AERODYNAMIC AND FLIGHT DYNAMIC REAL-TIME ANALYSIS DURING SPIN AND CAREFREE MANEUVERING TESTS OF THE SAAB JAS39 GRIPEN.

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1 Abstract

The Flight Control System (FCS) in JAS39 Gripen has a function called the Maneuver Load Limiter (MLL). Its purpose is to give the pilot maximum performance in every situation, without ending up in an out-of control situation or overloading the structure. Even if the MLL function prevents departures in the normal envelope, it is possible to enter an extreme low-speed situation if the low-speed warning is ignored. To evaluate the MLL function and the spin characteristics, flight test have been performed at Saab since 1995.

One new tool developed to increase efficiency and reduce costs during these tests is called ROMAC (Real time On-line Model and Aerodata Control). ROMAC includes a complete simulation model of the Gripen aircraft, running in real time using telemetry input data from a flying test aircraft. With a delay of only one second it is now possible to perform a real-time parallel simulation, comparing the results from the complete simulation model with flight test data.

To avoid that the simulation will diverge from the flight path of the test aircraft, a "wing man" pilot model has been developed. The pilot model acts as a wingman flying in formation with the test aircraft. ROMAC also includes a separate implementation of the JAS 39 Gripen aerodynamic model and real-time aerodynamic analysis of flight test data. In the last five years the time to get an aerodynamic comparison plot has decreased from half a day to a second.

The use of real-time analysis during carefree maneuvering and spin tests has significantly improved the efficiency of each test flight. It has also significantly improved the decision support during flight tests.

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2 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
F_V	Earth parallel vehicle carried coordinate system
F_W	Body fixed wind-oriented coordinate system
HAOA	High Angle of Attack
GE	General Electric
IG JAS	IndustriGruppen JAS
JAS	Jakt Attack Spaning
K_{PW}	Wingman pitch gain
K_{PFCS}	FCS pitch gain
K_{RW}	Wingman roll gain
K_{RFCS}	FCS roll gain
K_{VW}	Wingman velocity gain
MLL	Manoeuvre Load Limiter
ROMAC	Real time On-line Model and Aero-data Control
RM12	ReaktionsMotor 12
SAS	Stability Augmentation System
SwAF	Swedish Air Force
V_{TS}	True airspeed simulation model
X_{WA}	X-axis of the aircraft F_W
X_{WS}	X-axis of the simulation model F_W
Y_{WS}	Y-axis of the simulation model F_W
Z_{WS}	Z-axis of the simulation model F_W
$\Delta\gamma_L$	Wingman local climb angle error
$\Delta\gamma_L(\Delta H)$	Wingman local climb angle error due to altitude error
$\Delta\delta_{PS}$	Wingman additional pitch stick input
$\Delta\mu_L$	Wingman local bank angle error
$\Delta\mu_L(\Delta\chi)$	Wingman local bank angle error due to local course error
$\Delta\chi_L$	Wingman local course error
$\Delta\chi_L(\Delta H)$	Wingman local course error due to altitude error
$\Delta\delta_{RS}$	Wingman additional roll stick input
ΔT	Wingman tangential force error
ΔV_C	Wingman velocity error

3 INTRODUCTION

The Gripen program was initiated in 1982 after a Swedish parliamentary resolution. An industrial group, IG JAS, was formed including Saab, Volvo 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 this date is 204 by the Swedish Airforce (SwAF) and 28 by the South African Airforce.

4 AIRCRAFT DESCRIPTION

4.1 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 (figure 1). 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.

Figure 1. ***Three-view layout of the Gripen 39A single seater.***

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4.2 Flight Control System

Gripen is statically 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. To prevent the pilot from entering such a situation, an audible minimum speed warning has been integrated into the FCS.

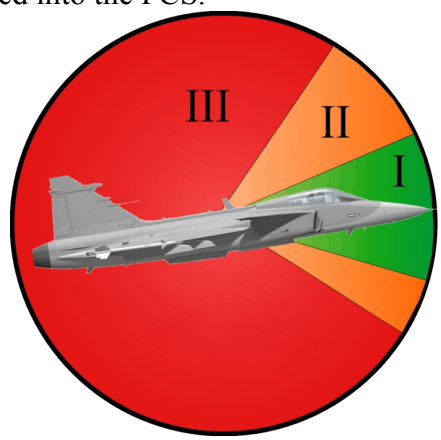

Figure 2. ***The different AOA regions in the FCL.***

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

Region I is the normal flight envelope.

The second region (II) is divided into two separate AOA segments as seen in the figure. The aircraft is still statically unstable in this region and a non-linear prediction of AOA (via alpha-dot) and an increasing feedback is used to recover the aircraft back into region I.

In region III the aircraft is statically stable and the control laws includes an auto-recovery function back to region I. The FCS in the test aircraft also has a backup direct-link mode to provide the pilot with full control of surface deflection. The direct-link mode is used to investigate spin behaviour.

5 HAOA TEST PROGRAM

5.1 The test aircraft

Three test aircraft were used in the HAOA flight test program for the single seater, 39A. The development phase flights were performed with test a/c 39-2 (figure 3), first with interim MLL limits and finally with the design goal MLL limits. The verification flights were performed in 39.101 and 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 potential deep stall. The cockpit instrumentation in 39-2 had conventional clock instruments instead of the multifunctional displays used in 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 two seater (39B) test aircraft 39.802 was modified with an anti-stall chute for the carefree tests. Prior to the spin tests two clock instruments were installed in the cockpit, one for AOA and the other for yaw rate. That was the only modification made on 39.802 otherwise everything was as a production aircraft.

5.1.1 The Gripen 39A HAOA Test Program

The objectives of the JAS39 Gripen HAOA 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 impor-

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tant to verify and if necessary update the aerodynamic database.

Figure 3. **Gripen 39A:** ***Test a/c 39-2***

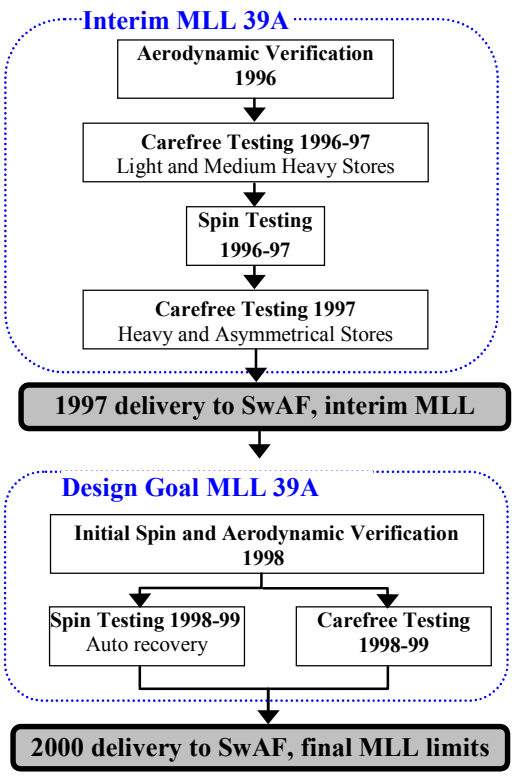

Figure 4. ***Gripen 39A HAOA flight test program.***

To achieve these goals, an extensive test program was initiated in 1995.

The initial part of the high AOA flight test program, as shown in figure 4, incorporated a 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 was completed the year 2000. This test program also included aerodynamic verification in spin and auto-recovery tests.

To verify all the production like systems in a spin situation, a spin program with a production aircraft was accomplished in the spring of 2001. No anti-stall chute was used during these tests thanks to the good experiences from the spin tests with 39-2.

5.1.2 The Gripen 39B HAOA Test Program

The carefree tests with the two seater, 39B, started in 2000 and were concluded in the autumn of 2001.

Figure 5. **Gripen 39B:** ***Test a/c 39.802***

A spin program with 39B was accomplished between June and September 2001 (figure 5-6). These tests were initiated as 39B has a longer nose section and thus has its cg shifted forward compared to the single seater. Experiences from spin programs of other aircraft projects indicated that a different nose geometry could give changed spin characteristics.

The test objectives were to find out the spin characteristics, to verify the aerodynamic model and to verify the auto recovery system.

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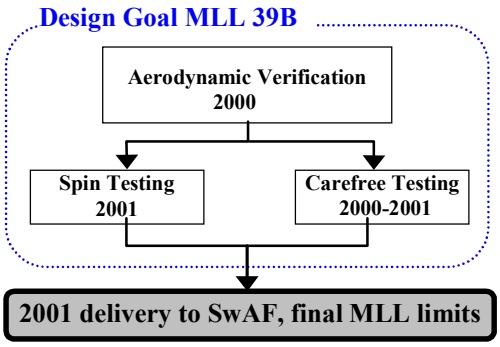

Figure 6. ***Gripen 39B HAOA flight test program.***

The tests showed there were significant discrepancies in the aerodynamic model and this has resulted in an update of the model. The auto recovery system worked well and recovered the aircraft without the need for pilot intervention. The FCS edition was delivered in the end of 2001.

6 FLIGHT TEST EVALUATION DURING THE 90'S

6.1 Batch-oriented post-processing tools

Most frequently used methods to evaluate the aerodynamic model is parametric identification and comparison between aerodynamic coefficients from the database and flown flight test coefficients.

Parametric identification tools are useful for post processing of test points flown in the normal, linear part of the flight envelop. For MLL and spin test maneuvers, comparison between aerodynamic coefficients from the database and flown flight test coefficients are, due to the non linearity, more suitable.

Feeding a complete aircraft simulation model with input data from a test aircraft, parallel simulation, has also been used. Until the development of the wingman pilot model described below, the usage was not that frequent.

The time to get a plot of aerodynamic coefficients from a test flight (together with aerodynamic data base coefficients) was about one day in the early 90's. The aircraft had to land before the recorded information onboard was available. The data from the aircraft was transferred to a data file with correct calibrations and scaling on all parameters. Normally the test flight was flown one day and evaluated the day after. Batch oriented tools were used, i.e. the data for the whole flight was processed in each step before it was transferred to the next step.

6.2 Using batch-oriented tools during tests

A need for evaluation between the test points came around 1993-94 when landing tests in high wind and turbulence were about to start.

The FCS response and the turbulence level were evaluated. The result was compared with the expected FCS response and turbulence before the next landing. This was a way to efficiently use the occasion of desired wind conditions without reduced flight safety. Telemetry data was transferred from the aircraft to the ground and flight test data was available a few seconds after the test point was finished. Post-processing routines, optimized to take short time to run, did the evaluations and the plots were ready after a couple of minutes. The evaluation was still batch-oriented, based on the normally used post processing routines. The same concept was used for MLL/Spin test for aerodynamic analysis (1997 – 2001). Post-processing routines are normally not optimized for time efficient processing. The routines used at Saab Flight Test are optimized for flexibility and clean structure. To process a one-minute test run using quick analysis, two to three minutes of computer time was used.

6.3 Real-time tools

In year 1999, tests indicated that it was possible to evaluate aerodynamic coefficients in real time with available computers. At the same time the idea with a wingman pilot model arised, that was the starting point for the development of ROMAC, a tool for real time parallel simulation and analyses of aerodynamic coefficients.

The telemetry data from the aircraft are transferred to ROMAC sample by sample via the presentation system VuSoftNT. ROMAC takes the data and execute the computations. The processed data is transferred back to VuSoftNT,

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where parallel simulated data and/or aerodynamic coefficients are presented in the same way as any telemetry parameter. The delay of data from the parallel simulation is mainly the delay (buffering) in the instrumentation chain, approximately 0.5 second. The delay for the aerodynamic coefficients is about 0.5 seconds longer due to delay in time symmetric low pass/differentiating filters.

Thus, the time from flown test point to a plot of aerodynamic coefficients has gone from one day to one second.

6.4 VuSoftNT

Saabs real-time presentation system is built upon a commercial product called VuSoftNT.

VuSoftNT can dynamically attach/detach different sub modules. So depending on the attached sub modules functionalities, VuSoftNT can perform different tasks in real-time.

VuSoftNT is mainly developed to decode fast telemetry data streams using soft decoders. During flight test the flight test engineer is fed with real-time data, video and audio. Primarily the data, video and audio are simultaneously recorded but each user has the possibility to record data locally for fast replays during the test flight. This functionality gives the user a great deal of flexibility. The data, video and audio recorded can be replayed synchronously after the test flight.

VuSoftNT contains a real-time mathematical calculator, capable of everything from simple addition and subtraction to real-time filters. The new calculated parameters can be viewed as if they were standard telemetry parameters.

VuSoftNT communicates with ROMAC, which runs on a SUN server, over a 100Mbit Ethernet connection.

7 PARALLEL SIMULATION

To be able to make a fair comparison between simulation model and aircraft it is of major importance that differences in flight condition do not affect the results. As there always will be differences between simulation model and reality, the flight conditions during a parallel simulation will sooner or later diverge from each other. In some way forces and moments have to be added to the simulation model to keep the flight condition similar. Model errors will then be seen as errors in both control signals and output signals. If for example the correction of the flight condition is made with large forces and moments a small error will be seen in flight condition but the error in the control signals will be large, and vice versa.

7.1 Aircraft simulation model

The aircraft simulation model used in ROMAC for the parallel simulation is based on the desktop aircraft simulation tool at SAAB, ARES (Aircraft Rigid Body Engineering Simulation). ARES is a six degree-of-freedom non-linear 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.

For the ROMAC application, all aircraft specific sub-models in ARES are extracted and adapted to a ROMAC developed interface. Input data to the simulation model is of two kinds, continuously changing data as telemetry data from the flying aircraft and constant settings from the operator defining aircraft configuration etc.

7.2 Control error signals

As mentioned, the simulation model has to keep the flight condition similar to the real test aircraft by adding extra forces and moments. The choice of the control error signals to minimize by the added forces and moments, depends of which variables to evaluate. In this case flight mechanic and aerodynamic related variables are typically of interest. For example rudder deflections, angle of attack, sideslip angle etc. The rule is not to control the signals to be evaluated, or signals hard coupled to these.

7.2.1 Velocity vector error

In this case the difference in velocity vector and bank angle between the simulation model and the test aircraft defines the control error. The primary control error signals to minimize

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are then the climb, course and bank angle as well as the absolute value of the velocity.

Since the aircraft and the simulation model will be moving independently with reference to axis of the vehicle-carried system F_V, a decision was taken to express the errors in the wind-oriented system F_{WS} of the simulation model.

The necessary transformation is performed by projecting the test aircraft velocity vector (X_{WA}) on the planes defined by the simulation model axes (X_{WS}-Y_{WS} and X_{WS}-Z_{WS}, see figure 7). The angle between the projections and the aircraft velocity vector are the local climb angle error, $\Delta\gamma_L$, and the local course heading error, $\Delta\chi_L$.

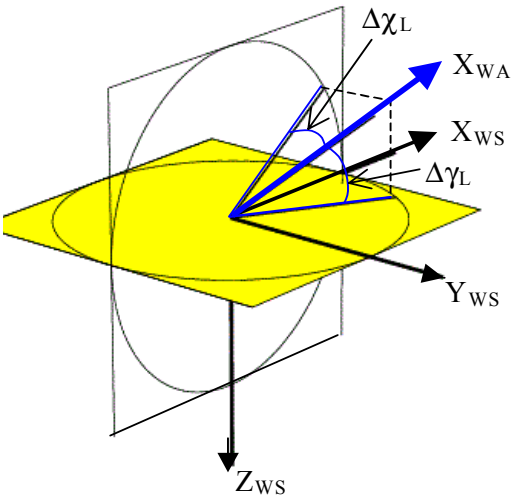

Figure 7. ***Definition of local climb and course heading errors.***

7.2.2 Altitude error

Secondary the difference in altitude is minimized. Difference in altitude is corrected in both the longitudinal and the lateral controller, depending on the bank angle of the simulated aircraft.

The error due to altitude is a vertical vector projected on Z_{WS} and Y_{WS}. The vertical vector is defined by using a "fishing rod" with length $\tau*V_T$, spanned between the simulation model and the real aircraft (figure 8). The fishing rod is the hypotenuse of a rectangular triangle where the opposite cathetus is the projection on the Z_{WS} and Y_{WS} axes. The two angles created, $\Delta\gamma_L(\Delta H)$ and $\Delta\chi_L(\Delta H)$, are then the local error in climb angle and course heading with respect to a difference in altitude. In the case of zero bank angle for the simulation model, the $\Delta\chi_L(\Delta H)$ is zero (as seen in figure 8).

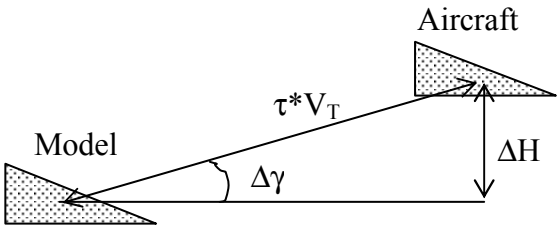

Figure 8. ***Fishing rod method***

7.3 Wingman pilot model

A pilot model has been developed, aiming to minimize the differences between the simulation model and the test aircraft. The pilot model acts as a wingman, flying in formation with the test aircraft.

The flight path is corrected by additional stick inputs from the pilot model (figure 10-2, 10-4). The additional stick inputs are added to the actual pilot commands from the flying test aircraft (figure 9). The forces and moments needed to act as a wingman are then in reality achieved by additional control surface deflections. By doing it this way the MLL function downstream in the FCS will protect the simulation model from departure when adding extra forces and moment.

Another way to reduce the flight path error is to add extra forces and moments to the simulation model. For a modern fighter, as the Gripen, the FCS is typically highly augmented. For a specific aircraft configuration and flight state a given pitch stick deflection commands a specific load factor. If the simulation model for some reason needs additional moment an unwanted "force fight" between the FCS and the added moment is the result. There is also a risk to override the MLL-function.

For the velocity control a tangential force is added. In this specific case there is no interaction with the FCS.

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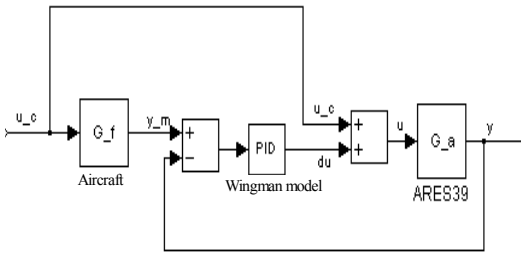

Figure 9. ***Wingman pilot model***

7.3.1 General design

The pilot model includes three controllers. The longitudinal controller augments on local climb angle and altitude. The lateral controller augments on local course angle, bank angle and altitude. The velocity controller augments on velocity. All three controllers are PID regulators. Flat earth estimation is used resulting in that the distances between aircraft and model in the xy-plane is of no significance.

Differences in velocity and bank angle have to be quickly minimized. A drift in calibrated airspeed affects performance characteristics much and a small difference in bank angle rapidly results in a large attitude difference (notice the curves with no wingman in figure 10-5,10-6). Thereby the velocity controller and the lateral bank controller need a high gain. The course heading and the climb angle control are less rapid.

During the design of the pilot model it is important that the controller gains do not interact with the aircraft augmented eigen-frequencies. By using frequency separation in the design process the time step responses for the pilot model will almost be of a first order system.

7.3.2 Longitudinal controller

Total local error in climb angle is the absolute local error and the local error due to a difference in altitude.

$$\Delta\gamma_{tot} = \Delta\gamma_L + \Delta\gamma_L(\Delta H)$$

The $\Delta\gamma_{tot}$ is scaled into ΔN_Z. By using the FCS internal gain, K_{PFCS}, defining load factor as a function of stick deflection the controller specific gain, K_{PW}, is simply a constant in the entire flight envelop. Additional stick deflection (figure 10-2) is then defined as:

$$\Delta\delta_{PS} = K_{PW} * K_{PFCS} * V_{TS} * \Delta\gamma_{tot}$$

7.3.3 Lateral controller

The lateral controller corrects the bank angle and the course heading as well as the altitude. Total error in bank angle is defined as:

$$\Delta\mu_{tot} = \Delta\mu_L + \Delta\mu_L(\Delta\chi)$$

where

$$\Delta\chi = \Delta\chi_L + \Delta\chi_L(\Delta H)$$

Difference in course heading is translated to an error in bank angle. By the introduction of a bank angle, the error in course will more or less be taken care of by the longitudinal controller as the error in course is translated to an error in local climb angle.

The FCS internal gain, K_{RFCS}, defines roll rate as a function of stick deflection. By using K_{RFCS} and adding a constant controller specific gain, K_{RW}, the additional roll stick deflection (figure 10-4) due to lateral errors is:

$$\Delta\delta_{RS} = K_{RW} * K_{RFCS} * \Delta\mu_{to}$$

7.3.4 Velocity controller

The error in velocity is controlled by additional tangential force according to:

$$\Delta T = m * \Delta V_C * K_{VW}$$

ΔV_C is the difference in velocity between the real aircraft and the simulation model. K_{VW} converts the speed difference to a difference in acceleration.

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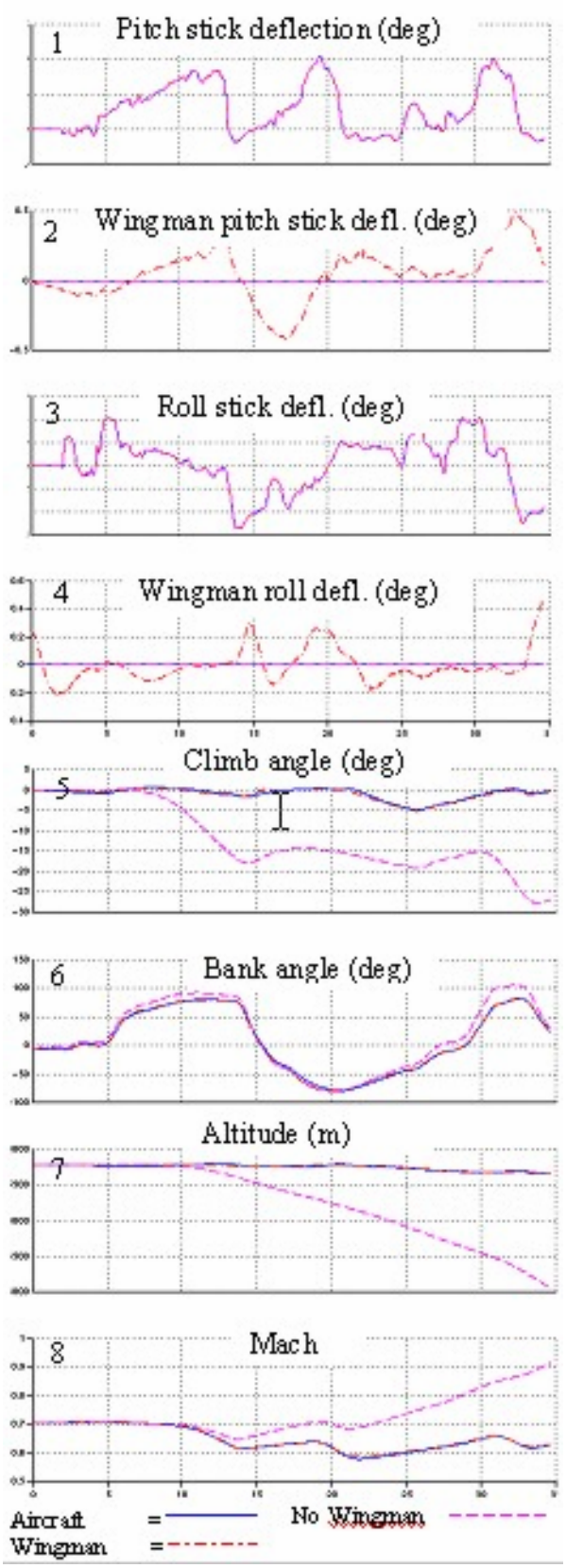

Figure 10. ***Parallel simulation with and without wingman pilot model.***

8 REAL-TIME AERODYNAMIC ANALYSIS

As a complement to the parallel simulation with the complete aircraft simulation model, ROMAC includes a separate aerodynamic analysis. The aerodynamic analysis consists of comparison of force and moment coefficients calculated from flight test with corresponding coefficients from the aerodynamic model.

The aerodynamic force and moment coefficients from flight test are calculated from measured load factors and angular accelerations. In order to get accurate results input values for mass, cg, moments of inertia, accelerometers, gyros and thrust must be correct.

To extract the coefficients from the aerodynamic model, parameters from the test aircraft like control surface deflection angles, AOA, AOS, Mach number etc are needed as inputs.

A comparison of the coefficients is then performed with time plots and cross plots, giving a good picture of the aerodynamic model status.

9 INPUT DATA REFINEMENTS

9.1 Telemetry interruption

The normal way to evaluate data at Saab Flight Test is via the instrumentation recording media (nowadays solid state, former tape) in the aircraft. Telemetry data has mainly been used to monitor the aircraft and its systems during the tests. Perfect telemetry coverage (everywhere and 100% of the time) was not the design goal for the telemetry system. The analyze tool must therefore take care of, or at least tolerate telemetry interrupts. It should be noted that the telemetry link has been very reliable during these tests. Only when far away (low signal strength) and in a small range of aircraft attitude (directions in the antenna diagram with low output) a few and short telemetry interruptions occurred.

Some data processing like filter (both smoothing and Kalman), integration and some statistical functions produce incorrect results close to telemetry interruptions. Filters need data before and after the time for the output to give a reliable result. The filtered data is less useful close to an interruption. Routines that in-

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crease (or decrease) sample rates will also give disturbed signals due to the used (filter-) algorithms.

In ROMAC two approaches are used for telemetry interruptions in the filter algorithm. The easiest is to initiate the filter with the first sample after the interruption, i.e. restart it. That is the same as saying that the whole history has this value. Initially the derivatives will be too small until the filter has forgotten the initiation after about one second. The other approach is to do a linear (straight line) interpolation across the interruption before the filtering. Both methods are used in ROMAC. The restart method is used after a longer (> 1 s) interruption and the straight-line method is used otherwise.

The simulation model does not use this interpolation at all. The artificial "wing man" takes care of the new flight condition after a shorter interruption and flies the model to the aircraft's flight condition. Longer interruptions need manually initiated (but automatically performed) restart of the flight condition.

9.2 Wind data

The actual wind condition for the real aircraft is valuable to include in the simulation model during a parallel simulation. Offsets between the simulation model and the real aircraft in sideslip angle and control surface deflections due to wind are thereby minimized. By comparing the measured INS speeds with calculated air data speeds the actual wind strength and direction is calculated and fed into the simulation model.

9.3 HAOA

At HAOA the signals from some of the sensors have to be disqualified due to either mechanical stops or inconsistent airflow conditions. Examples are the AOA vanes, the sideslip vane and the calibrated airspeed.

To obtain these signals at HAOA, an alternative method was used. By using data from INS, AOA, sideslip vanes and true airspeed in a normal climb it is possible to calculate the wind profile in the test segment at altitude shortly before the test. When the actual test is performed at the HAOA region it is then possible to calculate AOA, sideslip and true airspeed from INS.

The ambient temperature is neither measured well at HAOA. To be able to calculate dynamic pressure from calculated true airspeed the ambient temperature as a function of altitude from the normal climb is used.

10 THE USE OF ROMAC DURING FLIGHT TEST

Spin and carefree flight test is expensive and there is a lot to be saved by doing it right and efficient. Thus much effort has been put into methodology improvements of the analysis and simulation tools.

The use of real-time aerodynamic analysis and parallel simulation during carefree maneuvering and spin tests has significantly improved the efficiency of each test flight and made it possible to increase the rate of test flights. It has also significantly improved the decision support during a test point and in the analysis to give go-ahead in between test points.

10.1 Carefree flight test prior to ROMAC

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.

Figure 11. ***The telemetry station Houston.***

The result in AOA, AOS etc. from the ground-based simulator was written onto the

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test cards. In this way, the whole crew in the telemetry-station Houston (figure 11) 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 (±2° 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 an aerodynamic "quick-analysis" was made (shown in figure 12).

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.

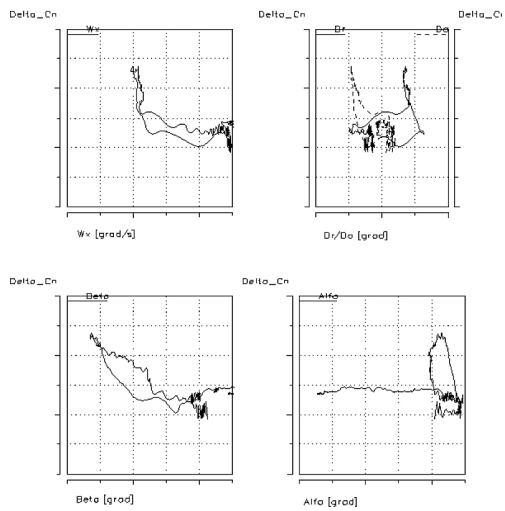

Figure 12. ***Quick analysis plots***

10.2 Using ROMAC during the carefree test

During the 39B carefree tests, ROMAC has worked very well and has given the flight test engineers a fantastic tool to evaluate how well the aircraft simulation model corresponds to flight test.

The influence of the wingman pilot on the simulation results is not always obvious. The pilot model is usually completely or partly put off just before the part of the test point that is going to be analyzed. Usually the velocity controller is activated through the whole maneuver. Thanks to the wingman model, the flight condition of the simulation model is more or less identical to the flight condition of test aircraft, just before the test point.

In some of the cases, the test points were approached with a step-by-step procedure. This procedure was used if simulation had shown a lot of sideslip and rudder deflection and/or high angle of attack. For example, desktop simulations indicated problems at high altitude. Since a model always has deficiencies and the data at high altitude was not extensive, it was decided to approach the critical flight conditions from a safe altitude. With ROMAC it was possible to study if the simulation was conservative or not by looking at the parallel simulation and the aerodynamic comparison. If the simulation was conservative it was possible to give a quick go-ahead. If not it required a more thoroughly analysis before the test team gave a go-ahead or not.

Compared to earlier carefree flight test campaigns the uncertainties during the 39B flight test campaign were less, as the simulation was made with exactly the same initial conditions and pilot input. The footprints made from simulations prior to flight test were naturally not performed with exact the same conditions as flight test. When using footprints in the analysis during an ongoing flight test this had to be taken into account when making comparison of the aircraft response between flight test and simulation.

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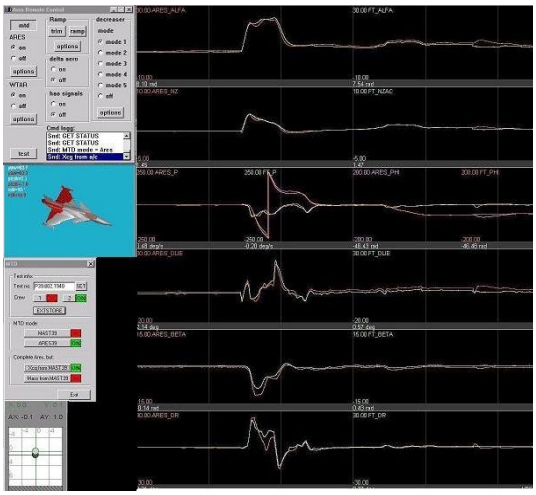

Figure 13. ***ROMAC parallel simulation session on screen in Houston***

To have real-time aerodynamic analysis was also a big improvement compared to the carefree tests before ROMAC existed. ROMAC made it possible to make an aerodynamic analysis on each test point. Before, only the test points that matched poorly with the footprint were analyzed.

There are examples from the carefree tests with 39-2 when an aerodynamic analysis was not made when it should have been made when looking at it in retrospect. In these cases the test engineers thought the footprint matched pretty good with flight test.

Thanks to ROMAC during the tests with 39B the analysis went faster and had a higher quality, which made the tests more safe and efficient.

10.3 Spin flight test

During the spin test with 39B the real-time aerodynamic analysis included in ROMAC was of great help.

Before the spin test a thoroughly aerodynamic tolerance study had been made. To find the derivatives of significant effect on the spin characteristics simulation were made with offset on one derivative at a time. The six most significant derivatives were picked and a matrix was put together with all the possible combinations of the six derivatives. Each derivative had a nominal value and a max and min value with a chosen tolerance. Spin simulations were made with all of these combinations in a batch simulation.

A lot of time was also spent in a fixed based simulator, STYRSIM (see figure 14), where the test pilot evaluated if the spin characteristics were acceptable or not when aerodynamic modifications were made.

From these studies the flight test engineers got a pretty good idea of which coefficients and derivatives to be especially cautious about if there were any discrepancies in the aerodynamic model.

Figure 14. ***STYRSIM Simulator.***

The studies also gave rules of thumb what magnitude of discrepancies to accept before making a more thoroughly analysis with new simulations with an updated aerodynamic model.

10.4 Using ROMAC during spin test

During the spin test with 39A the “quick analyses”-tool for aerodynamic analysis worked well. It took however three to four minutes longer than the new aerodynamic analysis in ROMAC. The time reduction was a big improvement since it put less time pressure on the engineers to make the analysis. The time to set up a new spin test point were usually five minutes. Most of the time, thanks to ROMAC, it was possible to keep up with the pace.

The analysis was probably also better compared to the analysis during the spin test of 39A, thanks to less time pressure on the flight test engineers. Even if the analysis always were supposed to take the time it needed, in reality there is always a pressure on the test engineers to come up with a quick and correct answer. For the test engineer the quicker there is data to analyze the better it is.

Parallel simulation was not used during the spin tests. There had been some thoughts of making a wingman pilot model that would work in a spin but unfortunately there was no time to develop it.

10.5 Other benefits with ROMAC

Another thing that has proven to be very valuable by doing online analysis is the possibility to make a thorough analysis of the results during the debriefing. Debriefing is one of the rare occasions when everyone are together, focused and with a fresh memory of the test flight. It has proved to be an effective way of deciding on what to do next and it often speeded up the rate of test flights.

ROMAC has also been valuable in the analysis after flight test to find out the cause of a discrepancy in aircraft response between flight test and simulation. For example studies can be made with changed mass and inertia or by simulate with an updated aerodynamic model.

11 FUTURE DEVELOPMENT AND USE OF ROMAC

ROMAC will be developed for GCAS (Ground Collision Avoidance System) flight test. By using ROMAC during GCAS flight test it is possible to get a quick and good verification of how well altitude loss during a pull-up is simulated. By verifying the simulation model it is possible to use the simulator to verify the flight path prediction calculated in the GCAS system.

ROMAC could also be used during flight tests of UAV:s and UCAV:s. For this the wingman pilot model has to be somewhat redesigned for a new aircraft configuration.

For aircrafts without FCS or SAS, it might be better to reduce the flight path error by adding extra forces and moments to the simulation model instead of stick input. With this solution the parallel simulation doesn't get influenced by cross-coupling effects or by non linear effects due to deflection of control surfaces.

It would be possible to verify more sub models than the aerodynamic model. Examples of sub models suited to run separately in ROMAC are the engine model and the hydraulic model.

12 CONCLUSIONS

The requirement on the simulation tools increases continuously, in order to reduce the need for flight test. It is important to know the limitations of the models, and flight test is still the only good way to verify a model.

Because of increasing requirement it is necessary to get higher fidelity of the models and in this process it is very important to get feedback from flight test in order to make the necessary updates. Unfortunately updates are a hard thing to accomplish due to time and cost and it usually requires an identified problem that has to be solved.

By making an update when a discrepancy is noted instead of waiting until a problem occur it would be possible to identify future potential problems in the simulator models instead of much later during flight test. By having a good and effective process for improvement of the simulator models a lot of time and money can surely be saved.

ROMAC is one of the necessary tools to be able to get feedback on the quality of simulator models in an efficient way.

Spin and carefree flight test is expensive and there is a lot to be saved by doing it right and efficient.

The use of ROMAC with its real-time aerodynamic analysis and parallel simulation capabilities has significantly improved the efficiency of each test flight and increased the rate of test flights during carefree- and spin tests. It has also significantly improved the decision support during a test point and in the analysis to give go-ahead in between test points.