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THE USE OF FLIGHT SIMULATION IN THE DEVELOPMENT OF THE SAAB AJ37 VIGGEN SYSTEM

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THE USE OF FLIGHT SIMULATION IN THE DEVELOPMENT OF THE SAAB AJ37 VIGGEN SYSTEM

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Abstract

The potential of flight simulation as a means of reducing development time and costs was appreciated at an early stage in the Viggen program, and expansion of the existing simulation facilities commenced in 1962. A brief description of the current equipment configuration is given, covering both analog and digital computers, simulator cockpits and special-purpose equipment.

The way in which these facilities have been and are being used in various phases of the Viggen program is described, including control-system and autopilot development, tactical mission simulation, head-up display optimization and dynamic program check-out for the airborne digital computer. Areas in which simulation has proved especially valuable are discussed and comparison is made with flight test results.

Fig. 1. The SAAB AJ37 Viggen aircraft

Introduction

The SAAB 37 Viggen system incorporates a basic flying platform which is to be built in four different versions for strike, reconnaissance, interception and training. Development effort so far has been concentrated mainly on the AJ37 version (Fig. 1), which is intended primarily for the strike role but is also capable of performing fighter missions.

For compatibility with the Swedish war-base system using stretches of ordinary roads, the Viggen has STOL characteristics, with Mach 2 performance at the other end of the scale. The tandem delta layout adopted is a simple, inexpensive way of providing STOL capability. The nose-up moment produced by the flapped canard surface in the landing configuration enables this layout to give some 50% more trimmed lift than an ordinary delta, with a correspondingly low approach speed. An automatic throttle control provides speed precision during the approach, and touch-down scatter is reduced to very small amounts (typically less than 50 m) by the use of a carrier-style no-flare landing technique in conjunction with the accurate aiming possible with the head-up display and good handling qualities in the landing configuration. Using the thrust reverser, total runway requirements for landing are only 500 m, which is also more than adequate for take-off.

The Viggen is a single-seat aircraft, and a closely integrated computer-based electronics system is therefore an essential part of the system. The airborne digital computer processes information from sensors and uses the results to drive cockpit displays. It also has important functions in the automatic navigation system, in fire control computations and in preflight check-out.

Another important factor in easing the workload on the pilot is the advanced autopilot which has refined hold functions to give him the extra help he needs during critical phases of a mission.

Development work started in 1962, the Viggen made its first flight on February 8, 1967, and deliveries of production aircraft will start in 1971. In order to maintain this schedule and also keep flight test costs to an acceptable level, it was apparent at an early stage that as much development testing as possible would have to be done, on the ground, well in advance of the first flight. The present paper is concerned with those parts of the development program which rely on computer-mechanized mathematical models, often in combination with some type of system hardware.

Simulation Techniques and Facilities

Two essentially different approaches have been used in simulation of System 37 - simulation using analog/hybrid computation and pure digital simulation. In the former type there is usually system hardware involved, necessitating real-time operation. whereas in the latter the simulation normally runs slower than real time and has no provision for hardware interfacing. The way in which digital techniques have been used will be described first, before going on to a description of the analog/hybrid facilities and associated hardware.

All-Digital Simulation

Digital Model 37. A comprehensive digital simulation system known as Digital Model 37 has been developed for use in systems analysis. It consists of a set of FORTRAN IV subroutines which can be combined as desired for each user´s specific application from among the following:

- Power plant dynamics with control system characteristics, thrust and fuel consumption, reversing.
- Aircraft dynamics with control surfaces, flaps, landing gear, etc. Separate versions for small perturbations or large amplitude manoeuvres.
- Autopilot and automatic throttle control system characteristics.
- Sensor characteristics, e.g. master reference platform, air data system, including nonlinear effects.
- Airborne computer operations in navigation, fire control, landing, etc.
- Head-up display electronic and optical transfer characteristics and imperfections.
- Pilot transfer characteristics for loop closure.
- Atmospheric effects including turbulence.

The largest combination requires about 40,000 words of storage, but less than half as much is sufficient for most applications.

Input to this model requires definition of flight condition with about 10 parameters. Other parameters are built into the model and automatic priority assignment ensures that over-specified or contradictory inputs are resolved without aborting a run. Pseudo-random number generating routines are used to introduce repeatable pseudo-stochastic errors as required.

Output can be printed and/or plotted on an off-line incremental plotter.

As fairly short integration steps must be used in order to preserve accuracy, this model is uneconomical for long runs such as would be required for simulation of complete missions. Normally it is used for short flight segments with quite short running times which are nevertheless sufficient for the types of problem studied.

This simulation model makes it possible to perform rapid system analysis, for instance to check the effects of suggested design changes. In many cases this can be done more rapidly than if the necessary modifications were to be made to an analog/hybrid model committed to real-time simulation, and without the attendant danger of degrading an established simulation, especially where a number of users all make their own changes.

Digital Model 37 has been in daily use since early 1966 for problem studies and systems optimization in the following areas:

- Control system performance with autopilot in control stick steering, attitude and altitude hold modes, including response to step inputs and acceleration.
- Standing oscillations in the control system using a small-signal model.
- Take-off and landing. Effect of pilot technique and external loads on take-off distance. Landing sequences with studies of bounces, tail clearance and braking roll. Landing precision studies. Ground handling characteristics with thrust reversing.
- Trim disturbances due to release of external stores.
- Fin loads during rolling manoeuvres.
- Matching of aerodynamic data from wind-tunnel and flight tests.
- Determination of altitude required for recovery from vertical dives, half-rolls and similar critical manoeuvres.
- Dynamics of the head-up display in combination with the airborne computer.
- Optimization of fire-control computations.
- Investigation of terrain-following using a simulated terrain model and radar sweep functions.
- Performance of the air data unit in combination with the airborne computer during transonic flight.
- Studies of total subsystem precision based on knowledge of component precision.
- Determination of required tolerances for production control of system components with regard to desired total system performance in flight.
- Post-stall behaviour.

Mimic. Special problems requiring facilities not provided in Digital Model 37 have been treated digitally using the Mimic continuous system simulation language.

One standard program written in Mimic is used for computing trajectories of external stores after separation from the aircraft and includes the effects of the flow field about the aircraft. The time required to get this quite extensive program operational was very much shorter than could have been achieved without the facilities provided by Mimic.

Standard Mimic programs are also used to compute and plot control pulse responses for dynamic check-out of the 5-degree-of-freedom analog model used in much of the control system simulation.

Mimic has been found very useful for studies where results are required quickly and there is no time to develop a possibly more efficient program in Fortran or Algol.

Analog/Hybrid Simulation

Simulation of the Viggen system using analog and/or hybrid computers has been in progress since 1963 at the Saab Simulation Centre in Linköping and at the Division of Aeronautics at the Royal Institute of Technology in Stockholm.

The analog computing equipment at Saab consists of seven consoles of Electronic Associates 100-volt equipment, types 31R, 131R, 231R and 231R-V. There are also four 10-volt computers - three EAI TR10 and one TR48. The 100-volt computers have a total complement of some 800 amplifiers, 20 servo multipliers, 70 electronic multiplier products, 20 servo resolvers and 7 electronic resolvers, together with function generators, noise generators, comparators, control logic, etc. The two 231R-V consoles have servo-set potentiometers controlled by an ADIOS system.

The digital computers used in hybrid simulation are two early prototypes (NSK3B) of the DATASAAB airborne computer for the Viggen. The equipment required for interfacing them to the analog computers and system hardware has been built at the Simulation Centre. See Fig. 2 and 3.

Fig. 2. Digital computer operators' consoles

Fig. 3. Digital computer and interface cabinets

Each computer has two coincident-current ferrite core memories, one of 1024 26-bit words, the other of 8192 13-bit words. Add time is 6 μs and multiply time 83 μs, using fixed-point twos-complement arithmetic. There is a fixed-interval interrupt system.

By virtue of their original application, the computers are well equipped with both analog and binary input and output channels. Each of them has 39 analog input channels and 19 analog outputs. In addition, they have 10 fast D/A converters built at the Simulation Centre for connection to binary outputs. Several hundred binary inputs and outputs (1-bit channels) are also available, although only 60 inputs and 96 outputs are in use at present.

The purpose of the interface equipment is to match the ± 10V of the digital computers, to protect the analog and binary inputs of the digital computers against excessive voltages, to reduce the noise level to well below the resolution limit of the A/D converters, and to provide access to the digital computer inputs and outputs for connection to other equipment.

The peripheral equipment includes 8-channel and X-Y recorders, and special on-line data processing equipment for computing and recording mean or RMS values. An Ampex FR100B analog tape recorder provides up to 24 narrow-band and wide-band recording channels, with marking and calibration signals standardized so that recorded data can be processed automatically at the Saab Test Data Evaluation Centre.

Trunk and control lines from all the analog and digital computers terminate in a central console (Fig. 4) incorporating a standard-size PACE 231R patch-board, where they can be interconnected and routed to simulator cockpits or other hardware. This console also includes provision for readily slaving together any combination of analog consoles, with remote mode control if desired.

Fig. 4. Central interconnection console

Simulator Hardware. Cockpits, system hardware and other equipment are housed in rooms grouped around the computer area and communicate with the central interconnection console by means of signal trunks and control lines terminating in coaxial connectors on strategically placed wall panels. This provides great flexibility and permits high utilization of the available resources.

Initially instruments, outside-world display equipment, communication equipment, closed-circuit TV, etc. were shared among several groups of users, necessitating careful scheduling, but the trend has been towards more permanent facilities for each specific task, as additional equipment has become available and demands less diversified.

Early simulation tests used a simple cockpit (Fig. 5) which was built before the Viggen layout had been finalized and was therefore not intended to resemble it in detail. This cockpit has an analog-controlled hydraulic control-loading system and a collimated outside-world display. Converted 270° moving-coil instruments are used in the interests of simplicity and flexibility.

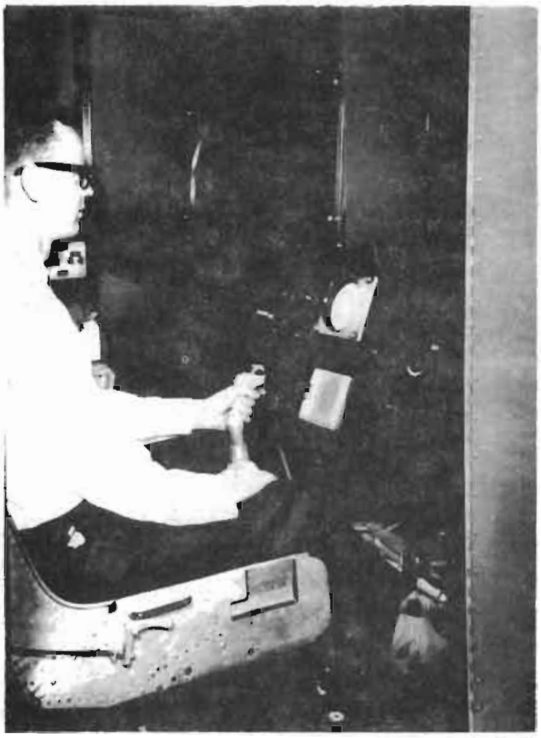

Fig. 5. Simple, general-purpose cockpit

The majority of the control-system simulation work has been done in the hydraulic system rig (Fig. 6), which includes a full-scale replica of the actual control system and is structurally equivalent to the aircraft as regards stiffness and mass distribution. It has a rudimentary cockpit with basic instruments and a collimated outside-world display for pilot-in-the-loop tests. For work on the primary flight control system (PFCS), this facility is interfaced directly to analog computers. To this combination is added an autopilot prototype for studies that involve the automatic flight control system (AFCS).

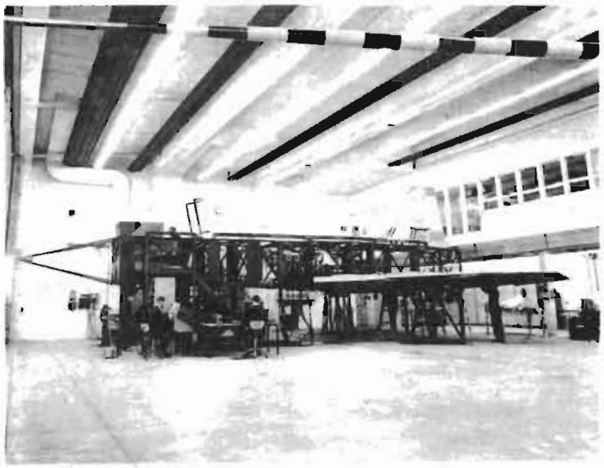

Fig. 6. The hydraulics and control system rig

The outside-world display is drawn on a 24" TV tube using oscilloscope-type deflection. It provides up to 16 straight lines whose end-point coordinates are controlled by analog signals, permitting a wide range of configurations to be programmed, e.g. a runway with glide-slope indication, height references, centre line, etc., which is displayed in essentially correct perspective. The display is collimated by means of glycerine-filled plexiglass lenses.

Development of the head-up display symbology and control laws has been done in a special simulator rig consisting of a pilot's seat and basic flight controls, a head-up display with symbol generator, and a synthetic outside-world display.

The outside-world display in this case is similar to that used in the control system rig, but used a projection tube rather than a TV tube (Fig. 7). The control feel system uses replaceable torsion springs and adjustable friction damping.

This simulator makes use of special programming equipment for rapid adjustment of parameters between runs by means of pre-punched paper tape. Special data logging equipment is also used, with printed and punched-tape output, the latter for subsequent processing in a digital computer.

A Saab-built G-seat (Fig. 8) has been used for studying longitudinal handling qualities and in particular high-speed, low-level flight in turbulent air. This unit has a vertical travel of ± 0.42 m, a maximum velocity of 3.5 m/s and a maximum acceleration of 15 m/s^2. Its response is flat within 1 dB up to 13 Hz and within 2 dB up to 18 Hz. It is hydraulically driven and is well provided with safety devices. Various mechanical control systems can be installed, together with basic flight instruments.

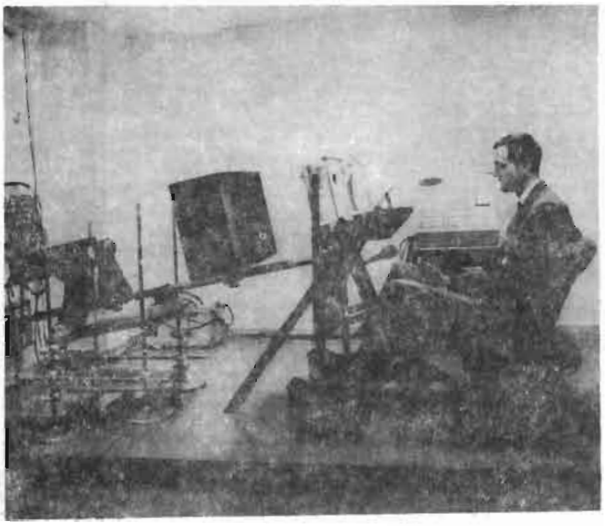

Fig. 7. Optical system for HUD simulator

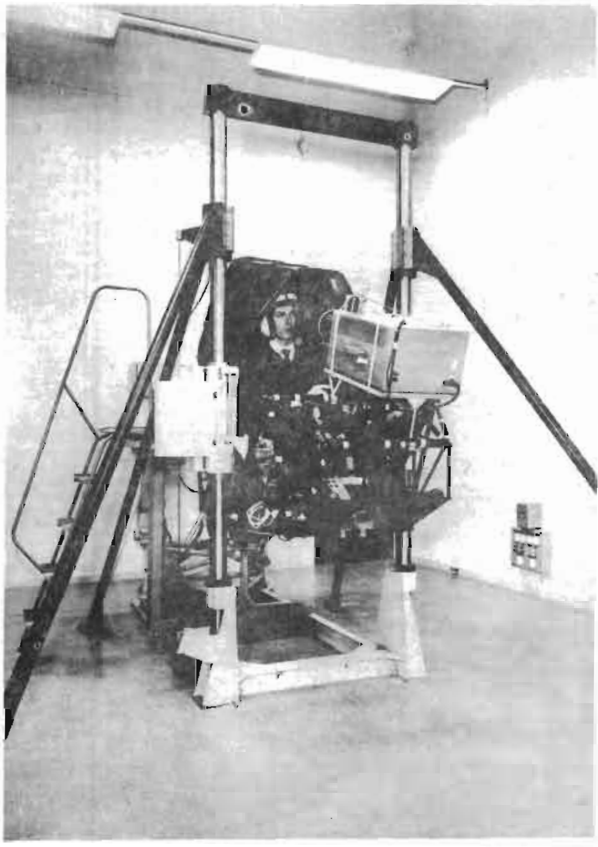

Fig. 8. The Saab-built G-seat

The AJ37 tactical equipment was flown at an early stage of the development program in two modified SAAB 32 Lansen aircraft, and this activity was supported by ground rigs in which flight tests could be prepared, duplicated and supplemented. These "breadboard" (Fig. 9) have now been dismantled, and work of this type is done in the tactical simulator.

Fig. 9. One of the Lansen breadboard rigs

The tactical simulation facility has a very completely equipped fixed cockpit as its central unit. The cockpit incorporates a hydraulic stick feel system which can be programmed to provide a wide range of force/displacement characteristics. A sound system simulates engine, afterburner, aerodynamic and landing gear noise to provide the pilot with important aural cues rather than merely to improve realism.

The collimated outside-world display currently used a modified Conrac large-screen oscilloscope. Various types of symbol generating equipment have been used, the present system employing one of the digital computers to draw configurations of up to 60 line elements. No special symbol generating unit is used, the deflection voltage ramps being simply and economically provided by the time constant of the D/A converters feeding the X and Y inputs.

A closed-circuit TV camera looks down onto the head-up display reflector glass and relays a combined head-up display/outside-world display picture to a monitor at the operator's desk.

Surrounding the cookpit there are numerous items of equipment such as head-up display symbol generator, servos driving instrument synchros, flight control system logic, feel system electronics, radar simulator, etc.

At the operator's desk there is a malfunction simulator from which a wide range of faults can be introduced and the pilot's actions and aircraft behaviour monitored.

An essential feature of the tactical simulator is the CK37 digital computer which has a central place in the airborne system. The unit used is provided with special interfacing to the simulator environment but operates with essentially the standard aircraft programs.

Extensive simulation computer facilities are required for the tactical simulator, which has full flight envelope capability. The configuration now in use consists of a 231R-V, a 231R, a 131R and a 31R, and an NSK3B digital computer. The complete simulator thus includes four consoles of analog computing equipment (more than 400 amplifiers) and three digital computers, in addition to extensive system and simulator hardware.

In addition to Saab's facilities, the simulation laboratory at the Division of Aeronautics at the Royal Institute of Technology (KTH) in Stockholm has participated in the development of the AJ37 system.

As the majority of the testing at Saab has been done in fixed-base simulators, the moving-base KTH simulator constituted a valuable means of checking whether misleading results might be expected.

The cockpit of this simulator is mounted on a motion system with three degrees of freedom - heave, pitch and roll. It incorporates a hydraulic control loading system and a collimated, synthetic outside-world display similar to that used in Saab's control system rig.

The computing equipment at KTH consists of a PACE 231R-V and a number of smaller 100-volt computers used for controlling the control loading system, outside-world display, etc.

Applications of Analog/Hybrid Simulation

Simulation is used in various ways at different stages in the progress of the system being developed. Initially there is a system definition phase in which a choice is made among various conceivable ways of providing the specified performance or functions. In this phase, limited data are available for the construction of detailed mathematical models, and the simulator hardware differs substantially from the final aircraft configuration.

As definition of system components proceeds, there is a steady transition towards the system development phase, in which the performance of various components is optimized within the framework of the overall system. Simulation during this phase typically involves increasing amounts of aircraft hardware and more detailed mathematical models for those parts not available as hardware.

The development phase culminates in the first flight of the first prototype, from which point there is a steadily increasing flow of information back to the simulation facility, establishing the validity or otherwise of the models used and conclusions drawn, and enabling corrections to be made for the next simulation phase - support simulation for flight test - as well as continued system development.

Support simulation serves both as a powerful means of dealing with the problems encountered during flight testing and of more fully investigating the flight envelope. It is also of great value when the flight test envelope is being expanded into potentially dangerous areas, such as malfunction cases in high-speed, low-level flight.

The following sections of this paper describe some of the tasks handled by simulation in the Viggen development program and the lessons learnt in the process.

Flying Qualities

The simulation effort in the area of handling characteristics has been very largely devoted to development of the flight control system rather than to studying the flying qualities of the aircraft with some form of idealized control system. As regards stability with controls fixed, experience with the SAAB 35 Draken had shown that wind-tunnel tests could yield very reliable aerodynamic data for use in routine stability surveys.

Some simulator studies were however carried out in order to gain insight into certain areas where there was doubt as to the validity of the Flying Qualities Specification (1). One such area was longitudinal control, where simulation in the G-seat was used in developing a new short-period response requirement taking account of load factor change per radian angle of attack, short-period frequency, short-period damping ratio and absolute damping. A block diagram of the simulator set-up is shown in Fig. 10.

The G-seat has also been used in developing a criterion for avoidance of pilot-induced oscillations (PIO), and a series of tests was run with a range of values for stick force and stick deflection per unit load factor in order to study the effects of these parameters on pilot opinion of longitudinal handling qualities. Comparative runs with and without cockpit motion showed no significant differences for flight conditions with pitch natural frequencies of 0.2 and 0.7 Hz but substantial differences at a frequency of 1.2 Hz, at least with high stick sensitivity.

The requirements based on these studies are presented in reference 2. The studies in the G-seat were not solely restricted to the Viggen but included the class of combat aircraft to which it belongs, thus also providing basic data for future use. Apart from this, the majority of the simulation effort at Saab has been specifically concerned with the Viggen configuration and systems.

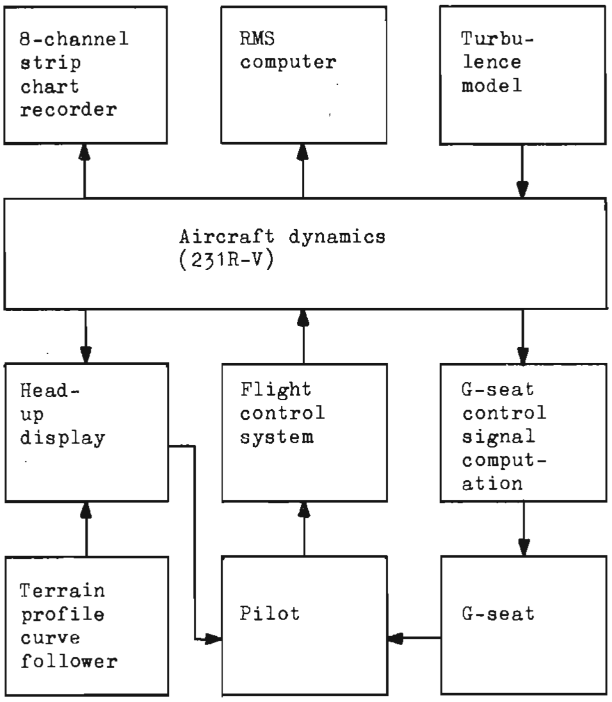

Fig. 10. G-seat simulator block diagram

Studies were run in 1964 using the simple fixed cockpit shown in Fig. 5 together with a schematic outside-world display in order to check that the required short take-off could be achieved with adequate rotation control. The display showed runway edge lines with transverse lines every 100 m, and provided the necessary information up to the moment of rotation, when all information vanished owing to the narrow field of view ($50^{\circ} \times 30^{\circ}$). In order to provide the simulator pilot with essential cues after rotation, aural means were used to indicate lift-off and - in the case of over-rotation - tail contact. These studies showed that after-burner take-offs from 500 m runways were readily achievable without over-rotation.

One lesson learnt from these early studies and confirmed by later experience was that pilots used to flying combat-type aircraft are in general significantly better simulator pilots than are both non-pilots and amateur pilots, whose performance tends to be fairly similar. In a series of simulated take-offs, the professional pilots had much less scatter in both ground-roll distance and tail clearance than did subjects from the other two categories, even when the latter subjects had accumulated considerable training time in the simulator.

Flight Control System

A substantial proportion of the Viggen simulation program has been concerned with flight control system development and performance verification. The total number of effective "flying hours" (excluding time to set up and debug the simulator, change flight conditions and other parameters, etc.) accumulated so far (mid-1970) in control system simulation is of the order of 1500. This figure applies to simulation with a pilot in the loop and does not include the extensive testing that has been done using standard pulse inputs rather than pilot evaluation. It is estimated that fully 1000 one-hour test flights would have been required to replace these 1500 hours of simulated flight.

During the period 1965-66 the main emphasis was on the primary flight control system (PFCS), which is required to provide at least the handling characteristics level needed for emergency operation as specified in the Flying Qualities Requirements.

Early difficulties with a full 6-degree-of-freedom (6-d-o-f) analog model prompted the adoption of a 5-d-o-f (constant airspeed) model for most of the subsequent work, with checks using an improved 6-d-o-f low-speed model in the important landing case. A block diagram of the simulator set-up for PFCS tests is shown in Fig. 11.

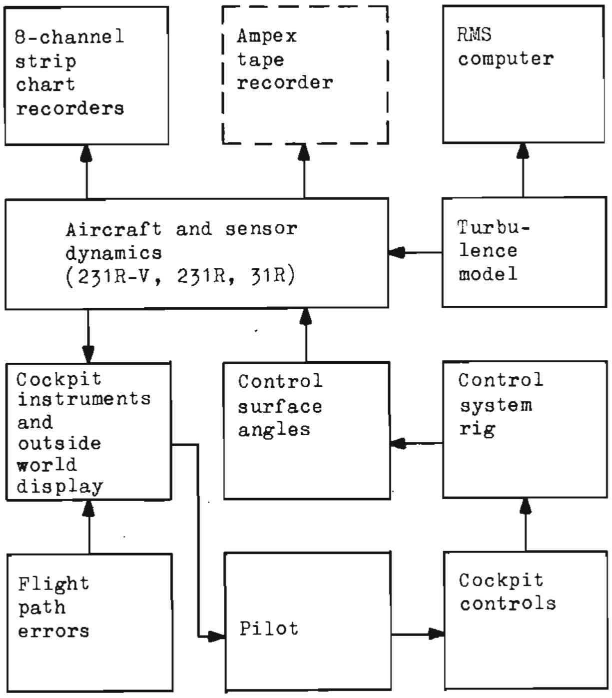

Fig. 11. PFCS simulator block diagram

This approach keeps the aircraft model down to a manageable size and dispenses with the extensive nonlinear equipment otherwise required to deal with airspeed variations. Using the standard Mimic program for this model, control pulse responses for some 20 variables are computed digitally and plotted for each flight condition and parameter combination to be studied, and used to check the dynamic performance of the analog model after each parameter change. The combination of a compact, easily maintained analog model and good checkout aids makes it a simple matter to switch flight conditions and gives a high proportion of effective "flying hours" to total accounted computer time.

Simulation proved its value at an early stage in the PFCS work when poor pilot ratings were traced to flow forces in the elevon servo valves being felt in the stick. The valves were modified to balance out the flow forces, thus eliminating a problem which would have been difficult to detect in open-loop testing and could have had serious consequences on the flight test program.

During verification of the operational safety of the PFCS in the simulator, a potentially hazardous condition was discovered. In the landing configuration, with canard surface flap deflected, the elevon angle to trim the aircraft is close to zero in certain loading conditions. If the pitch channel gearing were to go from the landing position to the high-speed position during such an approach, the pilot would notice no effect on the aircraft until he wanted to make a flight-path correction, when the response to his stick input would be much less than expected. As the pitch response time constant is fairly long in this flight condition, the time that would elapse before he became aware of the malfunction might be long enough for him to get into a critical situation. An effective warning system for this possible malfunction is therefore necessary in addition to reliable hardware.

Some idea of the match between pilot assessments of overall handling qualities in simulation and flight may be gained from Fig. 12, which shows comparative Cooper ratings for five flight conditions with the unaugmented PFCS. The figures are averages for 3-4 pilots and apply to the clean aircraft in the combat configuration. Agreement of this order indicates the validity of the fixed-base simulator and 5-degree-of-freedom model. It must be remembered, however, that this would not hold true, at least in the low-level M=0.9 case, if the stick sensitivity in pitch were increased until PIO tendencies appeared, in which case realistic ratings would not be achieved without cockpit motion.

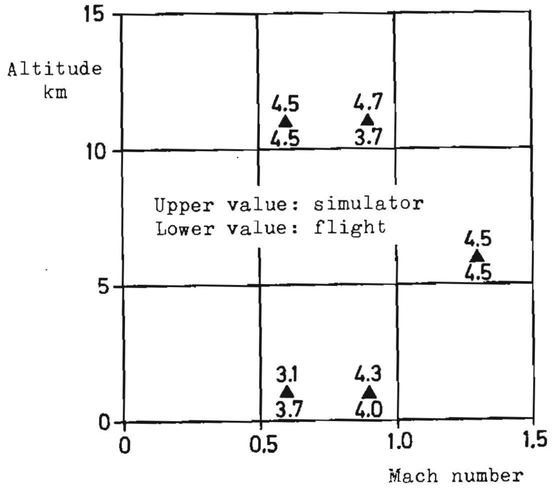

Fig. 12. Comparison between pilot assessments of overall handling qualities PFCS in simulator and flight.
Clean aircraft, combat configuration

For development of the automatic flight control system (AFCS) the simulation facility is essentially the same as that used for the PFCS, with the addition of an AFCS prototype (or analog model in the early stages). The simulation testing of the AFCS falls into the following categories:

- Development of AFCS functions
- Performance verification of stability augmentation system (SAS), control stick steering (CSS) and hold functions.
- Tolerance studies
- Safety
- Switching logic and levels
- Solution of problems encountered in above areas

The above list is not, of course, a chronological one; whenever a modification has been made in order to solve a problem encountered during previous studies, or aerodynamic or structural data have been revised, the performance must again be verified in the areas affected.

During the early stages of the development program, much of the simulation with SAS and CSS functions was done as pilot evaluation. It quickly became apparent that certain pilots both from Saab and from the Air Force Test Centre were extremely good at evaluating the system in the fixed-base simulator. They could detect quite minor errors in the mechanization, for instance an inadvertently altered derivative potentiometer (prior to the consistent use of digitally computed dynamic test data). Using experience gained during cross-checks with a 6-d-o-f aircraft model and with the moving-base KTH simulator, these pilots were able to allow for cues absent in the simulator used for most of the program. This very subjective kind of testing certainly seems acceptable, at least in a field like handling qualities evaluation, provided that the right pilots can be found.

Adequate cues must however be provided, and the outside-world display must be adapted to suit the task. In landing, the display cannot merely show the outline of a runway: it must also provide some glide-slope information and means of judging absolute height near the threshold as replacements for the textural information present in the real-world visual scene. Again, in order to assess precision steering characteristics, the display can consist of a ground target and an aiming dot tied to the aircraft velocity vector.

One area in which the simulator results turned out to be too optimistic was the automatic trim system originally used in the CSS mode. Although an apparently acceptable mechanization was developed in the simulator, when flight testing of the autopilot started it was quickly found that the resulting stick activity could not be tolerated.

Most other appreciable discrepancies between simulation and flight test are ascribable to shortcomings in the data available. Elevon effectiveness in flight and certain aero-elastic effects differed sufficiently from estimates to have an appreciable effect on flying qualities in certain flight conditions. Transonic trim changes encountered with external loads necessitated modifications to the flight control system. When these problems had been identified and revised data incorporated in the mathematical models, the simulation facility proved extremely valuable in working out solutions.

The later phases of performance verification have been done by means of standard pulses rather than pilot assessment. Response time histories are tape recorded and analysed using the same techniques and facilities as for flight test data. Digital time-history plots are generated, with the specified upper and lower bounds superimposed on the graph.

Head-Up Display

The simulator set-up used for development of the head-up display symbology and control laws is shown diagrammatically in Fig. 13. The Viggen head-up display principles are described in reference 3, and the experimental methods used are covered in reference 4, together with some of the results obtained in simulator studies.

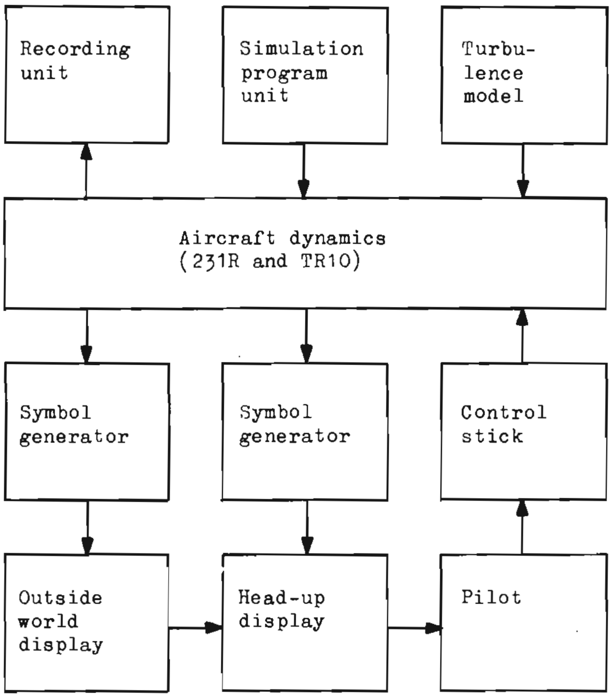

Fig. 13. HUD simulator block diagram

In addition to optimizing the display control laws, the simulator studies included an investigation of the effects of sensor imperfections on the results achievable with the display.

In contrast to the control system simulation technique using subjective assessments by a few hand-picked pilots, the procedure used in studying the head-up display was based on statistical treatment of measured data from randomized experiments with a larger number of pilots. In the case of handling qualities it is notoriously difficult to specify measurable quantities which give a useful correlation with pilot opinion, whereas the performance achieved with a head-up display, say in landing, can readily be defined in terms of deviations from the desired flight path and touch-down point.

As the head-up display is an essential part of the system that makes precision landings possible, the majority of the associated simulation program was devoted to the landing case. Checks with the moving-base cockpits at both Saab and KTH indicated that display performance measurements in the fixed-base simulator could be used with confidence.

In experiments to measure steering precision with a head-up display it is essential that the errors introduced by the simulator mechanization should be as small as possible. In particular, care must be taken not to control the head-up display and the outside-world display by variables generated in separate open-ended integrations, otherwise they will drift apart in an unpredictable manner and invalid results will be obtained.

Tactical System

The volume of simulation performed in connection with the Viggen tactical system is of the same order as that for the flight control system and is estimated to be equivalent to more than 1300 one-hour test flights.

The airborne digital computer system (5)forms the core of the tactical equipment carried by the aircraft, and therefore has a central role in the simulator facility in which ground testing and development of the tactical system is carried out. A block diagram of this facility is shown in Fig. 14.

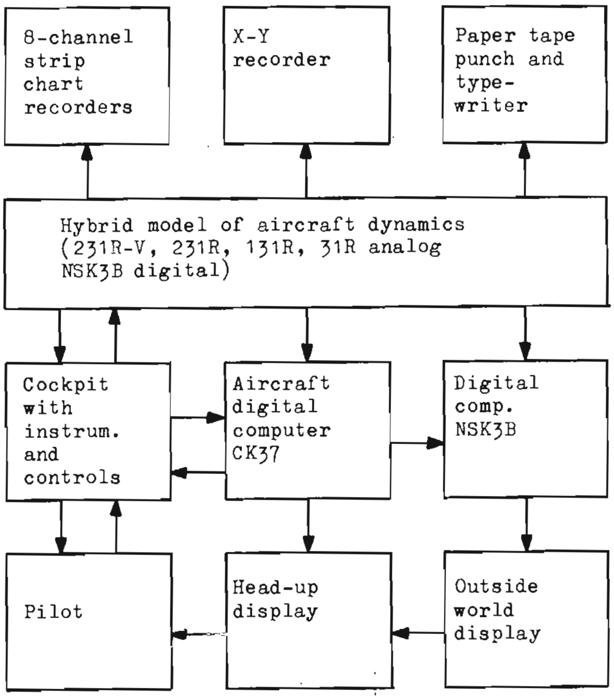

Fig. 14. Tactical simulator block diagram

The following types of task have been handled by the tactical simulation facility:

- Simulation of complete missions for mission analysis
- Dynamic checkout of digital computer programs
- Development of tactical functions such as fire control and navigation
- Simulation in support of flight tests
- Pilot training, especially in emergency procedures.

Simulated missions have been flown with different armament alternatives against various types of target in order to determine whether the airborne system and the specified mission profile are thoroughly compatible, and that the workload on the pilot is within his capacity, even when simulated emergency conditions are inserted at critical times. Without the dynamic environment provided by real-time simulation it is difficult to take proper account of the time factor in mission analysis, and too much may therefore be expected of the man-machine system in certain situations. The missions studied in the simulator excercise many of the important system functions in the process of take-off, way-point navigation, run-in, weapon delivery, evasive action, return navigation, perhaps to an alternate base, landing navigation, visual final approach and landing.

Although the programs written for the airborne digital computer can be checked statically for logical and formal errors, the only way of making sure that they perform as intended is to test then dynamically. As described in reference 5, the digital filtering of state variables forms an important part of the computer´s function, and it is very necessary that the algorithms used to achieve this do in fact provide the desired effect when interfaced to system hardware. A substantial proportion of the work done in the tactical simulator has therefore been devoted to dynamic program checkout.

In view of the central position occupied by the airborne computer in the tactical system, virtually all tactical simulation can be considered as some kind of dynamic program test. Fire control computations are a case in point. In the optical sighting mode for guns and rockets, the essential elements are the head-up display, the master reference platform and a computer program. Optimization of the sighting function is done by means of the computer program rather than by hardware modification. Here, as in many other contexts, the simulator is invaluable in that it enables the systems analysts to fly the system themselves and discuss its behaviour on reasonably equal terms with the pilots responsible for flight testing. In this way shortcomings in the system can be isolated and corrected much more effectively than if the analyst only had flight test reports to work from.

Simulation in support of flight test is in many ways a direct continuation of development simulation. Problems found during flight testing are referred back to the simulator for study and solution, which usually entails program modifications in the digital computer. In addition to this type of work, the simulator facility is used for rehearsing difficult flight tests and also for studying the performance of the system in dangerous manoeuvres, for instance ground attack runs down to zero altitude or turns very close to the ground. The calendar time required to solve a problem is generally much less in the simulator then in flight test, where cut and try methods must be used rather than real-time information feedback. When analysing a problem in the simulator it is often advantageous to study the effect of changing a single parameter, something which may be physically impossible in the actual aircraft.

The tactical simulator has many of the features normally found in a training simulator, although it was not built with this application in view. The presence of the malfunction simulator used in mission analysis makes it particularly useful for training new pilots in emergency procedures.

General Considerations

The piloted tests done in the control system and tactical simulators together are estimated as equivalent to more than 2300 one-hour test flights. This figure should be seen in relation to the total flight test time actually accumulated during the first two years of flight testing - 1100 hours. Division of the total cost of the simulation program by the equivalent flight-test time gives an hourly cost that is only one-fifth of the marginal cost for one hour of flight testing. In fact, several additional test aircraft would have been needed if simulators had not been available, and the cost differential would therefore have been even larger. There are clearly strong economic arguments in favour of simulation, even when the substantial amount of simulation done without pilots is left out of consideration.

It will always be necessary to leave the final polishing of handling qualities and system functions to flight test. No matter how sophisticated a development simulator may be, it is still dependent on the input data used in the mathematical models. It is unrealistic to hope that the data will ever include all the minor effects and imperfections which combine to make at least the fine structure of the aircraft´s characteristics differ in some respects from that realized in the simulator. The situation can be improved by using actual hardware as in the control system rig, but there are limits on how far it is worth going to achieve maximum fidelity in a development simulator.

In retrospect, there are a number of unforeseen benefits from the Viggen simulation effort which should not be forgotten when specifying future programs:

- Pilots become thoroughly familiar with the aircraft systems and the flight conditions at which they are to be tested in the air, and are thus able to get more out of each test flight, especially at the beginning of a new series.
- Flight test programs can to a large extent be checked out by pilots in the appropriate simulator, enabling cases of doubtful value to be eliminated.

- As many of the simulator tests (especially on the flight control system) have been conducted by the same people who later are responsible for the flight test program, these people receive an early training in the overall behaviour of the system and their specific problem areas.
- Whenever suitable, problems encountered during flight testing can be referred back to the appropriate simulation facility where systems analysts can work out solutions without disrupting the flight test program.
- Systems analysts and test pilots can work together in the simulators, enabling each group to gain a much better understanding of the other´s problems than would otherwise be possible.

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