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DESIGN AND EXPERIENCE WITH A LOW-COST DIGITAL FLY-BY-WIRE SYSTEM IN THE SAAB JA37 VIGGEN A/C*

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Abstract

A digital Fly-By-Wire system has been designed built and evaluated as a rig system and as a flight system installed in a JA37 Viggen test aircraft. Headlines for definition of the system have been low complexity and low production cost, met by trading off complexity against safety and reliability margins. System characteristics are minimized servo hardware, minimized channel interconnections and maximum replacement of hardware by software including servo loop closures. Functional development areas are application of optimal control technique for multimode laws and for servo loop computations. The paper will present system definition, system mechanization in test aircraft, ground test and flight test information.

I. Introduction

This paper presents a FBW system configuration, designated ESS01, developed and tested at SAAB-SCANIA, Linköping, Sweden.

The objective has been to design a low-cost digital FBW system which meets specified performance and reliability requirements without extra built in "safety margins".

The importance of keeping the complexity down and the cost low is illustrated in Figure 1, which shows the complexity/cost of control servos of various degrees of redundancy.

A low cost FBW system is assumed to be a system with:

- few components, hardware replaced by software
- simple redundancy and monitoring concept
- no excessive reliability/safety margins

The system configuration was defined after a number of trade off studies and rig tests. The configuration backgrounds are given in item II and III.

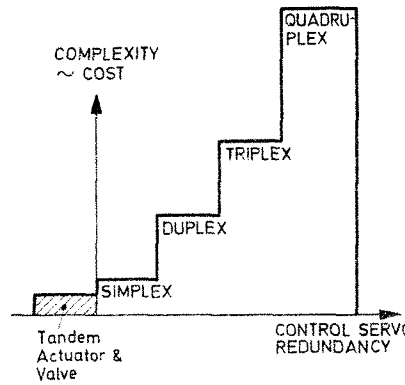

FIGURE 1. Electrohydraulic servo cost

II. Requirements

The following major requirements and general definitions have been guidelines for selection and development of the ESS01 configuration:

Requirements on Flying Qualities:

MIL-F-8785C requirements on Level I, Level II and Level III performance are applicable.

Requirements on Reliability and Flight Safety:

MIL-F-9490D requirements are applicable, i.e.:

Probability for loss of Level I performance:
$<10^{-2}$ per flight hour

Probability for loss of Level II performance:
$<10^{-4}$ per flight hour

Probability for loss of Level III performance:
$<10^{-5}$ per flight hour

Electric and hydraulic power supplies are included

Requirements on aircraft transient when a failure occur:

The JA37 failure transient requirements apply, e.g.

The following n_z requirements are applicable for the chosen JA37 test aircraft:

Failure resulting in Level I or Level II:
$n_z < 1g$

Failure resulting in or loss of Level III:
$n_z < 3g$

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In failure probability calculations, loss of Level III flying qualities is conservatively defined as loss of the aircraft.

III. System Definition background

The requirements of MIL-F-8785C shall be met by control laws designed by optimal control technique accounting for the sampled digital computations, the FBW servos and the Viggen aerodynamics.

The MIL-F-9490D requirements can be met with various ambition and design methods. For instance by

1 few reliable components, minimum redundancy (high MTBF)

2 any number of components, extensive redundancy (low MTBF).

Method 1 means design to the MIL-F-9490D requirements.

Method 2 may mean design to the MIL-F-9490D requirements and additional requirements such as dual fail operation, fail safe etc.

Method 1 was selected as the basic principle for the low-cost FBW configuration. The availability of highly reliable integrated circuits make it possible to meet the requirements on loss of function with less sophisticated redundancy than what used to be required. It was understood however when method 1 was choosen that the aircraft environment in which the FBW-system shall operate must be correctly defined and specified and that the FBW-system must be designed and tested according to the worst case environmental conditions. Otherwise the nuisance disengagement may become a severe problem and the predicted failure probabilities will not be true.

The well-known relations between the Viggen surface transients and a/c response show that the a/c transient requirements will be met by the suggested monitoring system.

Thus the assumptions for this low cost FBW-system in summary are:

- performance acchieved by control laws, designed to efficently use the capability of the digital computers

- reliability and requirements on loss of functions met by minmum hardware and stright forward in flight monitoring

- requirements on failure transients can be met as indicated by Viggen experience.

Hardware for the configuration were mainly selected from the JA37 Viggen digital automatic flight control system presently under production in Sweden.

The configuration was evaluated in rig simulations 1979-80 before the decision to build flight worthy hardware was taken.

A JA37 prototype aircraft was modified 1981 to accomodate the redundant sensors computers and controlservos. A clutch mechanism was developed and installed.

IV. System Description

The description below refers to Figure 2, System Concept and Figure 3, ESS01 system lay out as actually installed in test aircraft 37-21. Necessary considerations when applying ESS01 to this specific aircraft are noted separately.

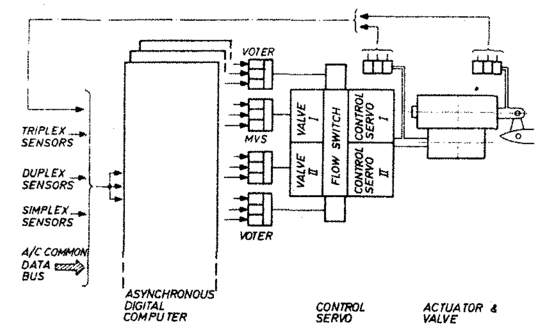

FIGURE 2. ESS01 System Concept

System Redundancies

System Components are

- Sensors
- Computer Channel System
- Servo System
- Safety and Warning Logic

The degree of redundancy within each component group is given in table 1.

TRIPLEX	DUPLEX	SIMPLEX
Flight crucial sensors	Flight Critical sensors	Non-critical components
Computer systems	Control Servos	Safety crucial/ critical components with high quality and reliability
Gyro sensors	Servo Drive Electronics	

Note. In A/C 37-21, gyro sensors are not crucial as the A/C is stable.

Table 1. Hardware Redundancies

Sensors

Sensors are of conventional types with degree of redundancy as in Figure 3.

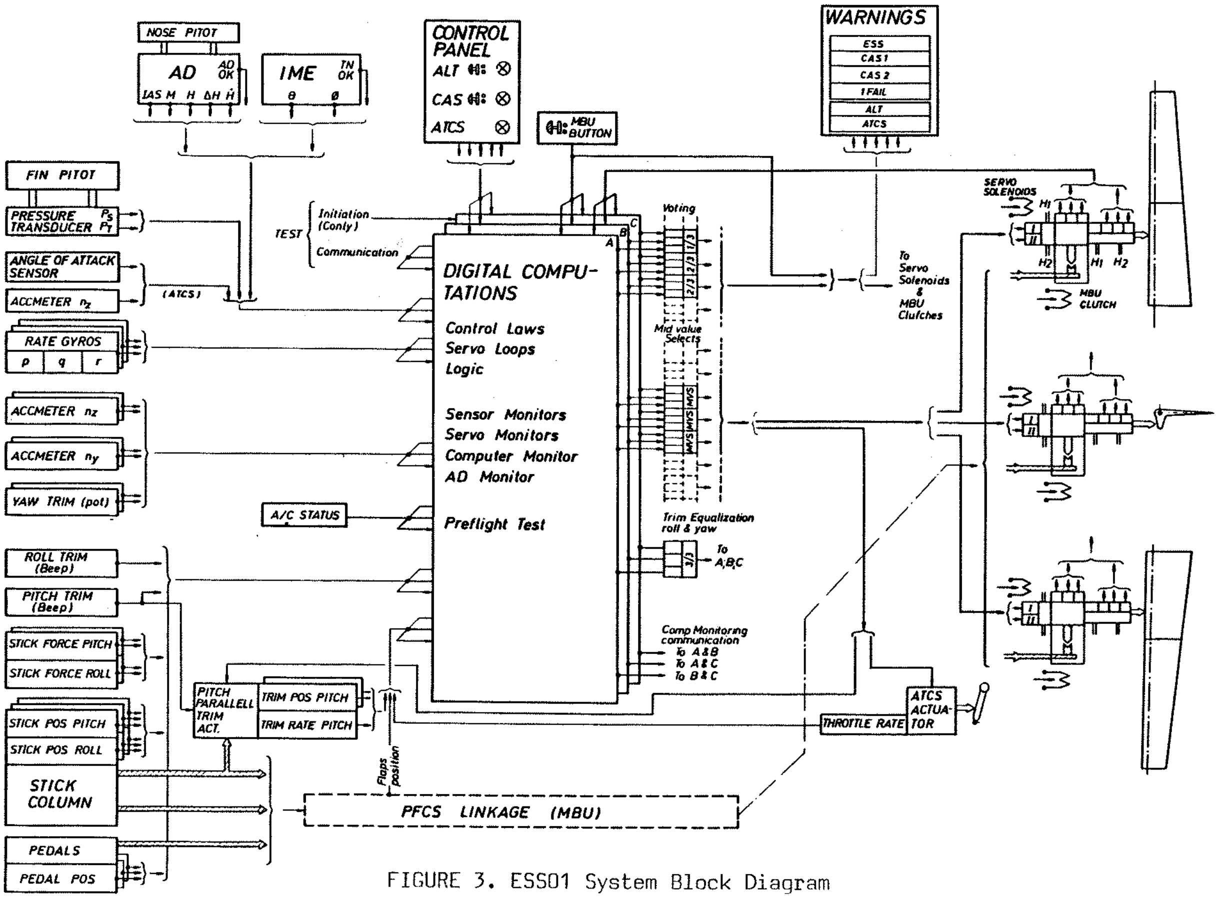

FIGURE 3. ESS01 System Block Diagram

Control Modes

Mission requirements are reflected by the following control modes, manually or automatically available by control law reconfigurations:

- Stability Augmentation — CAS
- Pilot Flight Path Control
- Take off/Landing mode
- Automatic Flight Path Control (Extended stabilization)
- Aiming Modes (air to air, air to ground)

with the following relief functions

- Altitude Hold — ALT
- Autothrottle Control — ATCS

Computer System

Each of the three channels are running asynchronously independent of remote channels in order to reduce risks for common mode failures and distrubances.

Channel communication is limited to logic and analog signal transfer (each channel to remote channels) of:

- trim integration pulses in roll and yaw for channel equalization of trim levels
- computed surface commands for computer monitoring

Note. In A/C 37-21 pitch, trim integration is provided by a common trim actuator in the MBU system.

Computations

Each digital channel performs the computations defined below

- Control Laws
- Servo Loops (Outer and inner loops)
- Triplex Sensor Mid Value Select
- Sensor Monitoring
- Computer Monitoring
- Servo Monitoring
- Primary Data Monitoring
- Preflight Safety Check

Computation requirements are

Computation rates:	Control Laws	40, 20, 10 Hz
	Servo Loops	80 Hz
Through put:		130 kops
Memory Size (18 bit words):		14 kwords

Note. Given figures are for 37-21 system computer HDC-301.

Monitoring

As indicated above, all ESS01 monitoring is performed in software.

Sensors channels:

- Triplex sensors:

  Mid Value Select
  Cross Comparison and
  Self Healing Capability (Triple 3)

- Duplex sensors:

  Comparison

- Simplex sensors and primary Data:

  Signal validation is individually adapted to signal authority, time constants etc.

Computer channels:

Mid Value Select (Hardware)
Servo commands computed by all three channels are compared by each channel.
Self Healing Capability

Servo channels:

Control servo monitoring is acchieved by comparison to a Kalman filter servo model available in the digi tal servo loop control law.

Servo and elevon position sensors are monitored as triplex sensors above.

Primary Data:

From ADC data (IAS, Mach number, Alt) Static and Total pressure are calculated and compared to P_S and P_T from separate pressure transducers.

Computer outputs

After D/A conversions, Mid Value Select networks provides

- consolidation of servo command signals
- transient suppression at first failure.

Consolidation of servo channel switching discrete signals and failure warning discrete signals is provided by voting networks.

Servo System

Figure 4 indicates servo system components and loop closures in the digital computer channels.

Specific servo hardware is

- Duplex electrohydraulic control servo with

  Channel I active
  Channel II active/standby

- Channel switching is performed by solenoid-activated hydraulic switches

- Conventional hydraulic tandem valve mechanically tied to the control servo

- Conventional hydraulic main actuator

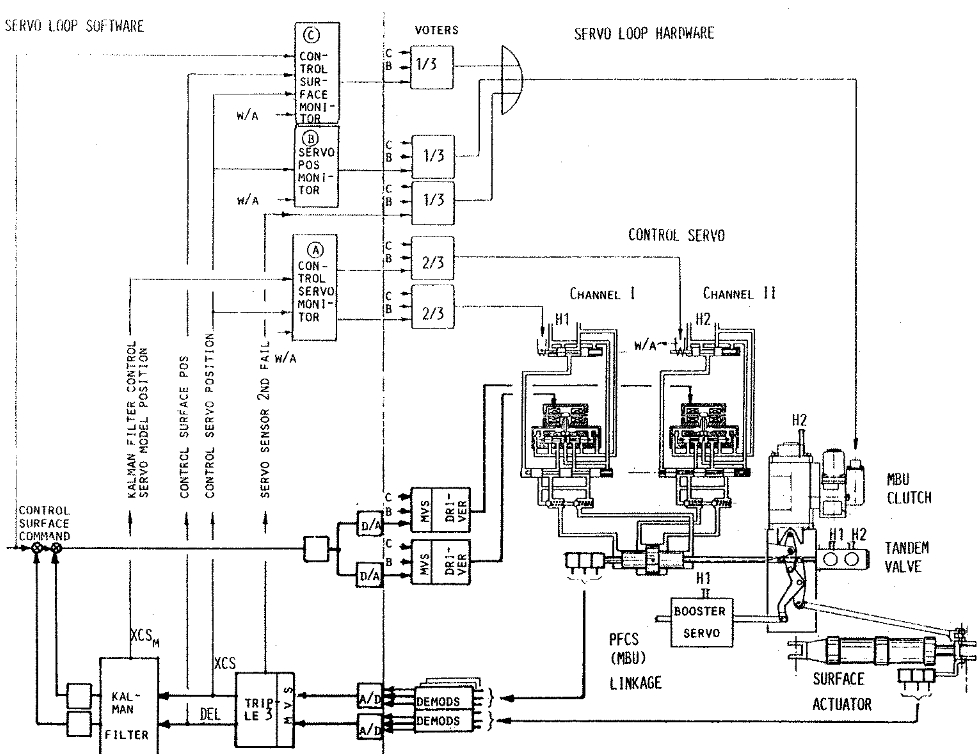

FIGURE 4. ESS01 Servo Loop

- Control servo position transducer (triplex)

- Actuator position transducer (triplex)

As a specific added arrangement to the servo installation in test aircraft 37-21, Figure 4 includes the mechanical interface between the ESS01 servo system and existing Primary Flight Control System, kept as a mechanical back up (MBU) during the ESS01 flight evaluation.

The interaction between ESS01 and MBU is briefly described below.

Mechanical Back Up System (MBU)

MBU is identical with existing PFCS in the test aircraft.

Figure 3 and Figure 4 indicates the following arrangements:

Stick and Pedal Commands are mechanically transferred through PFCS linkages.

Downstreams, three clutches are added, disconnecting PFCS linkages from the tandem valves in ESS01 modes.

The following features are achieved by this arrangement:

- Pilot inputs (stick and pedals) are common for ESS01 modes and MBU mode.

- Pitch trim position in PFCS linkage corresponds to elevon trim position which means minimum switching transients

- In ESS01 modes, PFCS linkages are mechanically isolated from ESS01 Servo Systems and have no dynamic influence on servo performance.

Power Supplies

ESS01 is supplied from 37-21 existing Hydraulic and Electric Power Supplies with no modifications.

Hydraulic power is supplied from two independent system, one for each of the two servo channels. Probability for total loss of hydraulic power is 10^{-9} a thus conforms to ESS01 safety requirements.

Electric power for ESS01 in normal operation is supplied by a main ac generator with a ram trubine generator as back up. Probablity for total loss is 10^{-5}.

Failure Probability Predictions

Table 2 shows the effect of component failures on ESS01 control signals.

Table 3 shows preliminary calculated probabilities for loss of Level I, II and III. Table 2 failure effects are used together with table 3 component failure probabilities.

COMPONENTS	FAILURE EFFECTS	
	1 failure	2nd failure
Duplex Sensors	no sensor signal	-
Triplex Sensors	isolated by MVS self healing	MBU
Triplex Computers	isolated by MVS self healing	MBU
Duplex Control Servos	stand by channel activated	MBU

COMPONENT	Number	Failure Probability $\cdot 10^6$		Probability$\cdot 10^6$ for loss of Level		
		Each	Total	I	II	III
Gyros						
pitch	3	60	180	.024	.024	.024
roll	3	60	180	.024	.024	
yaw	3	60	180	.024	.024	
Acc-meters						
normal	2	25	50	50		
lateral	2	25	50	50		
Pilot Commands						
pitch	3	10	30	.005	.005	.005
roll	3	10	30	.005	.005	.005
yaw	3	10	30	.005	.005	.005
Trim; switches	6	2	12	12	12	.01
Airdata P_s P_t	2	50	100	100	100	
Pressure Sensors P_s P_t	2	50	100	100	100	
Computer Channels	3	300	900	.33	.33	.33
Control Servo Channels	6	80	480	.045	.045	.045
Tandem Valves	3	.1	.3	.3	.3	.3
Tandem Actuators	3	.1	.3	.3	.3	.3
Safety Logic						
Single	1	.01	.01	.11	.11	.11
Redundant	2	2	4	.11	.11	.11
Electric Power						
ac	3	30	90	Included in above figures		
dc	1	.1				
Hydraulic Power						
System I	1	80	92			
System II	1	12				
TOTAL			2509	313	213	1.24

TABLE 2. Component Failure Effects
TABLE 3. Failure predictions

V. Ground Tests

The qualities of the described ESS01 FBW system was evaluated with reference to the requirements defined in section II.

- Flying qualities was evaluated in extensive ground tests including ESS01 rig simulations and simulations with A/C 37-21 in the loop.

- Failure probability calculations were performed. Inputs to the calculations were

  in flight monitoring effectiveness and failure mode effect analysis.

- Aircraft transients following ESS01 components failures were evaluated in rig and aircraft simulations.

- Additional tests such as

  EMI-tests
  ground vibration tests and
  electrical power supply tests

  were also performed.

The ground tests covered the following basic steps:

- General check out of the ESS 01 system and the MBU

- EMI-testing

- Ground vibration tests

- Closed-loop simulation

Check out of the ESS 01-system and the MBU

The following topics were covered during the general check out in JA37 test A/C:

- Check of the electrical power supply ("smoke test")

- End to end test of all signal paths.

- Performance evaluation of sensors and servos.

- Calibration of the recording system in the A/C.

- Regular check-out of the MBU.

- Verification of hardware logic.

- Verification of the software for the Operational Flight Program (OFP) by end-to-end frequency response tests and tests of software logic and mode switching. A sample of the type of data obtained from this test is shown in figure 5. The frequency response of the actual system, from sensor to control surface deflection, is compared to the pre-calculated result based on the analytical definition presented in the software requirement specification.

EMI-testing

In addition to the separate EMI-tests of the basic system components, a full scale EMI test was performed with the complete system running in the test aircraft.

After minor improvement of the safety logic with regard to EMI susceptibility, the tests passed with satisfactory results.

Ground vibration tests

The ground vibration tests have been performed verifying that ESS 01 system fullfills the flutter requirements with respect to body-bending filter attenuation in all axes. The body-bending filters used in ESS 01 are non-linear digital filters of the same type as used in the JA37 digital automatic flight control system. Filter characteristics are shown in figure

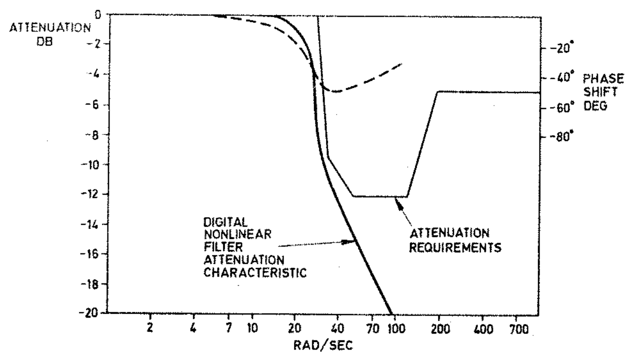

Figure 6. Nonlinear Body-Bending Filter

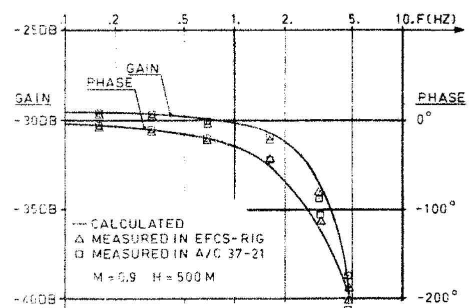

Figure 5. Pitch Rate-to-Elevon Pos Response

Closed Loop Simulations

The ground test facilities used during the closed loop simulations are shown in fig 7.

The aircraft with all flight control hardware, is connected to a six degree-of-freedom (6 DF) digital simulation of the airframe dynamics, (see Figure 7). This model is an integral part of a permanent system simulator for A/C 37, which also provides outside-world and Head-Up Display (HUD) presentation. Aircraft motion signals were transmitted from the A/C model to the flight control computers in the JA37 test aircraft, through an analog computer used for signal adaption and sensor models. Control surface deflections and throttle commands were fed from the JA37 test aircraft to the digital simulation of the airframe.

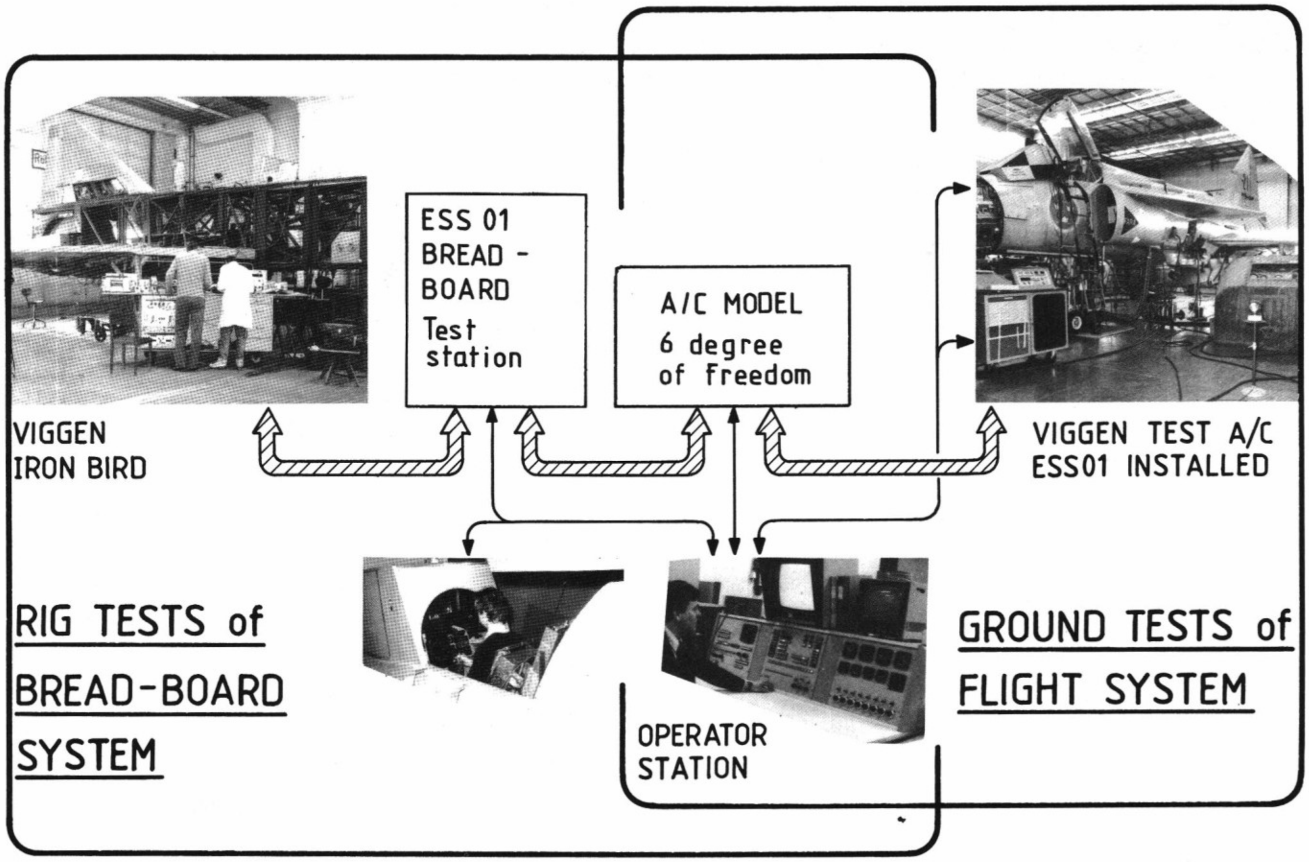

FIGURE 7. ESS01 Ground Test Facilities

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The outside-world and HUD presentation was transferred from the permanent simulator cockpit to a TV-monitor in the JA37 test aircraft. This facility, despite a very narrow field of view, provides a complete closed loop operation of a total mission from the cockpit in the JA37 test aircraft.

The following items, with or without pilot in the loop, were covered during this simulation phase:

- Closed-loop validation of flight safety by failure simulation. Critical modes of the flight control system were tested to assure proper operation, mode swithching and transients following a failure.
- Closed-loop validation of both normal modes of operation and degraded control modes caused by sensor failures. The main part of the validation of the OFP, with respect to function and logic, were performed by this evaluation.
- Validation of the Safety Check software. Critical failure modes in the safety system were implemented to evaluate that the Safety Check detected these failures.
- Pilot-in-the-loop simulation. Pilot evaluation of the FBW-system and the MBU with respect to flight safety and handling qualities. Four test pilots participated in this evaluation, which covered both normal operation and a number of failure states.

Apart from some problems during the check out of the simulation set up, resulting in a time spent for the check out of more than twice the time assigned in the time schedule, both the accomplishment of the simulation and the results from the simulation were very satisfactory. A sample of results are shown in Table 4 and Figures 8 and 9.

FAILURE	TRANSIENT n_z	TRANSIENT n_y	REQMT n_z	REQMT n_y	SYSTEM DEGR TO	PILOT WARN
SENSORS						
q Gyro: 1st	<.2	<.1	1.0	.5	-	-
2nd	<.2	<.1	3.0	.75	LEVEL 3	CAS
Elevon transd: 1st	<.2	<.1	1.0	.5	-	1FAIL
2nd	<.2	<.1	3.0	.75	MBU	ESS
Roll Command: 1st	<.2	<.1	1.0	.5	-	1FAIL
2nd	<.2	<.1	3.0	.75	MBU	ESS
COMPUTER: 1st	<.2	<.1	1.0	.5		1FAIL
2nd	2	.3	3.0	.75	MBU	ESS
ELEVON SERVOS						
1st CHII Open	0	0	1.0	.5	-	-
2nd CHI Open	1.8		3.0	.75	MBU	ESS
1st CHI HO	1.5	.35	1.0	.5		1FAIL
RUDDER SERVO						
1st CHII HO	0	0	1.0	.5	-	-
2nd CHI HO	0	0	1.0	.75	MBU	ESS

TABLE 4. Failure Mode Evaluation (Sample)

VI. Failure probability calculations

The effectiveness of the inflight monitoring and preflight safety check were verified by analysis and simulations. In the rig simulation a great number of hardware failures were introduced and the detection and isolation of the failures were verified. The basic principles for monitoring of redundant components MVS, crosschannel or model comparison made the monitoring effectiveness verification fairly straight forward.

The failure mode analysis included all ESS01 components and interfacing A/C systems. Totally, about 1700 failure modes were analyzed and a fault tree created. Calculated probability for loss of ESS01 control function is:

Level III (reversion to MBU) $3 \cdot 10^{-6}$

This figure includes

ESS01 components
Interfacing A/C avionic systems effects on ESS01
Logic for reversion to MBU

Not included are

Test aircraft PFCS (MBU)
Test aircraft AC power supply

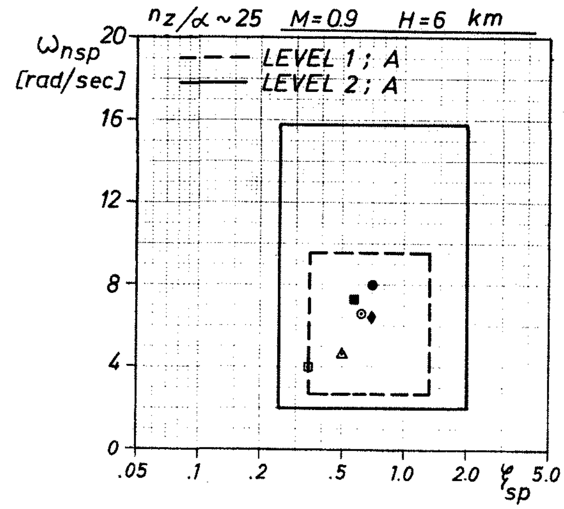

FIGURE 8. Pitch Short Period Dynamics

- ■ ALTITUDE HOLD
- ● PITCH CAS
- ◆ AIMING MODE
- ⊙ AD-FAIL
- △ n_z-FAIL
- ⊡ 2nd FAIL q-gyro

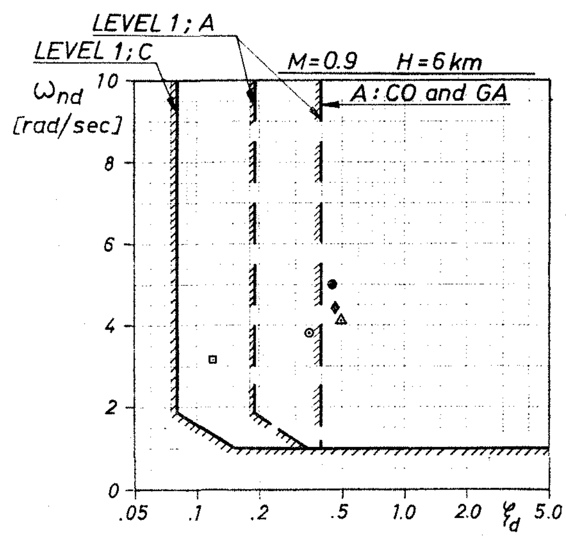

FIGURE 9. Dutch Roll Dynamics

- ● LATERAL CAS
- ◆ AIMING MODE
- ⊙ AD-FAIL
- △ n_y-FAIL
- ⊡ 2nd FAIL r-gyro (or p-gyro)

Transient requirements

The failure transient requirements were verified in rig and aircraft closed loop simulations as described above. The most severe failure transients occurred for computer second or servo second failures. The requirements were met except for a few second failure transients were in supersonic the mismatch betwen the FBW and the MBU load factor command caused transients of up to 4 g's when a second failure was introduced during a high g-command.

VII. Flight test program

The flight testing of the FBW-system contains about 40 flights, and covers the following items:

	No of flights
- Check out flights	2
- Safety verifications flights	15
- Pilot assessment and performance verification flights	15
- Loading configuration with aft c.g.-position	5

VIII. Conclusions

The described program has shown that the ESS01 Fly-By-Wire System meets the stated requirements and design goals.

Performance requirements are met, in most cases with good margins and test results have good confidence through close correlations to the wellknown performance characteristics of the A/C 37 Viggen.

Safety requirements are verified through an extensive analysis and good experience so far of actual hardware and monitoring software.

The low complexity/cost approach has been kept throughout the design and development phase, no need for major changes of the concept has shown up.

Looking into the future, a "reduced redundancy" concept as ESS01 will probably be favoured also by the probable increase of number of control surfaces required on high performance aircrafts, i.e.

- increased importance of the servo cost part
- added "no cost" surface redundancey by software reconfiguration at servo failure.