FLY-BY-WIRE FOR THE SAAB 2000 CONCEPT, DEVELOPMENT AND TESTING

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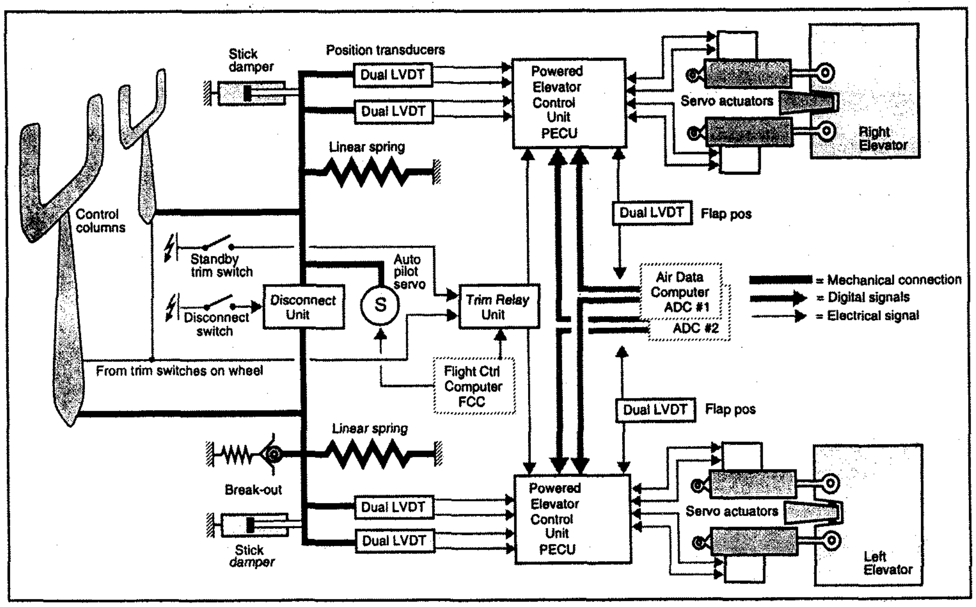

Fig 1. PECS configuration

The SAAB 2000 Jetprop is a modern high-performance turboprop designed for short and medium haul of 50-58 passengers at near jet speeds. The aircraft received its type certificate in March, 1994.

The flight controls were to be of a mechanical type except for the rudder. During the initial development stages it was discovered that longitudinal stability and control were inadequate in some corners of the envelope. A decision was then taken to develop a simple but reliable Fly-by-Wire pitch control system.

This paper describes the system concept, design philosophy, testing methods and certification process of the new flight control system called Powered Elevator Control System (PECS). It also discusses the use of special task forces for a more efficient development process.

The pitch flight control system was to be simple, reliable, and easy to install and maintain. In addition it was to use existing aircraft sensors as far as possible. Since the short period stability of the aircraft was adequate, no augmentation was required for that mode, and only the long period stability modes were to be improved. The Fly-by-Wire concept was chosen to reduce weight and maintenance time, and to simplify the design. The concept was based on the powered rudder control system (RCS) used on the original design without remarks.

Introduction

During the first year of development flight testing, the aircraft systems were being improved in order to meet all the certification and customer requirements. As in all new projects, problems were encountered and compromises made. One of these areas was identified as the pitch stability and control in the extreme corners of the proposed flight envelope.

An intense design effort was followed by a flight testing period to try and extend the Mechanical Elevator Control System (MECS) flight envelope. As the certification period was reached it was assessed that MECS would meet all the requirements but within a limited speed and c.g. envelope.

These operational and economical penalties were assessed as short term marketing "show stoppers" and a solution was needed.

It was made clear by previous tests that a new design was needed in order to meet the original design requirements. Saab management specified a system that could be designed, tested, certified and delivered to the customer within 18 months. In addition the system was to be economically affordable (since the customer was not expected to pay more) and be possible to retrofit on the fleet of aircraft already in service.

Task Force Concept

As the design task was somewhat challenging it was decided to form a Design Build Team (DBT) that would include all the necessary design functions in order to develop, qualify and install the system within the given time. Within the DBT the following subgroups were formed:

- Systems
- Structural, mechanical design and installation.
- Electrical wiring installation.
- Development Test Team (DTT) (active during development flight testing).

The DBT main group - which included representatives from each subgroup - had weekly review meetings where the progress and problems could be evaluated and appropriate actions taken. Risk assessment was continuously performed and "bottle-necks" given priority to ensure certification on time.

Design Philosophy

System function and requirements

The system architecture is based on the Rudder Control System (RCS) used without remarks on the aircraft already in service. As the certification basis was the existing FAR/JAR Part 25 rules, it was decided to make the system fully conventional in terms of pilot handling qualities. To deviate from the existing certification rules and design the system using C* or similar control laws would require "Special Conditions" to be negotiated with the certifying authorities which could be time consuming. The system is conventional but utilizes electrical, in lieu of mechanical, cables.

The system is designed to provide the following functions:

- Artificial stick forces.
- Stick-to-elevator function with a variable stick-to-elevator gearing as a function of Indicated Airspeed (IAS).
- A serial trim function with a variable trim rate as a function of IAS.
- Stability augmentation based on IAS, load factor (N_Z), and flap position.

The design requirements that generated the system architecture and redundancy were the following:

- The probability for total loss of function (no stick-to-elevator control) be less than 10^{-9} per flight hour.
- The probability for an elevator hardover or runaway be less than 10^{-9} per flight hour.

- The probability for loss of damping (flutter risk) on one elevator surface be less than 10^{-9} per flight hour.
- The probability for loss of stability augmentation on one elevator surface be less than 10^{-5} per flight hour.
- System retrofit capability.

Artificial Feel System

As there is no feedback to the pilot from the aerodynamical elevator surface hinge moments, an artificial feel system that provides stick forces to the pilot was necessary. The system provides a breakout around neutral column position plus a linear force as a function of column position. The system uses a spring and cam for the breakout force and a torsion bar for the linear force. As the forces do not change as a function of the flight condition, a stick-to-elevator gearing as a function of IAS is implemented in the Powered Elevator Control Unit (PECU) to give the pilots an approximately constant stick force per g over the entire flight envelope. In the event of loss of all valid IAS the system will revert to a fixed gearing that is a compromise between the slow and high speed flight conditions.

Trim and stability augmentation

The trim function is implemented as a serial trim with a trim rate that is a function of IAS. In the event of loss of all valid IAS the system will revert to a fixed trim rate.

In order to fully comply with the FAR/JAR Part 25 requirements in the full c.g. envelope, stability augmentation in the following areas are required:

- Improved Static Speed stability (F_e/V). The augmentation is based on IAS as measured by the Air Data Computers (ADC).
- Increased stick force per g (F_e/V). The augmentation is based on normal load-factor (N_z).
- Reduced aircraft pitch response at flap extension and retraction. The augmentation is based on flap position.

The basic short period stability was sufficient and did not require any augmentation.

System architecture

The system is divided into two identical but independent sides, one for the left elevator surface and one for the right elevator surface. The only communication between the left and right side is the mechanical link between the left and right control columns. A schematic of the system is shown in Figure 1 (page 1).

In the event of a mechanical jam on one of the two sides a disconnect function is provided. When disconnected, the left and the right columns can be operated independently. In order to meet the flutter requirement two hydraulic servo actuators are installed on each elevator surface. One actuator is fully sufficient to control the elevator over the full flight envelope. One actuator with functional damping is sufficient for flutter protection beyond max. Dive Speed (V_D). Safe flight and landing can still be performed with three actuators in damped mode and only one remaining functional.

Each elevator side has one electronic PECU which provides control of two hydraulic servo actuators. The PECUs are installed in different compartments to provide maximum physical separation. Each PECU is divided into two Servo Actuator Channels (SAC) where each SAC provides control over one servo actuator. Each SAC has its own power supply and can operate independent of the other SAC. The SAC has two lanes (primary and secondary) to provide cross-lane monitoring for fault protection. The basic stick-to-elevator function is implemented using analog circuitry. Each SAC has two micro-processors, the primary processor and the secondary processor which are of dissimilar hardware and software.

The primary processor provides the following functions:

- Stick-to-elevator gearing computations for the primary lane.
- Computation of SAC local trim and stability augmentation commands. The local commands are cross-SAC monitored for failure protection.
- Preflight Built-In Test (PBIT).
- Input and output communication with the aircraft via ARINC 429 data busses.

The primary processor in each SAC computes a trim and stability augmentation command which is added in series to the control column command. For monitoring purposes the trim and stability augmentation command is cross-SAC monitored both before and after D/A conversion. A miscompare will disable the function. The secondary processor can provide a backup trim function in the event of a primary processor failure.

The Secondary processor in each SAC provides the following functions:

- Stick-to-elevator gearing computations for the secondary lane.
- Interlock for PBIT to prevent inadvertent PBIT in flight.
- Input communication from the aircraft via ARINC 429 data busses.
- A backup trim function in the event of a primary processor failure.

The column position is sensed by two dual Linear Voltage Displacement Transducers (LVDT) per side. The position LVDTs are installed below the flight deck floor close to the column force torsion bars.

For detection of dormant failures a Preflight Built In Test (PBIT) function is implemented. PBIT is automatically initiated before each flight and consists of an internal check of all PECU monitors and an active drive test of the servo actuators.

The system status for failure annunciation and maintenance information is transmitted from each SAC to the aircraft Data Concentrator Units (DCU). The DCUs will then annunciate failure messages and store maintenance information in non-volatile memories.

Actuator design

The actuators have two modes of operation - the normal active mode, and the damped mode which is the failure mode. In normal operation the actuators are all in the active mode (active/active). To solve the problem of force fight between the two active actuators, the servo actuator main control valve is of the PQ type (Moog manufactured and patented) with pressure feedback to reduce the pressure gain (psi/mA) of the actuator main control valve. The same concept was previously used very successfully on the SAAB 2000 RCS.

Hydraulics

Hydraulic supply to the servo actuators is provided by three separate hydraulic systems. Systems 1 and 2 pumps are engine driven with electrical standby. System 3 is pressurized by a continuously running electrical pump, and is dedicated to PECS, with no other user. System 1 supplies the left outboard and the right inboard actuators. System 2 supplies the right outboard actuator, and System 3 supplies the left inboard actuator.

Electrics

AC power is supplied by two engine driven wild frequency generators and one APU driven generator. DC power is generated by three Transformer Rectifier Units (TRU) that provide power to the on-line DC busses and also charge the batteries. Emergency DC power in the event of total loss of AC power is provided by four batteries. The batteries can provide DC power to the required electronics for safe flight for at least one hour. In the event of a loss of both engines and the APU, i.e. fuel starvation, the batteries can provide power to the required electronics and hydraulic System 1 DC pump for at least 25 minutes. As the maximum gliding time from maximum altitude (31000 ft) is 23 minutes, the system will give the pilots a functional flight control system all the way down to ground level.

Testing Methods

In order to meet the target dates the testing process was planned in detail allowing for one or two iterations due to flight test results. The majority of the people involved in the design phase were also involved in the testing team thus allowing for real time decision making.

The testing methodology was based on the following plan:

- Update the development simulator to the new configuration and perform an intensive development test series.
- Evaluate the critical dynamic phases of the flight using the Calspan in-flight simulator and make changes if needed.
- Perform closed-loop simulations and failure case analysis using the fixed base simulator and the hydraulic rig with the prototype hardware and software.
- Perform initial envelope opening flight tests in a safe but accelerated program.
- Collect aero-data in order to update the fixed base simulator.
- While waiting for the final software, update the simulator and repeat the simulator development testing and certification runs in order to discover deficiencies.
- When all simulator and software testing is completed commence pre-certification and certification flight tests, to include also airfield performance testing, ice testing and failure case evaluation.

Introduce a second prototype as soon as the flight control system configuration is frozen in order to speed up certification.

Development

Based on wind tunnel research, analytical methods and the experience from the MECS aircraft, the basic variables were determined and implemented into the control system as aircraft hardware and flight control software.

Since the aircraft's basic problem was the hinge moment problem in the spring tab elevator system, it was determined that the non-reversible powered elevator would eliminate the control force deficiencies and improve the short period stability (due to the non-floating elevator).
The major area of concern was how to achieve a system that, using simple control laws, would produce control characteristics that meet the requirements, and produce satisfactory flying qualities over a wide c.g. range.

After passing the control system gains and scheduling through the usual analytical static and dynamic tests, it was essential to test the system with the pilot in the loop. For this purpose a limited task simulator is a good tool if combined with in-flight simulation testing in a realistic environment.

Fixed Base Simulator

The development flight simulator is a fixed base cockpit with a three-screen, high resolution visual system. It is equipped with partial cockpit instrumentation and full dual pilot primary and secondary cockpit controls.

Since the new elevator control system relied on a precise control feel system (springs, dampers and mechanical cams) it was decided to install the real aircraft hardware. This allowed the test team to develop an optimized feel system long before the aircraft was flown. Since lead time in production of aircraft hardware tends to be long, this process reduced the risk for last minute changes to aircraft hardware.

A systematic matrix of flight conditions was evaluated using a few chosen sets of flight control parameters. The tests were repeated with 4-6 test pilots and a few pilots less involved in the project. The pilots rated each task of the simulated flights which included normal and extreme configurations, calm and stormy weather and a variety of failure conditions.

At this stage the first flight control law configuration was frozen.

The steady state conditions showed reliable results and were a compromise between the long term speed stability at the extreme aft c.g. and the control authority limitations at the max. forward c.g.

Like any fly-by-wire system, the control law included delays and lags. Despite satisfactory rating in all flight phases in the simulator, and based on previous program experience, two areas of concern were raised.

The first was the dynamics of the electronic bob-weight in quick pilot reversals and in real "g" environment.

The second was the pilot response to the non-linear gearing between the control column and the elevator movement on a high gain task like precision landings .

In order to evaluate such behavior, manufacturers usually modify an existing aircraft with the new flight control system and evaluate it in flight prior to the first fully integrated prototype. Such was the case at Airbus, Boeing and almost all military projects. Since there was insufficient time for such a process, and since the system was designed to be as simple as possible, an alternate method was required.

Based on previous experience with in-flight simulation the potential of such a simulation was determined sufficient and flexible enough for our program.

The chosen simulation tool was the Calspan Lear 25 Variable Stability aircraft.

<u>In-Flight Simulation</u>

The Calspan test aircraft was programmed to simulate the characteristics, response and control feel of the SAAB 2000. In order to make the process efficient, only two critical flight conditions were simulated and only 4-5 flights were planned. The onboard equip-ment allowed for real-time changes to be made and tested in order to find the optimized solution in actual high gain piloting tasks. This tool is the safest method for determining the risk for Pilot Induced Oscillations (PIO) without taking the risk of the PIO getting out of hand (the system disconnects when reaching certain limits). It allowed us to perform landings in gusty conditions and excite the system down to touchdown.

Two deficiencies were identified and corrected during the in-flight simulation phase:

The bob-weight lag filter time constant was found to be too long (200 ms) causing oscillations during 1.5g turns at cruise speeds.

The non-linearity in the stick-to-elevator gain was found to have too large gradient changes within the high pilot activity band during approach and landing, resulting in risk for divergent PIO.

These problems were corrected and retested, and the changes introduced into the first prototype design the same week. These were the only control law design changes made after the design freeze date prior to first flight.

<u>Flight Control Test Rig</u>

The test program was supported by a number of test rigs. Rig testing reduced the time needed for pre-flight system tests on the aircraft and helped in achieving a fault free first flight.

The hydraulic rig included the actual aircraft hydraulics, servos and control units. Air loads and engines were simulated, allowing near realistic testing environment. The rig was used throughout the test program to check modifications and new software and hardware items before implementation in the test aircraft.

Closed-Loop Simulation

As the final test prior to the first flight, an end-to-end checkout was performed. This was done by connecting the hydraulic rig to the simulator with a high-speed link. The pilots, sitting in the simulator, flew a range of flight profiles activating the flight controls and getting the feedback from the actual control surfaces.

Normal and failure modes were checked and confidence level increased for the first flight. This phase confirmed that the full system, using the actual flight test modules, was functioning in real time conditions. It should be stated that despite the high-speed link the simulation suffered from a time delay of 250 ms which made the landing phase simulation unreliable .

Development Flight Test

Development Test Team (DTT)

Shortly before first flight a Development Test Team was formed as an additional subgroup to the DBT to function during the flight test development up to a certifiable system. The team was collocated at the flight test center and consisted of specialists from Saab amd vendors:

- PECS system responsible engineer
- PECS Control Law responsible engineer
- Flight dynamics specialist
- Aero data specialist
- Flight test planner
- Workshop planner
- Engineering test pilot
- Flying quality flight test engineer
- Flight control flight test engineer
- System vendors.

The team's main task was to develop the system from first flight up to a level that would allow start of certification flights. In addition a very important sub-task was identified, to start the airfield performance test flights in prototype 002. as soon as possible. This involved the following:

- Open up the flight envelope sufficiently to allow start of performance flights.
- Achieve handling quality acceptable for takeoff and landing performance testing.
- System check out of prototype 002.

This task turned out to be a lot easier than expected as very few changes to the original optimization done in the development simulator were necessary.

The DDT was given full responsibility and authority to achieve the task.

The flight envelope opening and possible problem mapping process was initially discussed within the group and it was concluded that it could be done in 25 flights. After the initial 25 flights it was planned to go back to the development simulator for the final development process of the control laws. This was found unnecessary due to the satisfactory results from flight tests.

The content of the initial 25 flights was in general defined shortly after the team had been formed. It was decided that the team should always have flight test cards for the next five flights available. Each morning the coming day activities were discussed and details could be added or subtracted to the flight tests. Testing that deviated from already existing and approved flight test plan documents had to be approved by the Chief Flight Test Pilot before they could be carried out.

Once a week a plan for the following week's testing was defined in general. As the DTT contained all the necessary expertise and was located within one room, the development of the system became a continuous process with discussions and arguments from individuals within the team, which proved to be beneficial to the program.

The flight envelope opening process was reviewed by an independent Flight Envelope Opening Board composed of senior members from Saab Aircraft AB as well as Saab Military Aircraft (JAS 39 Gripen).

The first five flights were flown in the development simulator, both before and after the actual flight. This proved to be very fruitful as it provided essential feedback of simulator fidelity.

First flight was performed on May 19 1994; by early July, after about 30 flights, the final specification was issued to system vendors. The final configuration was successfully flown in the beginning of August. Shortly thereafter the certification flights could begin and the DTT was disassembled.

Initial Flight Test - Unaugmented

In order to determine the basic characteristics of the aircraft and minimize the risk of the augmentation system failure modes the initial 10 flights were performed with the augmentation disengaged. This was done by the use of a special test switch that allowed disconnection of all augmentation for planned testing or as a safety switch. This feature allowed us to find out the basic stability of the aircraft and to predict if the designed augmentation was sufficient or excessive without actually testing all the flight conditions.

The initial tests showed us that the basic aerodynamic effectivity of the elevators was greater than predicted and that "Bob-weight" augmentation might be too low at the extreme aft c.g. It also showed us that the basic aircraft had excellent handling characteristics in all phases of flight and the augmentation would only be needed to comply with all the certification requirements.

Early aero-data flights for simulator update

As explained earlier, the development and optimization of control gains was to be done in the development simulator. It was essential to update the aero data model of the simulator, and the number 2 priority for flight testing was the collection of aerodata of the basic aircraft. This was very unique for such a flight test program since normally the full envelope opening flights come before aerodata flights.

Optimization in the simulator

The simulator was updated using the aerodata collected during flight tests. The whole process was planned ahead in detail and was done in record time since it was the most time-critical for gain freeze. As it turned out, the second optimization phase in the simulator was not necessary. The simulator was, however, used as planned for the certification of failure cases. These were flown and documented; some using the full closed-loop procedure, i.e. failing the actual box or function in the rig while the pilot was reacting real time in the simulator.

Final Flight Tests and Certification

After receiving the updated flight test flight control boxes, the standard certification flight phase was initiated. The advantage was that by now we were not expecting any certification problems. This was true throughout the flight envelope except for one extreme point; during final certification we discovered that the initial max. operating speed (Vmo) tested was not corrected for compressibility (VCAS to VEAS).

This resulted in control forces slightly below those required for a max-g (Nz) turn at Vmo at very low weights and aft c.g.. In order to overcome this without a system change, the limit load for light weight was increased without changing the operational limitation for max. g. This was approved by the authorities and the change was transparent to the pilot.

During this period the second test aircraft completed the airfield performance tests and other loads and system demonstrations. Although most failure cases were demonstrated in the simulator, some cases that required the full warning system function were demonstrated in flight.

This phase was completed by the JAA and FAA certifying the new modification.

Improvements

Wide flight envelopes

The main goal for the modification was to achieve a wider flight envelope allowing for more flexibility and payload. The weight/c.g. envelope was extended to meet specifications. The PECS flight control system has the potential for future growth in both c.g. and weight without the need for redesign.

Max. cruise speed increased from 250 KIAS to near 280 KIAS at mid altitudes, allowing for better cruise flexibility and higher descent speeds.

Enhanced flying qualities

In addition to the wider envelopes achieved with the new control system it was determined that handling characteristics in all flight conditions and configurations had improved. Most apparent were the reduced forces required to maintain speed while applying power, and during take-off rotation. In general it could be stated that the aircraft handling in pitch changed from just meeting the requirements to being satisfactory without a need for improvement.

Improved airfield performance

The improved handling characteristics were immediately translated into shorter take-off runs, lower approach speeds and the ability to perform steep approaches into short runways. In addition an optional takeoff configuration (Flaps 0) was certified for use in "hot-and-high" conditions.

Improved climb- and cruise performance

One of the most positive spin-off effects of PECS was the 10 kts increased cruise speed (using the same cruise power) and 5% improved climb performance. This was attributed to the lower form drag of the new stabilizer and elevator design, lacking tabs and aerodynamic balancing.

Future potential

In the near future we are looking at extending the flight envelopes by increasing Mmo and improving landing performance by reducing landing speed.

This gives an excellent base for the coming SAAB 2000 derivatives and growth options.

Lessons learned

The PECS program has been a great success. The development and certification process was a result of lessons learned.
During this program we have also learned how we should plan for similar future tasks:

- Use Designated Task Teams for limited periods with a defined task. Disassemble the teams when the goal is reached.
- In-flight simulation is an effective and inexpensive tool for dynamic characteristics involving new flight controls and can be used to detect design misses early in the program.
- Updating a simulator with the latest aero-data can prove to be the highest -

although not the logical - priority in a classical development program.

- Despite all efforts to minimize late changes they will always be there. Hopefully they can be left to an improvement phase.
- When reaching the end of the development, try optimizing the system for the operators and not only for the highest safety for testing. The system is by then mature and what seems to be a minor bug for flight testing might mean cancellation of revenue flights.