 show precise aileron response at a frequency of about 1.7 Hz and a time delay of about 25 ms.

4.3. System Identification

In addition to the more qualitative control system evaluation mentioned above special flight tests were carried out to get precise information about the actuator dynamic behaviour in order to develop adequate actuator dynamic models for simulation purposes. To get the actuator response data all actuators had been excited in flight by computer generated stepwise inputs in a 3-2-1-1 time sequence with different amplitudes. Maximum likelihood methods were used to get the right parameters of the actuator model fitting the measured time response.

A typical result is shown in figure 20 [7] where the modelling of the DLC-flap system is represented. This figure shows the nonlinear behaviour of the actuator system and the required order of the dynamic model to match the actuator response. As it is seen a good match is only given if a second order model with rate and deflection limitation is used especially for large control inputs.

5. Conclusions

The flight control concept designed and developed for ATTAS proved as suitable and effective to fulfil the requirements of a powerful and flexible testbed for research applications as it was demonstrated in flight.

The decision to develope a complete ATTAS real-time simulation system for software development, testing and flight preparation turned out as very effective by shortening ground and flight testing effort. Our experience showed that flight software being validated in the ground based simulation under real-time conditions proved as very reliable in flight. All design errors and failures had been detected and corrected at least in the ground based validation process so that from flight tests no software changes were required.

The on board computer configuration comprising five fibre optic linked MIL-Spec. minicomputers worked very reliable. No problems with the fibre optic data bus occured.

Further, the software development concept and software development system configuration choosen for ATTAS development and operation was very well accepted by software design engineers and programmers.

Using a high order language for real-time processes was a big help for software quality assurance.

Main improvements for the future are seen in computer aided software development methodology and related tools to improve mainly system/software specification and software maintenance.

6. References

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Figures

Figure 1. ATTAS in flight

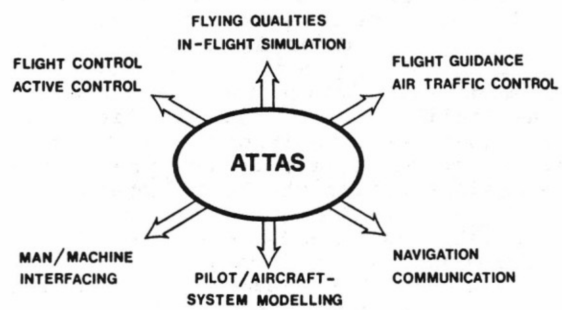

Figure 2. ATTAS R & D utilization

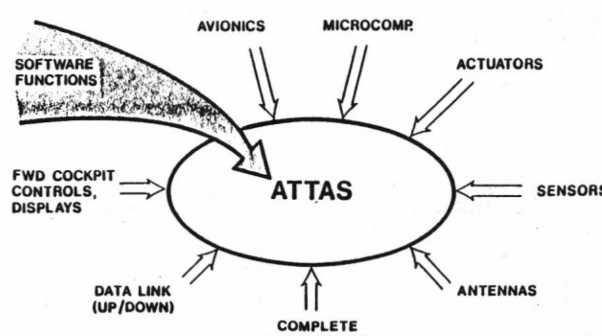

Figure 3. Hard-/Software testing capability

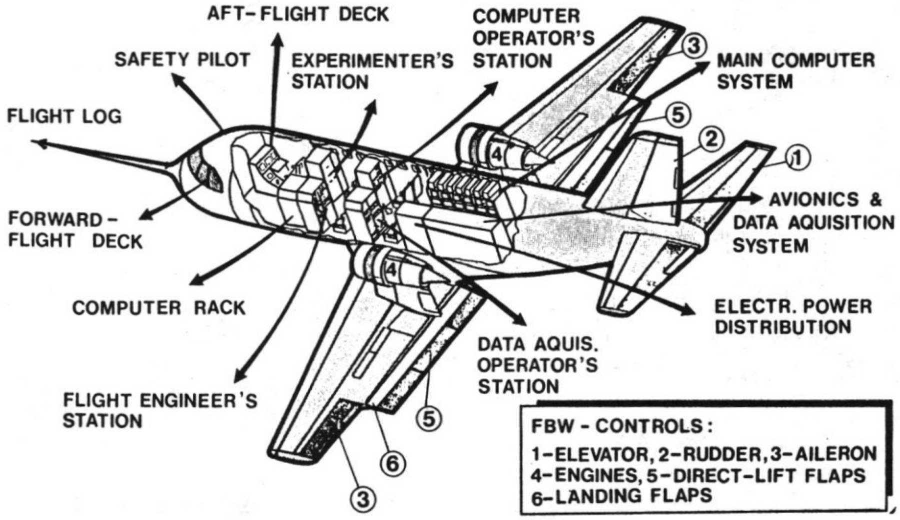

Figure 4. ATTAS modifications

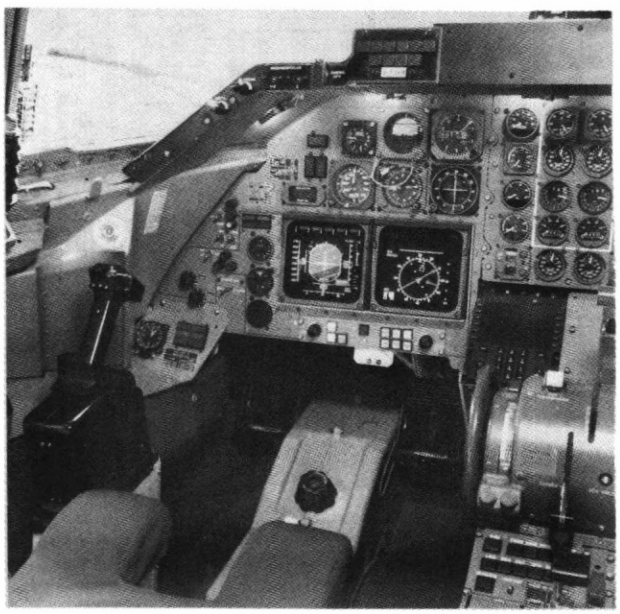

Figure 5. Cockpit instrument panel

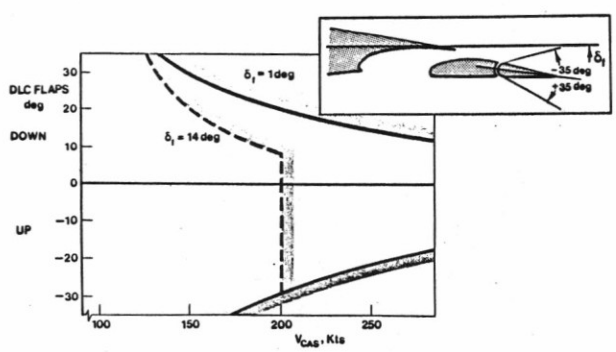

Figure 6. Direct lift control flight envelope

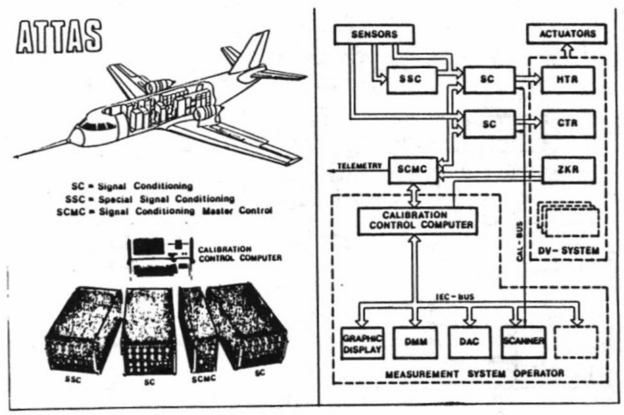

Figure 7. Data aquisition system

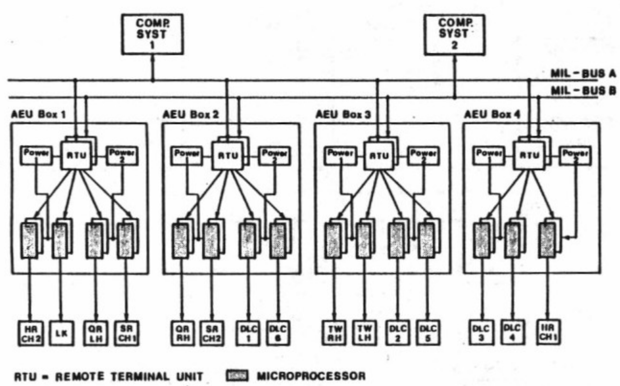

Figure 8. Actuator electronic units

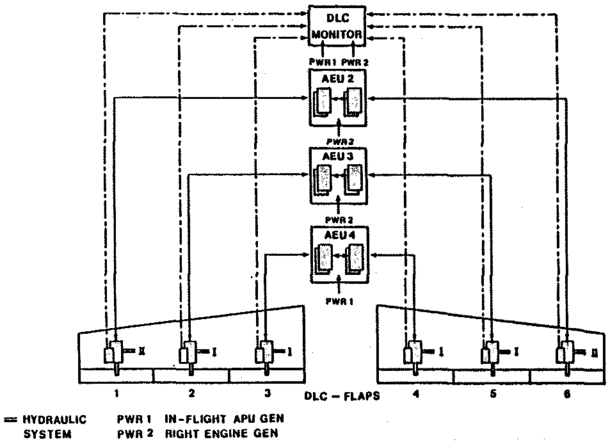

Figure 9. DLC redundancy concept

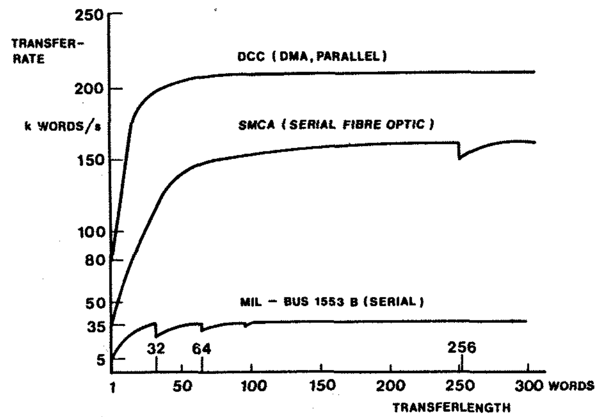

Figure 11. Data bus performances

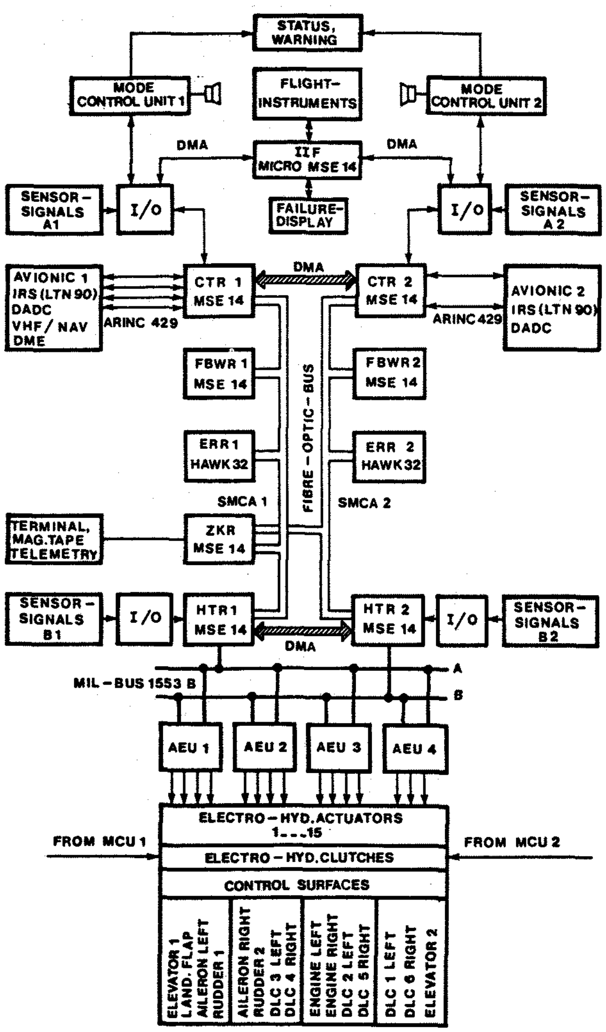

Figure 10. ATTAS dual redundant fly-by-wire/light flight control system

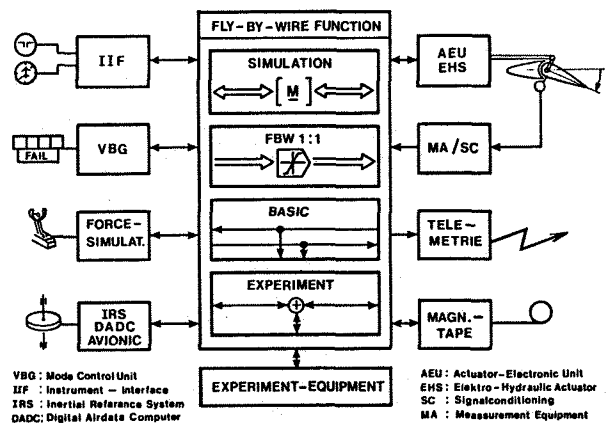

Figure 12. Fly-by-wire control functions

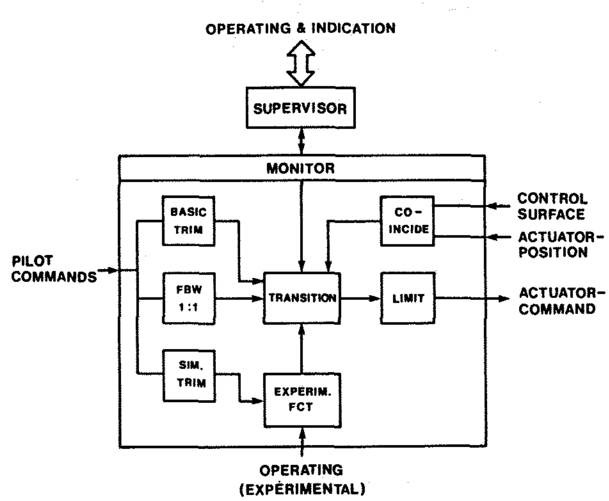

Figure 13. FBW function for elevator control

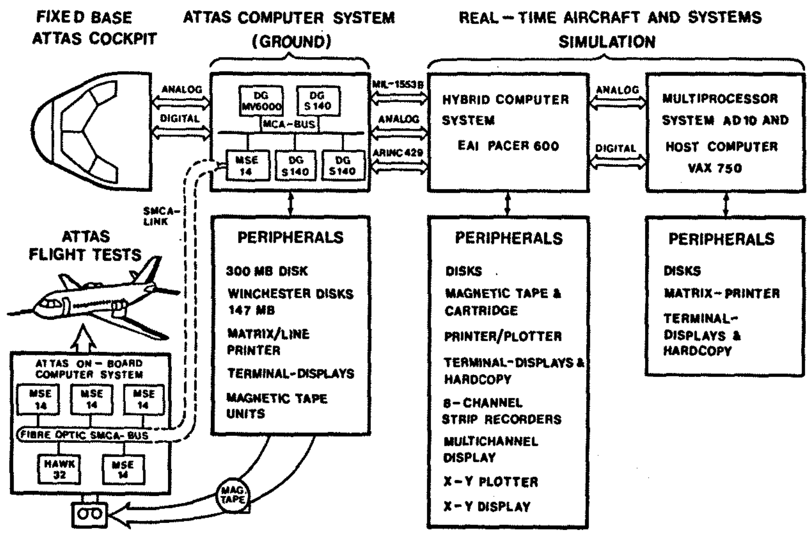

Figure 14. ATTAS ground based simulator

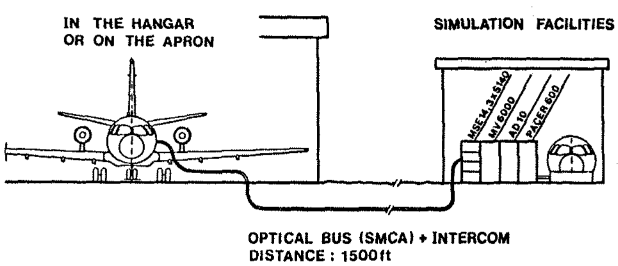

Figure 15. ATTAS fibre optic link to ground based simulation

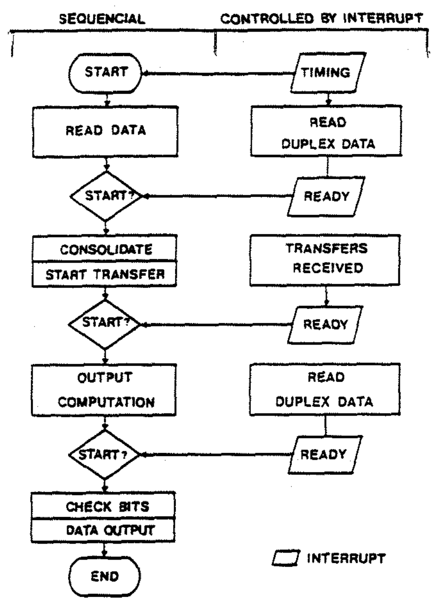

Figure 16. Software structure in data processing system

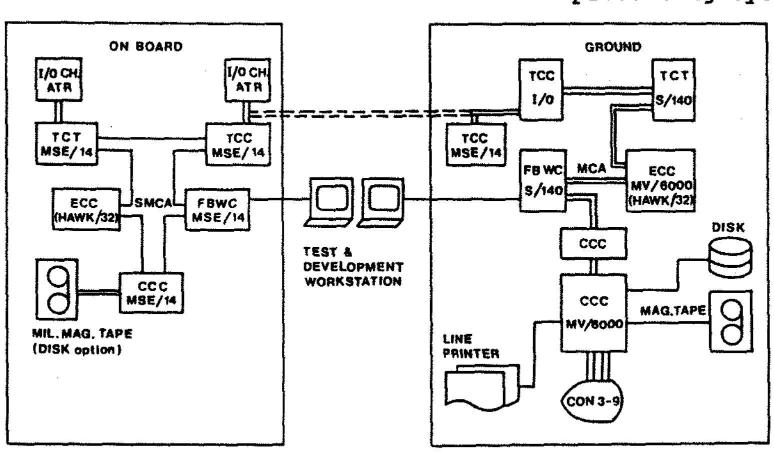

Figure 17. Software development system overview

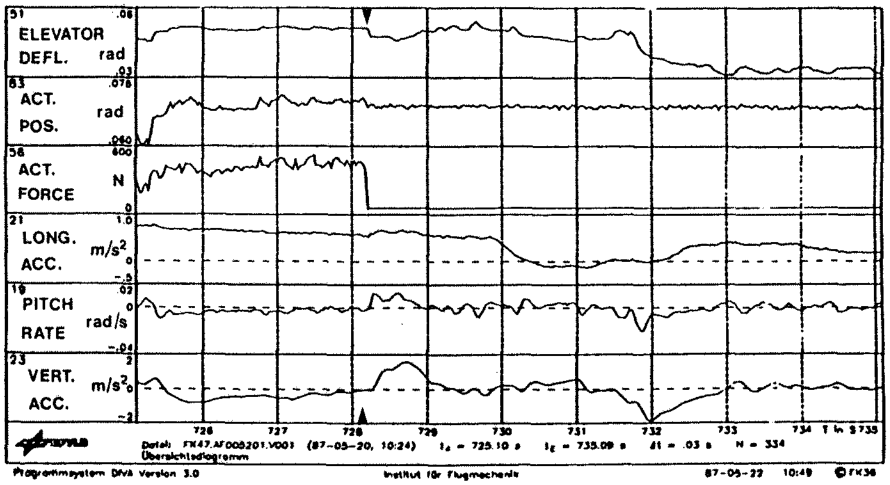

Figure 18. Transient functions histograms

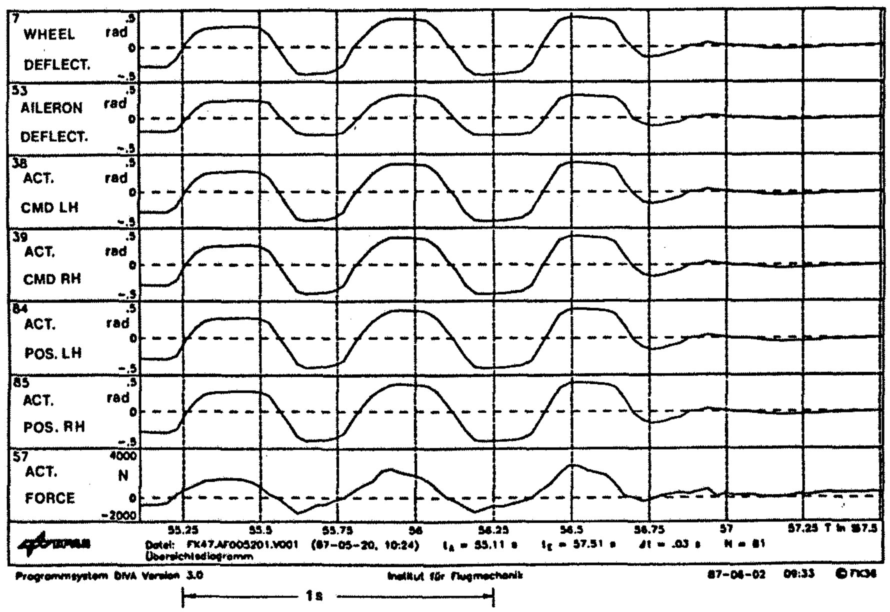

Figure 19. Aileron control system frequency response

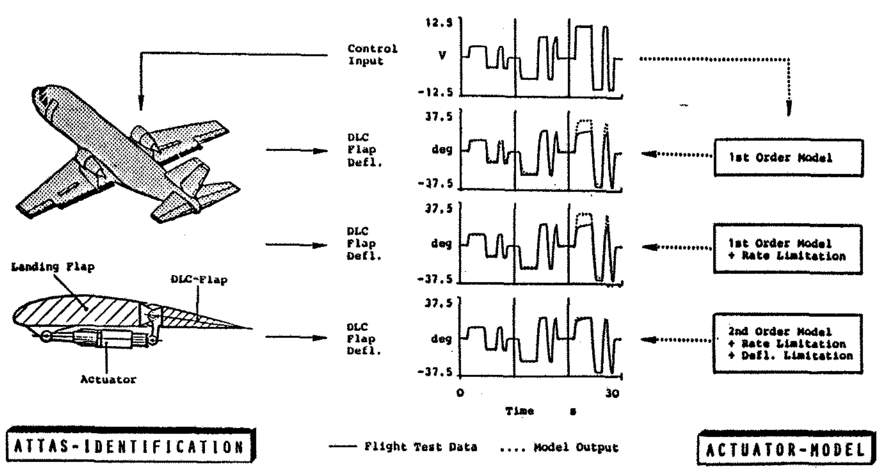

Figure 20. DLC flap system identification results