AERODYNAMIC MODELING USING FLIGHT MECHANICAL SIMULATIONS, FLIGHT TEST AND OPTIMIZATION

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Abstract

The development and modifications of modern fighters, like JAS 39 Gripen, rely to a large extent on flight mechanical simulations. In order to get simulated data as close as possible to data obtained from flight tests, the accuracy of the aerodynamic model is crucial. Hence the aerodynamic model has to be updated frequently when new data from flight tests, wind tunnel tests or CFD calculations is available. For example, during the time that Saab has been testing the care free maneuvering functionality in the FCS for the Gripen fighter, the aerodynamic model has been updated several times. This has been done to meet the demand for higher accuracy of the simulations that are used for FCS design, verification and validation.

The evaluation and updating procedure of the aerodynamic model often need to be performed manually and can thus be rather time consuming. The manual time can however be reduced by means of computer tools. Such tools have been developed and used at Saab for a long time.

Previously aerodynamic characteristics from flight tests were evaluated at Saab by exciting predefined control surface deflections from a trim condition. Aerodynamic coefficients and derivatives at the trim points were then obtained by resolving the derivatives from the disturbance in the airplane motion. This technique can however not be applied when evaluating flight tests which include dynamic maneuvers since it is simply not possible to get a trimmed state. For evaluation of these flight tests, simulations of the very same maneuvers that have been flown have to be performed.

*During the last couple of years a new tool, called **aero_opt**, has been developed at Saab. The aim of this tool is to support the user when developing and improving aerodynamic models by comparing aerodynamic quantities from flight mechanical simulation and flight tests, including dynamic maneuvers at the boundary of the flight envelop, with. The system also automatically updates the aerodynamic model.*

*A brief description of the work process of the evaluations and updating of the aerodynamic model, the **aero_opt** system and results using this system is presented in this paper.*

1 Introduction

Parameter identification (PID) is not a new method. It has been used to improve simulation models for a long time. Many of the PID techniques in flight physics are based on certain types of flight test maneuvers like step pulses or doublets.

In the late 70's Saab developed computer programs called PID (Parameter IDentification) [1] and DIVA39 (DerIVAtive identification) [2]. These identification tools could be applied to arbitrary systems and took care of linear updates at an arbitrary point in the flight envelop.

When the testing of the classical flight mechanical qualities for the JAS 39 Gripen was finished a good simulation model was needed in the nonlinear envelop to support development of control laws for care free maneuvering at the boundary of the flight envelop. Since the parameter identification methods PID and DIVA39 could not be applied due to nonlinearities a more manually laborious process had to be used instead.

Several methods for parameter identification have been studied and developed at Saab recently. In 2003/2004 a master thesis was carried out that analyzed different methods [3]. It focused on Fuzzy logic and artificial neural networks, both handling nonlinearity. However, these methods were based on a surface adaptation technique using optimization of a single aerodynamic coefficient without consideration of the flight mechanics variables developed in the simulation. It is possible to make good parameter identification by using surface adaptation on test data for the aerodynamic coefficients without consideration of the flight mechanical state variables, but this demands a database containing a good variety of data from flight test as mentioned in [4] and [5].

A typical example is the evaluation of steady heading sideslip maneuvers, where the sideslip angle, aileron angle and rudder angle have a high correlation. It can be quite difficult to find the best update approach without using data from other types of maneuvers or the flight mechanical coupling of the aerodynamic model.

To overcome these problems a new method which takes advantage of the information given both by surface adaptation and by simulation of the flight tested maneuvers has been developed. The method, **aero_opt,** uses an optimization technique which minimizes the difference between flight test and flight mechanical simulation data.

2 Theory

It would be extremely expensive to fly all maneuvers needed to cover the whole flight envelop. A much cheaper way is to simulate all these maneuvers. With a good simulation model that can be verified with flight tests this can be done.

2.1 Simulation

Ten to 15 years ago simulators was sparesly used in the model update process. The simulator ARES [6], Aircraft Rigid body Engineering Simulation, was developed for the analysis of the flying qualities of the JAS 39 Gripen. ARES is a 6 degrees of freedom nonlinear aircraft simulation model for workstation simulations.

ARES is based on a state-space model concept which means that all its 3000 internal states can be saved at any time during a simulation. The simulation can then be restarted from exactly the same conditions as when it was aborted. ARES contains a number of sub-models: Aerodynamic, Mass and inertia, Engine etc. and runs on UNIX workstations two times faster than real-time.

The user accesses the simulation model through a command-line interface with macro functionality for batch simulations. Any of the 2500 outputs can be registered on file for futher analysis.

ARES has been used in the updating of the aerodynamic model by using a concept called parallel simulation.

The principle of parallel simulation is to simulate the “exact” maneuvers that have been flight tested. This gives a measure of how good the simulation model is. First the initial condition of a flight tested maneuver is achieved in the simulator. Then the pilot command inputs, i.e. stick, pedal and power leverage movements, from the flight test are used as inputs to the simulation. A perfect simulation model would lead to a one-to-one relationship of all the state-space variables between the flight test and the simulation. Differences can be used to update the simulator sub-models ex. the aerodynamic model.

2.2 The aero_opt method

The idea behind the new method was, in the beginning, to aid the engineer with the labor heavy evaluation of multiple flight tests. This was to be done by using the way engineers worked, but with more computer power. A typical working process is given below:

1. Extract data from flight tests.
2. Make parallel simulations of the flight tested maneuvers.
3. Compute the difference between the aerodynamic model and data from the flight tests.
4. Update the aerodynamic model based on 3.
5. Make parallel simulation with the new model.
6. Compare the parallel simulations from 2 and 5 to evaluate the improvements.
7. If OK end otherwise begin from 4 with a new update approach.

During the development of the "computerized" updating method optimization was included to close the loop from 2 to 7 in the above schedule. The new method presented therefore makes use of differences in aerodynamic coefficients as well as flight mechanical state-space variables between simulations a flight test. The evaluation of the state-space variables that earlier was done as a check of the model update has now been included in the update process.

2.3 Optimization method

System identification signifies the procedure of representing the behavior of a real system (process) by a simulation. In this case the process represents the flight test and the simulation the ARES program. To enhance the simulation, an optimization model is attached to the simulation, see Figure 1. Process and simulation outputs y and $\hat{y}$ are compared yielding the error signal e. This error is utilized to adjust the parameters of the model.

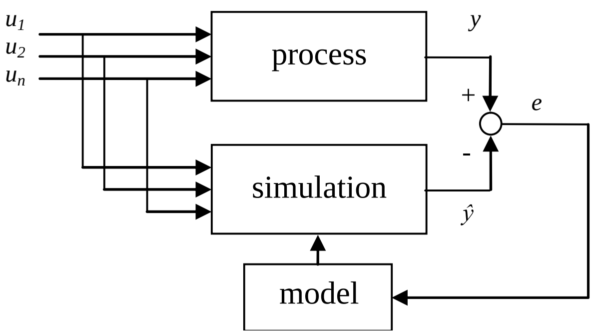

Fig. 1: System identification principle.

Since the aerodynamic model is non-linear in the flight envelop of interest a nonlinear polynomial model was chosen.

$$\Delta C = p_0 + p_1 x_1 + p_2 x_2 + p_4 x_1^2 + p_5 x_1 x_2 + \ldots \quad (1)$$

Where ΔC is the aerodynamic coefficients to be updated, $\overline{p}$ a parameter vector used for the identification and $\overline{x}$ a vector containing the state-space variables.

The objective function to be optimized is the total error (e) i.e. the L^2-norm of the difference between flight test data and simulated data where the L^2-norm is computed by summation over every time sample and all flight maneuvers. Since the error function might consist of several coefficients and variables of varying magnitude, weights w_j have to be introduced. The objective function is in this case given by a nonlinear weighted least square sum:

$$e(\overline{p}) = \sum_{i=1}^{m} \sum_{j=1}^{n} w_j \sum_{k=1}^{o} \left[y_{ij}(t_k) - \hat{y}_{ij}(t_k, \overline{p}) \right]^2 \quad (2)$$

Where i, j, and k are the indices which run over all manouevres, variables and times respectively. y and $\hat{y}$ represent both aerodynamic coefficients and flight mechanical state-space variables.

In order to minimize the objective function a line search method (approximate gradient based) is applied. The optimization starts from p=0 which means that the basic aerodynamic model is used at the starting point. The line search method consists of a steepest decent method with varying step size η. An approximate search direction i.e. gradient is calculated by finite differences. The objective function is then approximated along this line by a polynomial of one variable, η.. The objective function is initially evaluated in three points (the starting point and two more) and then a quadratic polynomial is fitted to those points. The minimum of this polynomial is then computed and the parameter vector updated according to

$$\bar{p}_k = \bar{p}_{k-1} - \eta_{k-1} \cdot \bar{g}_{k-1} \qquad (4)$$

Typically five line search iterations are performed thereafter a new optimal direction is calculated and the line search procedure repeated.

The optimisation process is speed up by using a parallelization technique were the flight simulations and function evaluations are distributed over several computers.

3 Results

To test the **aero_opt** method several aspects has been investigated. We have here focused on the following parameter variations:

1. The number of flight maneuvers
2. The number of optimization parameters
3. The degree of the polynomial in (1)
4. The number aerodynamic coefficients and state-space variables used in the objective function (2).

In the first test case the number of maneuvers was varied between 5-20 as can be seen in table 1. The objective function was built up, in this case, of totally 10 aerodynamic coefficients and flight mechanical variables and the number of optimization parameters 15 and 45. Table 1 contains results for both 1st and 2nd order polynomials.

No. of Flight test maneuvers	Degree of polynomial	
	1	2
5	9%	10%
10	12%	13%
15	14%	13%
20	14%	17%

Table 1: Error reduction.

We observe from table 1 that increasing the number of flight tests leads to a larger reduction of the error. This holds for both 1st and 2nd order polynomials. The optimization history using 20 flight tests and 2nd order polynomial is displayed in figure. 1.

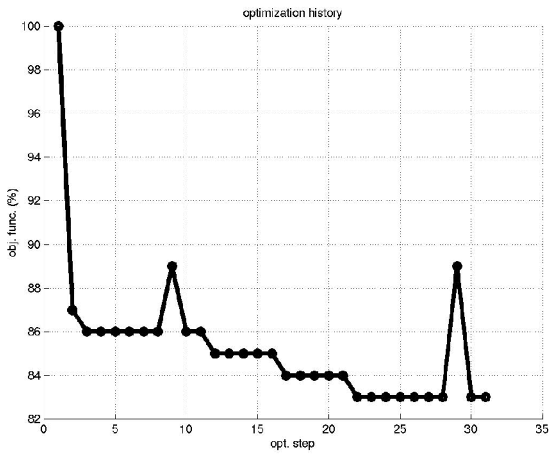

Figure 1: Optimization history 20 flight tests.

The output from flight simulations before and after optimization was studied and compared to the flight tests in order to understand the obtained results.
Figure 2 show an example of the improvement in rudder effectiveness for a BOT (Bleed-Off-Turn) from the case of 20 flight tests and a 2nd order polynomial. The total improvement of the model error is about 17% as can be seen in table 1. Other results show that if the longitudinal effects are updated first and the lateral/directional effects are optimized afterwards, a better total result can be achieved.

This is probably due to the fact that the longitudinal effects improve the angle of attack and Mach number and this improvement is obstructed when trying to improve the lateral/directional effect at the same time.

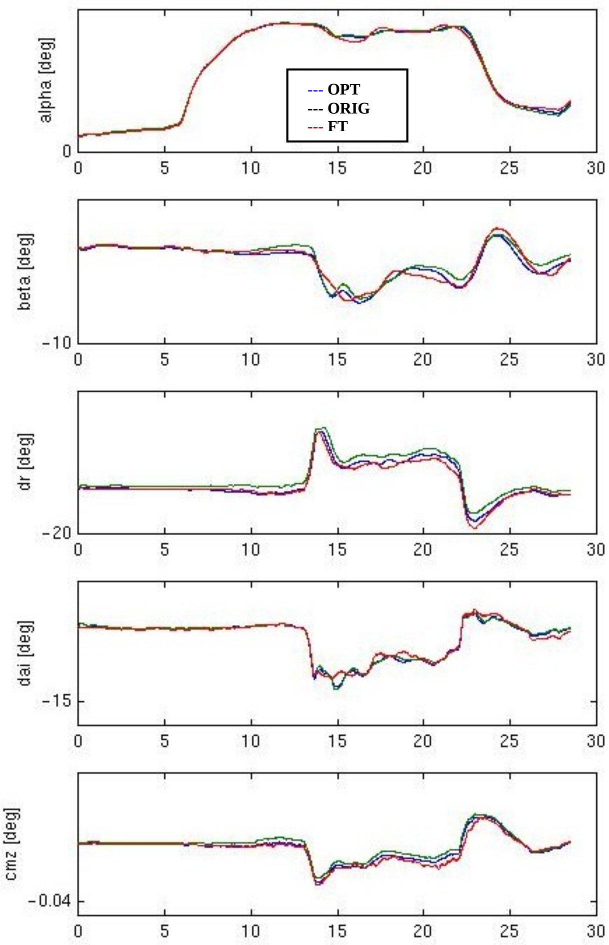

Figure 2: Results using 20 flight tests.

In the second test case the same number of maneuvers, as in the first test case, was used i.e. between 5-20. The objective function only consisted of one aerodynamic coefficients CMY (i.e. the pitching moment) and the number of optimization parameters 5 and 15. The reduction of the objective function is for all cases around 30% which can be seen in table 2. There is however no monotonic trend regarding the error reduction as a function of the number of flight tests. The higher reduction of the errors in table 2 compared to those in table 1 is due to the fact that the objective function consists only of one coefficient in table 2 compare to 10 in table 1.

No. of Flight test maneuvers	Degree of polynomial	
	1	2
5	25%	30%
10	31%	28%
15	34%	31%
20	27%	29%

Table 2: Error reduction.

Figure 3-4 below show coefficients and aerodynamic variables as a function of time for a BOT. Observe especially the improvement of the pitching moment i.e. the objective function in fig. 3. In figure 5-6 are the differences in coefficients and aerodynamic variables displayed.

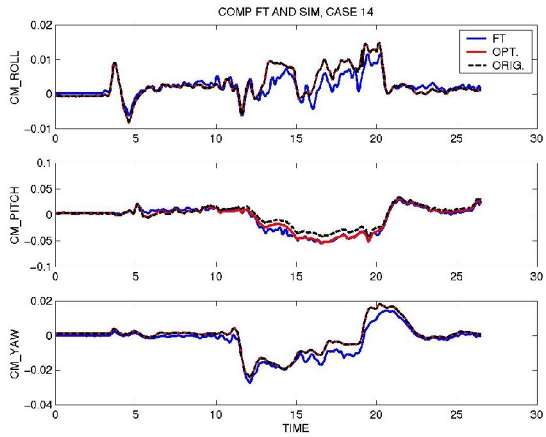

Figure 3: Coefficients using 20 flight tests

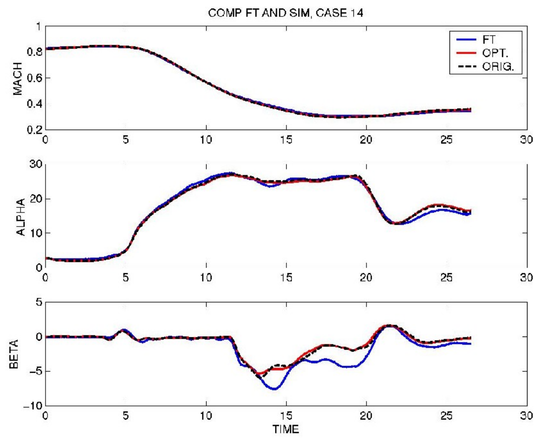

Figure 4: Variables using 20 flight tests

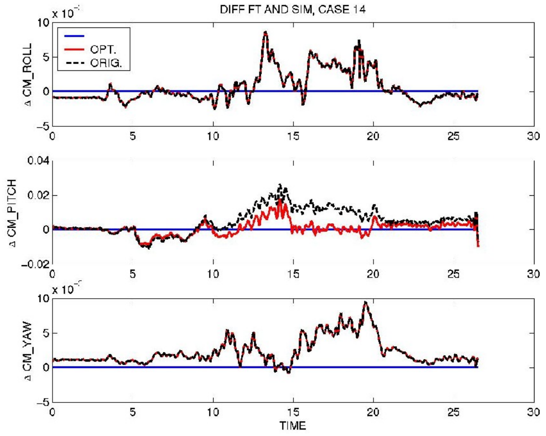

Figure 5: Diff. coefficients using 20 flight tests

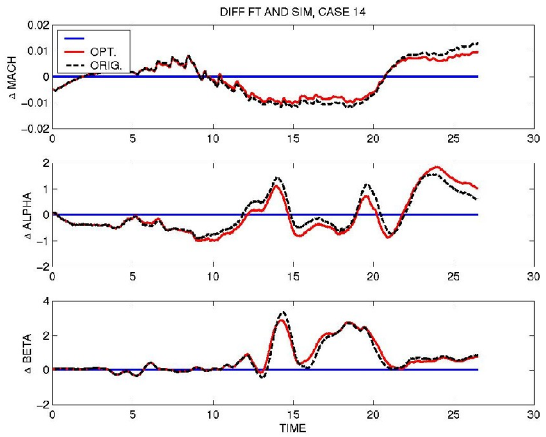

Figure 6: Diff. variables using 20 flight tests

One important aspect of automation of the update process of the aerodynamic simulator sub-model is the reduction of time for the update. Manual updates of nonlinear aerodynamic properties require the ability to work with several aerodynamic coefficients in a large part of the flight envelop at the same time. The optimization takes from about 10 hours for a linear case to 2 days for a quadratic case depending on the number of available computers. This can be compared to the time for reaching an accurate result using a manual process which is very time consuming and can take several month.

4 Conclusions

Using optimization together with flight mechanical simulation gives the engineer a powerful tool for parameter identification of the aerodynamic model. The tool makes use of as much information as possible for the identification.

Complex problems, where couplings between different coefficients are needed to make a good update of the simulation model, can be very hard to solve manually, but can be solved with the **aero_opt** tool.

Aero_opt is still under development. There are features that need some more consideration. The results show that the update gets better if the pitch problem is solved first and the roll/yaw problem is solved separately afterwards. Such a strategy could be build into the system. Other improvements that has been considered for further development is:

- Partition of the flight envelope.
- Possibility to specify different polynomial degreed of each parameter used in the objective function.
- The use of wind tunnel test data to fill out holes in the flight test database.

Last but not least a word of caution: Results from any computer program have to be checked since the computer only does what it is told to do. This is also true for **aero_opt**.

6 References

[1] Bjelkåker S. *PID - Teori*. Issue 0, Saab AB, 1996.

[2] Bjelkåker S. *DIVA39 - Teori*. Issue 1, Saab AB, 1996.

[3] Bergdahl E and Peterson T. Parameteridentifiering av aerodynamiska koefficienter. *ISSN 1651-7660 TRITA AVE 2004:6*, KTH Farkost och Flyg 2004.

[4] Paris A C and Bonner M. Nonlinear model development from flight test data for the F/A-18E Super Hornet, AIAA 2003-5535, 2003.

[5] Paris A C. Nonlinear aerodynamic model extraction from flight test data for the S-3B Viking, AIAA 2001-4015, 2001.

[6] Backström H. ARES - an overview description, Issue 1, Saab AB, 2004.