

# THE USE OF DESKTOP SIMULATIONS IN THE CAREFREE MANOEUVRING FLIGHT TEST PROGRAM OF JAS39 GRIPEN

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## Abstract

The JAS39 Gripen high Angle-of-Attack (AOA) flight test program started in the summer of 1995 and was completed in the spring of 2000. A part of this program consisted of carefree manoeuvring tests to evaluate the flight control systems ability to keep the aircraft within AOA, Angle-of-Sideslip (AOS) and load factor limits during extreme pilot inputs.

This paper describes the introduction of desktop simulations into the carefree test program and how this has created a very efficient test procedure. A brief description of the tools developed and the lessons learned from their usage in the high angle-of-attack flight test program are also provided.

## 1 Nomenclature

a/c	Aircraft
AOA	Angle-of-Attack
AOS	Angle-of-Sideslip
ARES	Aircraft Rigid body Engineering Simulation
FCS	Flight Control System
FCL	Flight Control Laws
FTF	Flight Test Function
MLL	Manoeuvre Load Limiter
SwAF	Swedish Air Force

## 2 Introduction

The Gripen program was initiated in 1982 after a Swedish parliamentary resolution. An industrial group called IG JAS was formed by Saab, Volvo, Celsius and Ericsson with the purpose of developing and manufacturing a new combat aircraft including weapon and support

systems. The first flight was made in December 1988. The total number of aircraft ordered to date is 204 by the Swedish Airforce (SwAF) and 28 by the South African Airforce.

## 3 Aircraft Description

### 3.1 General

JAS39 Gripen is a lightweight multirole combat aircraft, powered by a single Volvo Aero Corporation RM12 engine (a derivative of the GE F404-400), rated at 80kN with maximum afterburner. The aircraft has a closely coupled delta canard configuration with elevons, all-moving canards and a conventional fin. Basic empty weight is about 7 metric tons and maximum take-off weight is about 14 metric tons. About 25% of the structural weight is composite material, mainly carbon fibre.



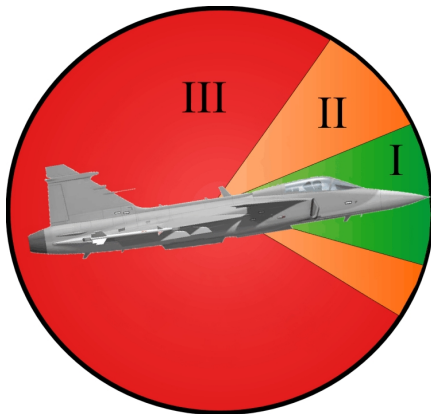
**Figure 1.** Three-view layout of the Gripen single seater.

### 3.2 Flight Control System

Gripen is aerodynamically unstable in pitch at subsonic speed and is controlled by a triple redundant digital Flight Control System (FCS), with a separate digital back-up mode. To improve turn performance and decrease buffeting, the aircraft has automatically actuated leading edge flaps. Longitudinal trim is automatically balanced between canards and elevons to minimise drag.

In order to provide the pilot with maximum performance without the risk of ending up in an out-of-control situation or over-stressing the structure, an automatic Manoeuvre Load Limiter (MLL) has been incorporated into the FCS. The MLL function limits maximum and minimum AOA and load factor (the AOS is always reduced by the FCS). However, it is possible to enter a low speed situation, with the risk of a departure or spin, from a vertical climb at flight idle. To prevent the pilot from entering such a situation, an audible minimum speed warning has been integrated into the FCS.

The high AOA Flight Control Laws (FCL) are divided into three different AOA regions as shown in figure 2.



**Figure 2.** The different AOA regions in the FCS.

Region I is the normal flight envelope where the limits depend on external stores, flight condition and fuel weight. All information is automatically sensed and the FCS adjusts the FCL between three different values of AOA-limit and four levels of maximum roll rate. The second region (II) is divided into two separate AOA segments. The segment on the

positive side is between the positive AOA limit up to  $55^\circ$ . The segment on the negative side is between the negative AOA limit down to  $-25^\circ$ . The aircraft is still statically unstable in this region and a non-linear prediction of AOA ( $\alpha\dot{\cdot}$ ) and an increasing feedback is used to recover the a/c.

In the last region III, from AOA above  $55^\circ$  ( $45^\circ$  on re-entry) or below  $-25^\circ$  ( $-20^\circ$  on re-entry), the aircraft is statically stable and the basic control law is full feed back, with auto-recovery from out of control. The FCS on the test a/c also has a backup direct-link mode to provide full control surface deflection. The auto-recovery function is normally engaged in both region II and III but the pilot has an option to switch between auto-recovery and direct-link mode in region III. The direct-link mode is used to investigate spin behaviour. The auto-recovery mode is divided into three phases:

1. Roll damping.
2. Yaw damping (anti spin)
3. Nose down (recovery from high/low AOA)

In the event of a departure, the FCS will first try to reduce any roll oscillation, then stop the yaw rate and finally pitch the nose down by using AOA and pitch rate as feedback signals.

The FCL used on the test aircraft has a special feature called Flight Test Function (FTF). The FTF is used to modify the FCL, for example gains or limits, or to send a pre-programmed deflection sequence to the control surfaces, which is used in aerodynamic database or flutter tests. During the carefree tests, these functions were used to increase the AOA limit above the nominal value in region I.

## 4 The Gripen High AOA Test Program

### 4.1 Objectives

The objectives of the JAS39 Gripen high AOA program were to demonstrate carefree manoeuvring with all types of external store configurations in the full envelope as well as spin and spin recovery characteristics. It was also important to verify and, if needed, update the aerodynamic database.

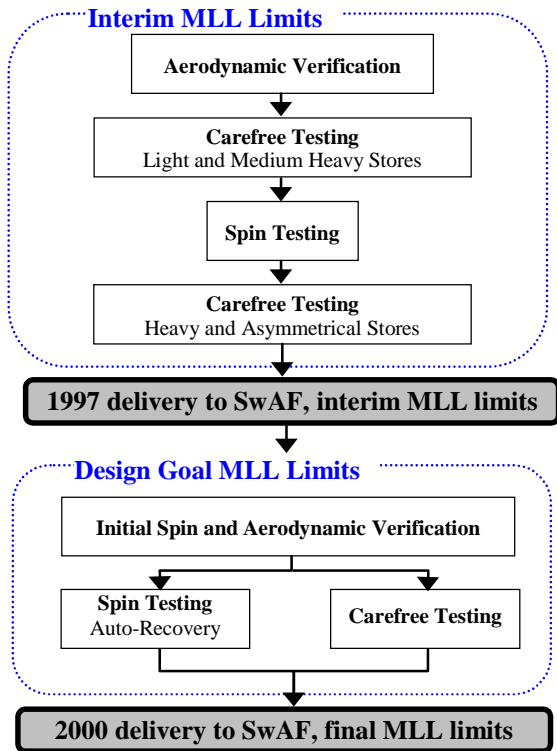


Figure 3. Gripen high AOA flight test program.

To achieve these goals, an extensive test program was initiated in 1995. By this time, the SwAF had already received their first batch of production aircraft and it was therefore decided to divide the carefree test program into two parts to allow early delivery and operational use of an interim MLL function. The carefree functionality was essential for the new tactical training of Gripen pilots, since it dramatically reduced the pilot workload. The initial part of the high AOA flight test program, as shown in figure 3, incorporated

reduced limit in AOA. The interim MLL limit test program also included aerodynamic database verification and spin testing to verify spin control laws.

The final part with the design goal limits started in 1998 and has recently been completed. This test program also included aerodynamic verification in spin and auto-recovery tests.

### 5 The External Store Classification System

Since the number of external store combinations (even with a limited number of weapons) is very large, Saab has developed an external stores classification system with four different classes. Combinations within the same class are considered to have similar flight mechanical characteristics. The classification formula is based on mass, inertia and aerodynamic parameters and result in one longitudinal and one lateral value. These values are used in the graph shown in figure 4. The borders between each class are defined by a few extreme store configurations. By concentrating the testing on these, a limited number of stores could clear all store configurations within each class. A build-up towards critical configurations was made by first testing stores from class I and II and finally stores from class IV. The configurations used during the final MLL limit tests are shown in figure 4.

Stores from class I and II have the full AOA envelope. Stores from class III and IV have a restricted AOA envelope, reduced roll performance as well as maximum load factor.

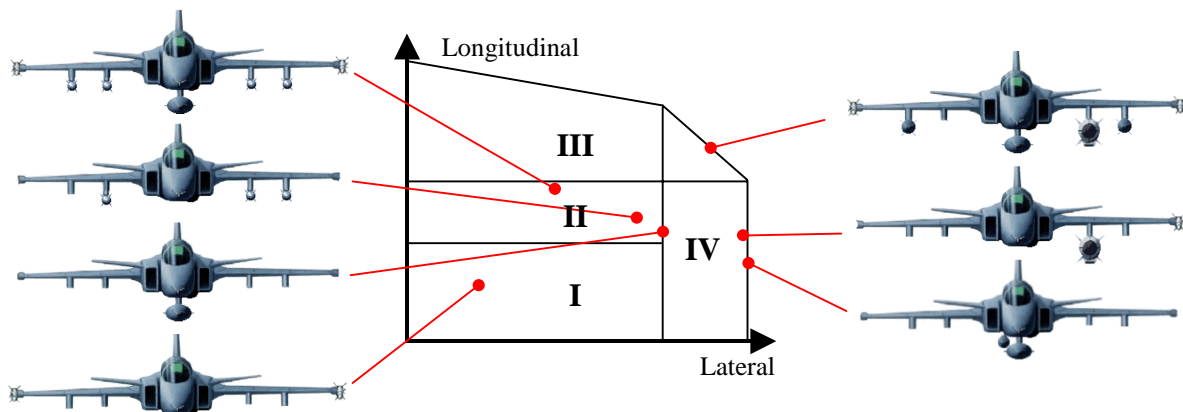


Figure 4. The Gripen external store classification system.

## 6 The Carefree Test Procedure

The carefree testing was divided into three blocks during the high AOA tests as shown in figure 3. Each block consisted of a development phase and a verification phase (figure 5). During the development phase, the AOA limit was increased above the nominal value with the use of FTF functions. The reason was to verify that the FCS could handle extreme overshoots or measurement errors of AOA on production aircraft. Any problems encountered during the development phase would be easier to handle with the specially equipped test a/c. The verification phase was performed with nominal limits in a more production like test a/c and was not as extensive as the development phase. Approximately half of the manoeuvres performed during the development phase were repeated in the verification phase.

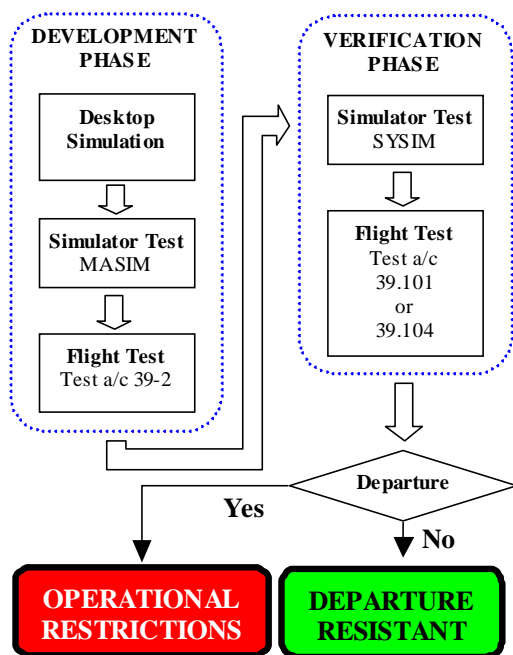


Figure 5. The carefree test procedure

## 7 The Manoeuvres

The carefree test program was designed with a build up in both store combinations and more difficult and hazardous manoeuvres. The initial manoeuvres were simple input in one axis and the most complex were combined inputs in all

three axes. The manoeuvres to be performed were divided into five levels:

1. Level A: Pitch input
2. Level B: Pitch and roll input
3. Level C: Pitch, roll and yaw input
4. PAL: Pitch and roll in landing conf.
5. ACM: Air combat and aerobatics

**Level A** type of manoeuvres consisted of pitch inputs towards the positive or negative AOA or load factor limits. All Level A manoeuvres started from high speed where power setting was reduced to flight idle. The different level A manoeuvres were:

- One-g deceleration.
- Maximum load factor turns.
- Minus one-g deceleration (inverted).
- Minimum load factor turns (inverted).

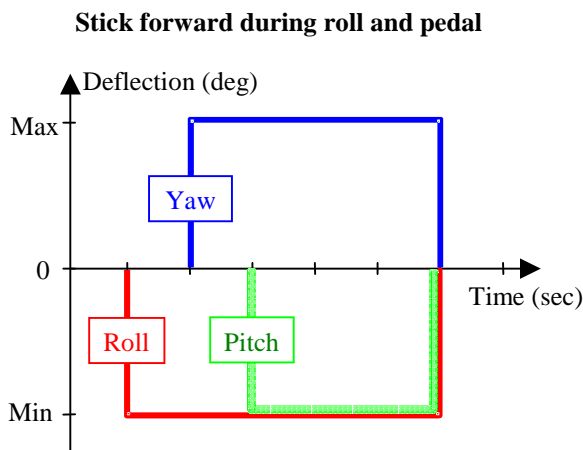
**Level B** manoeuvres were defined as roll input combined with pitch input. These manoeuvres were initiated from level flight or from full load factor turns. Level B manoeuvres included:

- Roll, 360° and 720°.
- Roll at maximum load factor.
- Roll during increasing load factor.
- Roll at negative AOA and load factor limit.
- Roll reversals at maximum load factor.
- Roll reversals, unloading during roll.

**Level C** included different combinations of pitch, roll and yaw inputs. This level also included manoeuvres to verify the minimum speed warning system. The different level C manoeuvres were:

- Roll and pedal into or against the roll.
- Stick forward during roll and pedal.
- Roll at maximum load factor and pedal.
- Stick forward at load factor roll and pedal.
- Increasing load factor roll and pedal.
- Roll and pedal at negative AOA-limit.
- Roll and pedal at negative load factor limit.
- Roll reversals and pedal at max load factor.
- Roll reversals and pedal, unload during roll.

Level B and C manoeuvres were all full stick or pedal deflection inputs as shown in figure 6. The different inputs were separated in time by approximately one second and the last input was held for at least three seconds. All inputs were relaxed at the same time.



**Figure 6.** Example of level C manoeuvre.

To verify the behaviour in landing configuration, a limited block of manoeuvres were also performed in the Power Approach Landing (PAL) configuration. Good handling qualities during landing are essential in the SwAF dispersed road base philosophy.

As a final test for each store configuration, a series of air combat and aerobatic manoeuvres were performed. There were no limitations in allowable manoeuvres and the test pilots decided themselves which manoeuvres to perform.

## 8 The Carefree Desktop Batch Simulations

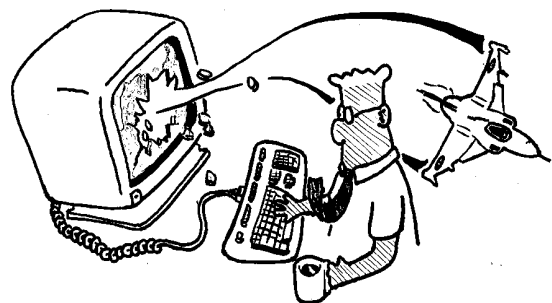
The batch simulation concept was developed during the initial tests of the interim MLL limits and was fully used in the final MLL limit tests. Since the number of possible manoeuvres and flight conditions was very large and the available flight hours were limited, it was decided to perform only the most severe and critical manoeuvres in flight test. Finding these manoeuvres was initially done in the fixed base simulators at Saab. This approach took a long time and involved a lot of people. Since the manoeuvres, as described in the previous chapter, were mostly of open loop type with maximum stick deflection, an idea was formed to use a desktop simulation model to find the most critical manoeuvres. By this time, a new version of the simulation model was released with a lot of useful features for batch simulations.

### 8.1 The simulation model ARES

The desktop simulation model used at Saab is called ARES (Aircraft Rigid Body Engineering Simulation). ARES is a six degree-of-freedom state space model used for flight mechanical analysis. It consists of several sub-models for aerodynamics, rigid body, FCS etc. The user has the possibility of reading and setting all state parameters in all the sub-models. The simulation can be controlled interactively or with the use of scripts.

The ARES source code is accessible to most engineers at the flight mechanical or flight test department at Saab. It is therefore possible to compile and run a local version of ARES with any kind of change in the source code.

ARES does not run in real time on a normal workstation, but this is possible with a more powerful computer and ARES is now the master model used in all ground-based simulators at Saab.



**Figure 7.** A typical engineer using ARES.

### 8.2 The graphical user interface

The initial batch simulation procedure required a lot of manual work. Several text files had to be provided and edited for each new case and the result had to be analysed manually. To simplify and speed up this process, a Graphical User Interface (GUI) was developed as seen in figure 8. The GUI was written in MATLAB<sup>®</sup> since several routines from the initial concept were already MATLAB-based and since MATLAB<sup>®</sup> provides good tools for easy and fast GUI design. The simulation model ARES had been updated to make it possible to call the MATLAB<sup>®</sup> calculation engine from the ARES prompt.



From the GUI, the user can easily specify all parameters needed to make one batch simulation. It is possible to select different versions of ARES and aerodata, or provide the path to a local ARES version. Any parameter in ARES can be set directly from the GUI or by calling a script file. One parameter can be varied from a minimum to a maximum value. This has for example been used to vary aerodynamic coefficients or fuel weight.

The initial flight conditions can be varied with respect to altitude and Mach or altitude and AOA. The starting point could be level or inverted flight or maximum load factor turns.

When the envelope points and parameters have been specified, all that is left is to select which manoeuvres to perform. All open-loop manoeuvres described in the previous chapter can be selected from listbox menus. It is also possible to provide a special user defined manoeuvre.

The simulation is started from the "Start Simulation" button. By selecting "Only File", it is possible to generate the script file and start the simulation later. The script contains all step-by-step commands necessary to control ARES.

Every simulation of a manoeuvre starts by reading a file with default settings. Any special parameter value is thereafter set before the trim

starts of the initial flight condition. When the model is trimmed, the result is saved in a temporary trim-file and the actual manoeuvre is simulated. The time history is stored in a temporary output file, which is evaluated immediately with MATLAB-based scripts. A search script finds maximum and minimum AOA, AOS, load factors, structural loads and the maximum deflections of control surfaces. Some special values, such as AOS at maximum AOA, are also extracted from the temporary time history file. A total of 30 values are extracted and saved from the time history. When the analysis has been completed, all temporary files are deleted and the simulation starts over with the next manoeuvre.

Each external store configuration was simulated with approximately 13000 variations in manoeuvres and flight conditions. Running these on a standard workstation would take several days. Therefore, a load-sharing software was used. By dividing the batch into smaller parts and sending these to several workstations, it was possible to complete one external configuration over night. The load-sharing program checks the status of all workstations in the network and submits the jobs to an appropriate machine.

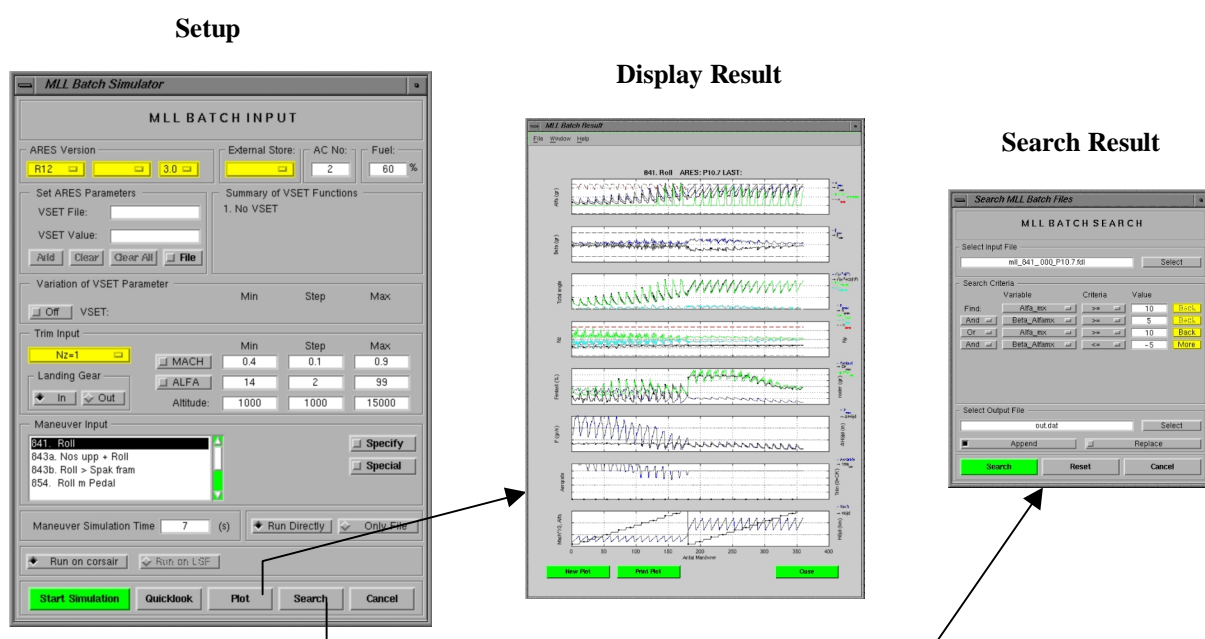


Figure 8. The desktop batch procedure.

### 8.3 Post-processing of batch result

The evaluation of the batch result is also done from the GUI. All extreme values can be plotted as shown in figure 8. Any overshoots of AOA or load factor limits are easily detected as interesting areas can be zoomed. Values can be extracted directly from the plot or by using the search-GUI also shown in figure 8.

From the search-GUI it is possible to create special search criteria in order to find critical or interesting manoeuvres. Cases with high AOA, AOS and large control surface deflections might need careful study of the time histories. A special plot-layout called Quicklook was created for this purpose. The Quicklook, shown in figure 9, can be created from the batch-GUI.

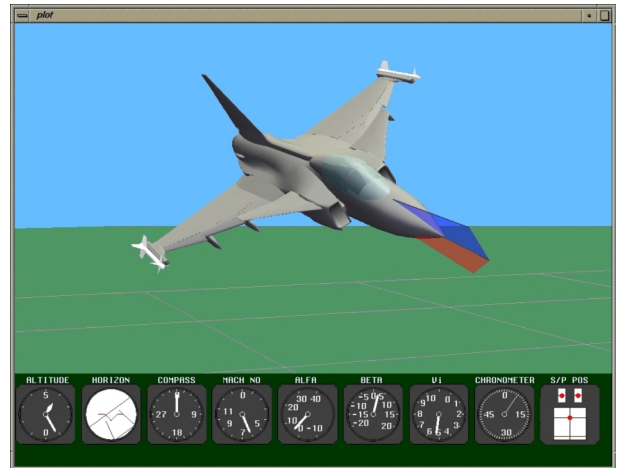


Figure 10. The graphical visualisation program VISOFLY

It is also possible to view the dynamic behaviour and control surface movements from a graphical visualisation program called VISOFLY (figure 10). This Saab-developed program displays AOA, AOS, speed vector and some of the cockpit instruments. It has proven to be a very helpful tool in understanding what really happens during both flight test and simulation.

### 9 The Carefree Simulator Test

During the first part of the carefree test program, with the interim MLL limits, ground-based simulators were used to find the most critical manoeuvres and to cover a larger envelope. Initial development phase was made in Saabs manoeuvre simulator and the verification simulations were done in the system simulator. Approximately 400 pilot-in-the-loop manoeuvres were performed in the simulator for each external store configuration. The simulator procedure was to first perform a set of manoeuvres at Mach 0.7 at 6 km altitude. For example: the roll with pedal can be performed in eight different ways. The roll can be initiated before the pedal input or vice versa and the commands can be left or right. When such a set of manoeuvres had been completed at M07/6km, a selection was made. The combination generating the largest AOS and/or AOA was repeated at higher and lower speeds and also at higher and lower altitudes.

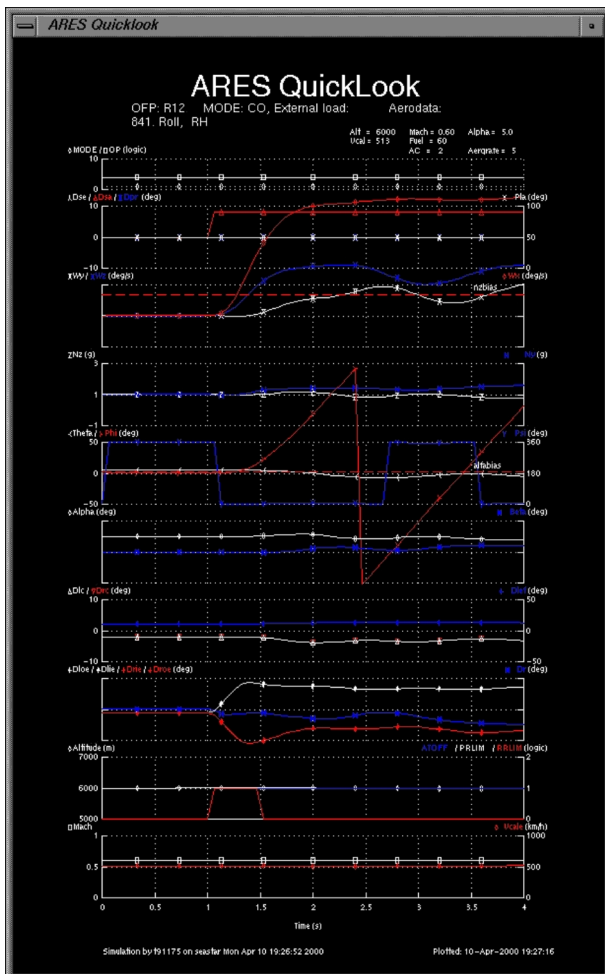


Figure 9. Time history plot of MLL manoeuvre.



**Figure 11.** The system simulator at Saab.

The drawback of this methodology was that it involved a lot of people, took a long time, was expensive and still could only cover a small part of the envelope. After the introduction of desktop batch simulations, the pilot-in-the-loop simulations have changed to only verify the desktop batch simulations, generate footprints and prepare the pilots and test engineers prior to flight test. Some closed-loop manoeuvres, for example roll-reversals, are still performed in the simulators first.

## 10 The Carefree Flight Test Program

### 10.1 Test aircraft

Three test a/c were used in the flight test program. The development phase flights, both with the interim and design goal MLL limits, were performed with test a/c 39-2 and the verification flights were performed in 39.101 or 39.104.

Test a/c 39-2 was modified specifically for the high AOA tests with anti stall chute, revised subsystems, special cockpit instrumentation and a new colour scheme. The anti-stall chute was small compared to a normal spin chute and its purpose was to help breaking a potentially deep stall. The cockpit instrumentation in 39-2 had conventional clock instruments instead of the multifunctional displays used on the production aircraft. Modifications of the cockpit also included stick position and yaw direction indicators. Several subsystems were revised

with better backup capacity in the event of engine failure. The black and white colour scheme was needed for optical tracking and to make it easier to recognise the attitude. The last flight of 39-2 was made on 22 of December 1999.

The verification phase test flights were performed with more production type test a/c. AOA-limits and FCL were nominal and the only difference from a production a/c was the instrumentation and telemetry system. Test a/c 39.101 was used initially but was replaced with 39.104 in the end of the program.



**Figure 12.** Test a/c 39-2 with anti stall chute.

### 10.2 Flight Test Procedure

Combinations of manoeuvres that generated high values of AOA and/or AOS were selected for initial flight test with 39-2. During the later part of the flight test program, after the introduction of desktop batch simulations, approximately 40 out of 13000 simulated manoeuvres were selected for pilot-in-the-loop simulation and flight test.

The result in AOA, AOS etc. from the ground-based simulator was written onto the test cards. In this way, the whole crew in the telemetry-station Houston (figure 14) was aware of what to expect at each test point and could assist in the analysis. The monitors in the telemetry-station were modified to display some critical values such as maximum and minimum AOA, AOS and load factors. They also showed time at control surface deflection limits and specially developed time histories and cross plots.

During a manoeuvre, critical parameters were monitored and compared with the values



from the simulator. If the difference was within a specified margin ( $\pm 2^\circ$  in AOA and AOS) and the footprints matched, the Houston crew gave clearance to continue to the next test point. This could be done within seconds.

The pilot was always informed of the expected maximum values in AOA and AOS before each manoeuvre. If the pilot saw that the actual values differed by more than the specified margin, the pilot would abort the manoeuvre immediately, since the ground crew always saw the values with some time delay.

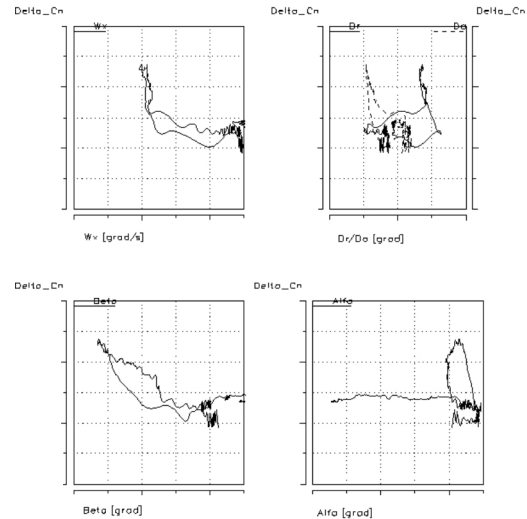
If the values differed or the footprints matched poorly, the a/c was put on hold and a “quick-analysis” was made. The aerodynamic coefficients were calculated from the telemetry data and compared with the aerodynamic database. The calculations took approximately one minute and the result could be presented as a difference between the actual, measured coefficients and the corresponding values in the aerodynamic database as shown in figure 15. If major differences were discovered, the flight could be aborted or critical test points could be postponed until a more extensive post-flight analysis was made.



**Figure 14.** The telemetry station Houston.

The flight test procedure turned out to be an effective and safe way to proceed and the carefree test flights were a great success. One external store configuration was covered with

two or three flights during the final MLL limit tests after the introduction of desktop batch simulations.

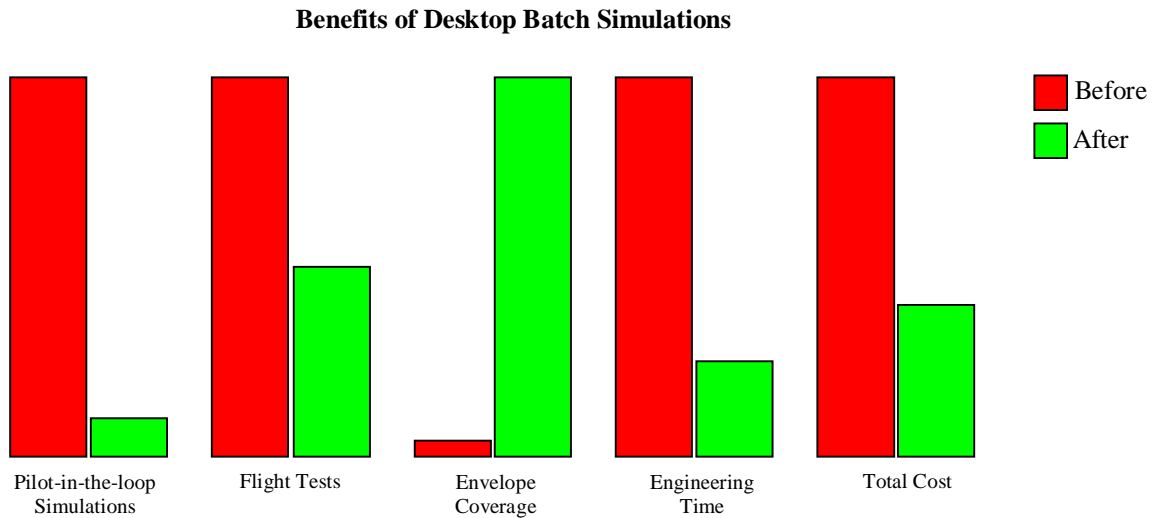


**Figure 15.** Quick analysis plots

## 11 Benefits and Limitations of Desktop Simulations

The benefit of desktop simulations was apparent already when the first batch was completed. Problems with the FCL were directly identified in certain points of the envelope that previously had not been found during the validation and verification of the FCL. High AOS values could be confirmed in the ground-based simulators and these problems resulted in an updated FCL. After this discovery, desktop simulations were also introduced in the validation process of the FCL.

The introduction of desktop simulations resulted in a significantly higher coverage of the operational flight envelope compared to the original method when ground-based simulators were solely used to cover the envelope and select manoeuvres for flight test.



**Figure 16.** Comparison before and after introduction of desktop batch simulations in the carefree test program.

The desktop simulations gave a very good overview of the FCS capacity and potentially weak areas. The batch result was used to focus the flight tests on uncertain points and approach these points with a step-by-step procedure. For example, desktop simulations indicated problems at high altitude. Since a model always has deficiencies and the data at high altitude were not extensive, it was decided to approach the critical flight conditions from a safe altitude. The flight tests proved the desktop simulations to be correct and this previously unknown problem area resulted in further updates of the FCL. This shows the strength of desktop batch simulations in finding tendencies, which makes it possible for the test engineer to find real problem areas. All desktop simulations were performed by the flight test engineer, which gave him or her a good knowledge of the a/c performance and an advantage when conducting the flight test.

The limitation of the desktop batch simulation approach is the model concept itself. The flight tests were performed to verify the model result rather than investigate the actual flight behaviour. ARES is based on a static coefficient database and the MLL test consists of highly dynamically manoeuvres. This fact raised questions about the usefulness of batch simulations but the result from the flight tests compared very well with the ARES result,

especially after initial updates of the aerodynamic database.

## 12 Conclusions

The primary objective of the carefree tests was to verify a departure free FCS with all type of external store without any operational restrictions. This objective has now been met with the latest version of the FCL that will be delivered to the SwAF in 2000. A total of 150000 manoeuvres with several store configurations have been simulated in the simulation model ARES and during the whole carefree program approximately 1000 manoeuvres have been performed in actual flight tests to verify these result.

The desktop batch simulation concept has reduced the need for test flights by 50% and the pilot-in-the-loop simulations by 90%. The total time and cost to clear one new store configuration was reduced by 75%. These reductions have been accomplished with a better coverage of the envelope and a higher confidence in the final result as shown in figure 16.

The desktop simulation concept (and GUI) has also proven to be valuable in several other flight mechanical investigations.