CP-593

Investigations on Handling Qualities and Aerodynamic Characteristics of EUROFIGHTER 2000 at DAIMLER-BENZ AEROSPACE Flight Test Centre

Dr.-Ing. Hans-Christoph Oelker, Erfried W. Muthsam
Daimler-Benz Aerospace AG, Military Aircraft Division
Postfach 1149, D-85073 Manching

Abstract

Currently the development flight test evaluation of EUROFIGHTER 2000 is under way. The present paper emphasises on analysis methods for flight mechanical and aerodynamical evaluation suitable for a very agile, highly unstable fighter aircraft at DAIMLER-BENZ AEROSPACE flight test centre. Methods are summarised and illustrated with some representative results.

Analysis methods in the time domain such as simulation of flown manoevres and in the frequency domain such as Z-transformation and Fourier analysis methods for system stability evaluations are presented. DASA's aerodynamic parameter identification method is presented. It resembles a unique equation decoupling approach to cope with the problems arising from the analysis of unstable aircraft. Representative results are given, which demonstrate the analysis capabilities of the presented methods.

1 Introduction

Next century's fighter aircraft for the air forces of Spain, Italy, United Kingdom, and Germany will be the EUROFIGHTER 2000 (EF2000). It is developed jointly as a very agile fighter aircraft by industrial partners of these four nations (CASA for Spain, Alenia for Italy, British Aerospace, BAe, for the United Kingdom and Daimler-Benz Aerospace, DASA, for Germany); the basic geometry is given in Fig. 1. The characteristic feature of this configuration is the canard, resulting in an aerodynamically highly unstable aircraft. It is therefore controlled by a full authority quadruplex redundant flight control system (FCS).

The current status of the programme is already a good way ahead in the development flight test evaluation of the aircraft. Flight test tasks have been split up between the four partner companies. At the moment four of seven development aircraft (DA's) are flying. DA1, the first flying aircraft, is allocated at DASA Manching, while DA2 is allocated at BAe Warton. These two development aircraft share the tasks for expanding the flight envelope as follows: DA2 expands the envelope basically in the direction of increasing velocity, whereas DA1 basically expands the envelope towards increasing angles of attack (AOA) respectively normal load factors n_z. Fig. 2 gives, as an example, an overview of wind up turns so far performed on DA1 with a reduced control law standard in the FCS. Since DA1 is also considered to be the 'data gathering aircraft' for validation of the aerodynamic stability and control dataset, flight conditions have been tested several times, as can be seen from the figure, with different load factors for purposes of aerodynamic parameter identification (APID). In this context the present paper emphasises on evaluation techniques which are suited to gain sufficient information on the validity of the mathematical model in use.

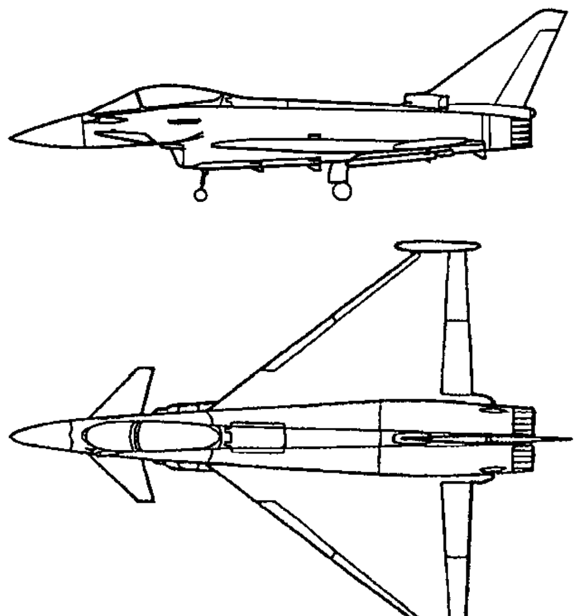

Fig. 1 Geometry of EUROFIGHTER 2000 Configuration

The current analysis approach at DASA is a mixture of online monitoring and analysis whilst the aircraft is up in the air and detailed offline analysis after the flight. During the flight emphasis is put on the total system, which in this context will be called the augmented aircraft. Due to the desired rapid progress during one flight the main emphasis is on monitoring the aircraft state with time histories (scroll plots) and cross plots. Due to limited personell detailed online

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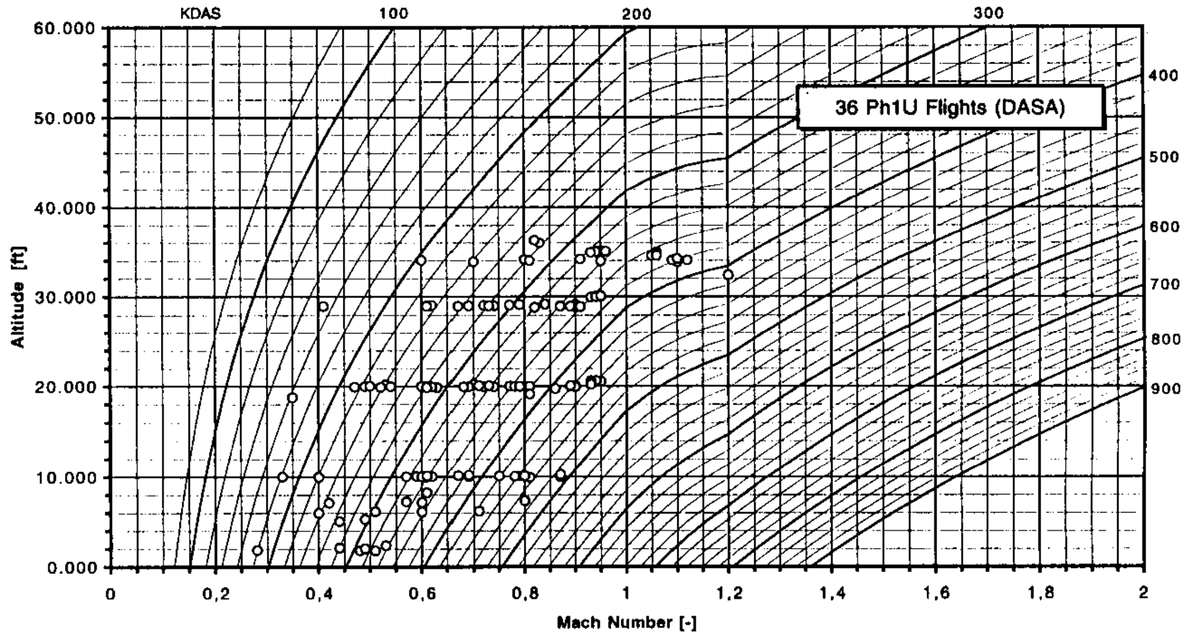


Fig. 2 Overview of performed Wind Up Turns

analysis procedures are not applied yet, the installation is still planned for this year though. One advantage of offline analysis procedures is the availability of on-board recorded data with generally a very high fidelity instead of not seldom disturbed telemetry data during online analysis. Also offline analysis gives much more time to think about the results, thus aircraft safety relevant decisions can be prepared in a better manner. Offline analysis also offers the possibility of investigation of the unaugmented aircraft via APID methods. In the following an overview of analysis techniques applied is given, which will be followed by some example results demonstrating the integrated use of these tools.

2 Analysis Methods

2.1 Flight Dynamics Simulation Check (FDSC)

Flight dynamics simulation check describes the process of repredicting the time histories of a flown manoeuvre after this manoeuvre has been finished. This can be done online in the quicklook room or offline in the office. For analysis on EF2000 this process is made up as follows:

The model is based on a nonlinear simulation kernel with 6 degrees of freedom with respect to the aircraft motion. This kernel has access to the nonlinear aerodynamic dataset. Linearisation of the aerodynamic data is not performed, for each integration step nonlinear aerodynamic data is used. In addition this kernel has access to the full model of the control laws as incorporated into the aircraft. Modelling of relevant hardware characteristics is included as well, e.g. actuation dynamics. This model is used at all EF2000 partner companies for development purposes. At DASA flight test certain additions to the model code have been made in order to evaluate flown manoeuvres at measured flight conditions with measured pilot's inputs.

Integration of flight data into a simulation programme is a simple straight forward procedure as long as unaugmented aircraft are under consideration. For augmented aircraft additional aspects have to be considered, especially for a controller with an integration of feedback signals as it is the case for EF2000. A principal sketch of the control law structure for the longitudinal motion of the aircraft is given in Fig. 3. The mentioned integrator is clearly visible. In reality this structure is much more complex. Controller gains are generally scheduled accordingly to the aircraft's state, thus this information must be fed into the controller in addition to the measured output of the integrator, which resembles the 'history' up to the start of the manoeuvre of interest. Two ways of control law initialisation are possible:

- Before start of the simulation analysis a trim calculation is peformed. In this case the trim target is either measured AOA at the beginning of the manoeuvre or measured n_z. Then the model is trimmed on the basis of the existing dataset. Therefore trimming for AOA cannot provide measured n_z and vice versa, since it must be expected that the dataset is slightly different from the real aircraft's aerodynamics, also control surface positions may not be in the exact position as in flight. The trimming procedure also provides a value for the integrator output, based on the dataset. For the mentioned reasons its value can differ slightly from the flight measured value. After the trimming is finished the simulation can be started using measured pilot's inputs from flight.

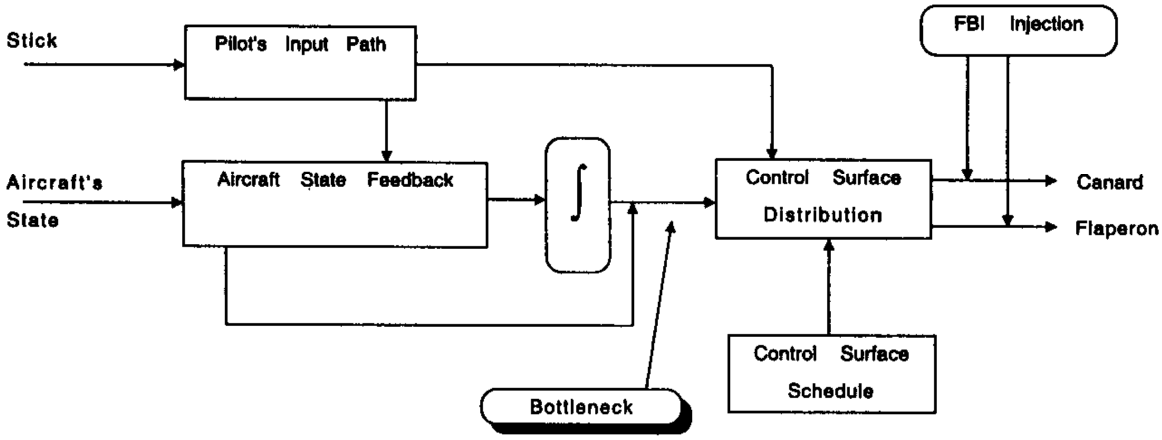


Fig. 3 Principal Control Law Structure (Longitudinal Motion)

- As much as possible data is taken from the aircraft at the beginning of the manoeuvre under consideration. A prerequisite is that all necessary data (control law specific air data, integrator output) is available via flight test instrumentation (FTI) recording. Now the necessary data to initialise the controller is taken from flight data as well as the trim condition. The simulation model is started with these values and flight measured pilot's inputs.

The advantage of the first procedures is that standard flight data are incorporated into a known process. Disadvantages are the dependancy on the aerodynamic model for the initial conditions and the necessary computing effort to calculate the trimming position. The second approach needs more FTI parameters but does not need the additional computing time for a trim calculation. It is therefore also better suited for online application of FDSC. For the results given here the second approach has been choosen.

Results of FDSC are well suited to gain a quick qualitative overview of model fidelity. If questions arise, model variations can be applied easily (e.g. variation of certain aerodynamic derivatives with respect to tolerance investigations) and their influence can be evaluated in comparison with flight data. FDSC results can also be used as inputs to other analysis tools, so with these tools so called predictions can be produced.

2.2 Low Order Equivalent System (LOES) Analysis

The low order equivalent system analysis approach is used to gain insight into dynamics of systems of complex order. For this analysis the assumption is made, that the observed system is approximately linear within the investigated amplitude range. In the time domain an appropriate system excitation is necessary with respect to the frequency spectrum of interest. The transformation into the frequency domain is then achieved via Z-transformation. Calculation of system poles and Eigenvalues is performed successively.

The advantage of the Z-transformation is the fact that the solution of a simple difference equation in the time domain provides the coefficients of the transfer function in the Z-domain. The basic equation , as described in Ref.1, is as follows:

$$y_i = -\sum_{k=1}^{N} \frac{a_k}{a_0} y_{i-k} + \sum_{k=0}^{M} \frac{b_k}{a_0} x_{i-k} \tag{1}$$

with
- y_i = system response at time i
- x_i = system excitation at time i
- a_k = coefficients of the denominator polynomial of the transfer function
- b_k = coefficients of the numerator polynomial of the transfer function
- N = degree of the denominator polynomial of the transfer function
- M = degree of the numerator polynomial of the transfer function

The solution of this equation provides the transfer function H(z) in the Z-plane:

$$H(z) = z^{(N-M)} \frac{\sum_{k=0}^{M} \frac{b_k}{a_0} z^{(M-k)}}{\sum_{k=0}^{N} \frac{a_k}{a_0} z^{(N-k)}} \tag{2}$$

From this equation the poles of the denominator can be calculated, representing the Eigenvalues of the system. Then the relationship:

$$z = \exp\{sT\} \tag{3}$$

yields the transformation from the Z-plane into the more convenient S-plane whereas T is the sampling intervall. Using this formula Eigenfrequency ω_N and damping ζ of a pole can be derived as follows:

$$
\begin{aligned}
|z| &= \sqrt{z_{real}^2 + z_{imag}^2} \\
\theta &= \arctan\left(z_{imag} / z_{real}\right) \\
\omega_N &= \sqrt{\left(\frac{1}{T}\ln|z|\right)^2 + \left(\frac{1}{T}\theta\right)^2} \\
\zeta &= \left(-\frac{1}{T}\ln|z|\right) / \omega_N
\end{aligned}
\tag{4}
$$

From Eq. 2 the impuls response in the time domain can be derived via partial fractions. From there the system response of the LOES can be calculated via the folding integral and compared with the originally measured system response, thus giving a qualitative measure of the fidelity of the LOES approximation.

LOES analysis has been performed very successfully at DASA flight test for 'conventional' unaugmented aircraft during envelope expansion flying, e.g. RANGER 2000 or unaugmented TORNADO. Analysis has been performed online, the results gave immediate information about the aircraft's stability. Post flight comparisons with APID results showed very good agreement. For augmented aircraft this method provides a tool describing the handling qualities as 'felt' by the pilot only. Information about the aircraft's stability margin cannot be derived. This requires a special analysis of the controller, as described below.

2.3 Frequency Domain Analysis

Frequency domain analysis is performed with the conventional discrete Fourier transformation. Applications are analyses of control law stability margins and of aircraft pilot coupling criteria.

2.3.1 Control Law Stability Evaluation

For stability margin evaluations the transfer function of the system with open feedback loop is calculated. With a known model it can be calculated in a relatively easy manner. For simple single branch systems the open loop transfer function can be derived from e.g. the measured closed loop transfer function with the well known formula:

$$
F_{open} = \frac{F_{closed}}{1 + F_{closed}} \tag{5}
$$

For EF2000 this formula is valid only at that point, where all feedback signals are fed through one common signal path. This is called the bottleneck and is indicated in Fig.3. For theoretical calculations the open loop transfer function can easily be calculated there. In flight test this can only be done if a proper signal injection is available.The current control law configuration does provide test signal injection into the controller, but not at the bottleneck.

For stability margin calculations some provisions are given in the controller. Fig. 3 shows at the output of the controller to the control surfaces two signal injections generated by the frequency and bias input facility (FBI). This tool is an integral part of the controller and can be used to generate arbitrary signals, which could be injected anywhere in the controller. Current software status allows injection of these signals at those points where the control surface excitation signal leaves the controller, namely at the canard and flaperon demand signals for the longitudinal motion; frequency sweeps are available. Injection of a signal at one of these points mathematically opens the feedback loop there, thus enabling analysis for a partially open loop transfer function only. Partially open, because the feedback loop over the other control surface is still closed. Ref. 2 provides a formula which calculates the open loop transfer function at the bottleneck from the partially open loop transfer functions at the canard and flaperon injection points. It is as follows:

$$
F_{openBottleneck} = \frac{\left(F_{closedCanard} + F_{closedFlaperon}\right)}{1 + \left(F_{closedCanard} + F_{closedFlaperon}\right)} \tag{6}
$$

Thus the application of two frequency sweeps via the FBI at the canard and at the flaperon demand signal path enables the analysist to calculate the open loop transfer function at the bottleneck for a given flight condition. In practice the aircraft has to fly to the desired test conditions twice and two FBI manoeuvres have to be flown. For future testing FBI signal excitation at the bottleneck will be available, thus reducing required testing time to 50%.

2.3.2 Aircraft Pilot Coupling Evaluation

The second application of Fourier transformation analysis is the evaluation of aircraft pilot coupling criteria. This procedure represents a straight forward analysis with a transfer function resulting from the stick input as system excitation and the aircraft's attitude as system response. For this analysis only pilot produced frequency sweeps are currently available. It is also planned to use the FBI for future testing on this subject.

2.4 Aerodynamic Parameter Identification (APID)

The verification of the used aerodynamic model is performed using aerodynamic parameter identification (APID) techniques. At DASA flight test an extended version of the well known output error approach has been used highly successful for many years.

The output error approach is based on a comparison of flight measured data of the aircraft's state with corresponding data derived from a simulation. The difference between these results, the output error, is evaluated by a maximum likelihood algorithm in order to find the desired corrections to the aerodynamic derivatives. Due to the mathematical nature of the estimation algorithm the involved simulation step has to

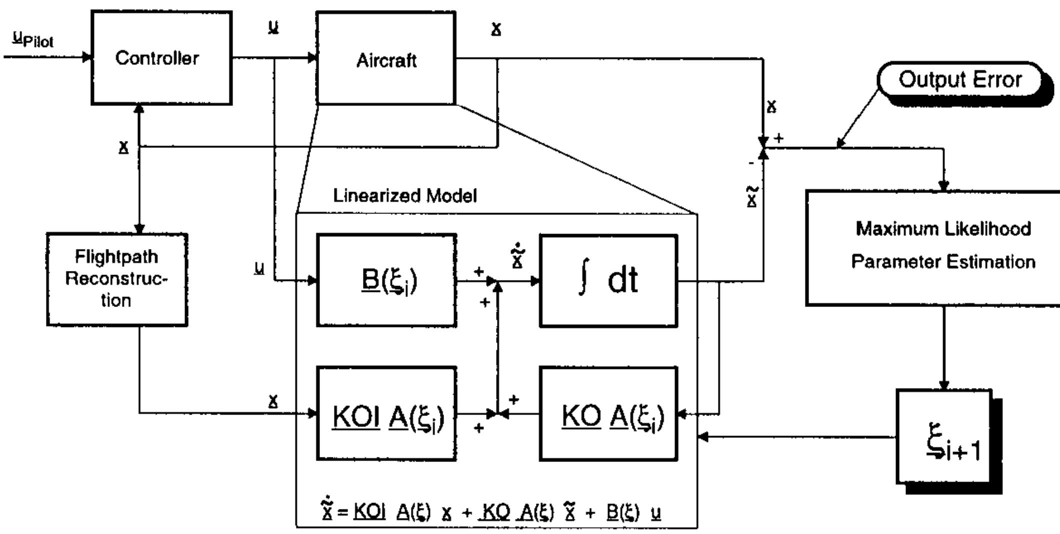


Fig. 4 Schematic Overview of Aerodynamic Parameter Identification with Equation Decoupling Technique

be based on a linearised aerodynamic model. For stable aircraft this procedure is well known and well established. For unstable aircraft this procedure fails because integration of the flight mechanical equations will generally diverge to infinite values, see e.g. Refs. 3 and 4. Therefore an output error comparison cannot be performed anymore. Ref. 3 gives a procedure, which introduces artificial stabilisation during integration of the equations. The method requires additional computational effort. At DASA flight test another approach has been followed, the equation decoupling technique as introduced by H. Schäufele in Ref. 5.

The basic idea of the equation decoupling techniques is based on the introduction of flight measured aircraft state variables into the integration of the flight mechanical equations. The usual state equation

$$\dot{\underline{\tilde{x}}} = \underline{A}(\underline{\xi})\,\underline{\tilde{x}} + \underline{B}(\underline{\xi})\,\underline{u} \qquad (7)$$

with $\underline{\tilde{x}}$ = simulated state vector
$\underline{u}$ = control vector
$\underline{\xi}$ = parameter vector
$\underline{A}$ = system matrix
$\underline{B}$ = control matrix

is then changed to

$$\dot{\underline{\tilde{x}}} = \underline{KOI}\,\underline{A}(\underline{\xi})\,\underline{x} + \underline{KO}\,\underline{A}(\underline{\xi})\,\underline{\tilde{x}} + \underline{B}(\underline{\xi})\,\underline{u} \qquad (8)$$

with $\underline{KOI}, \underline{KO}$ = decoupling matrices
$\underline{x}$ = measured state vector.

The decoupling matrices, introduced in Ref.5, are complementary, which means that at equal positions one matrix contains a '1' whereas the other contains a '0' at this position. The entire process, output error approach and equation decoupling, is summarised in Fig. 4. For general use at DASA also a flight path reconstruction is part of the process. The final result is a set of flight validated aerodynamic parameters, which now can be used to calculate the flight mechanical properties of the aircraft.

The given APID procedure has been successfully used at DASA flight test for different aircraft of stable and unstable basic airframe characteristics.The main programme of the past years was TORNADO, also experience on unstable aircraft has been gained, e.g. the German F-104 CCV (Control Configured Vehicle) in the early eighties and EAP (Experimental Aircraft Programme) in the late eighties. Also helicopters have been investigated successfully.

Currently the procedure is integrated in an extensive programme package. The analysis procedure is heavily automated although still giving enough possibilities for model variations in the APID process. Fig. 5 gives an overview. At DASA flight test strong efforts are undertaken to incorporated this process into an online environment. This would automatise the engineering work to collect manoeuvres and considerably reduce processing time.

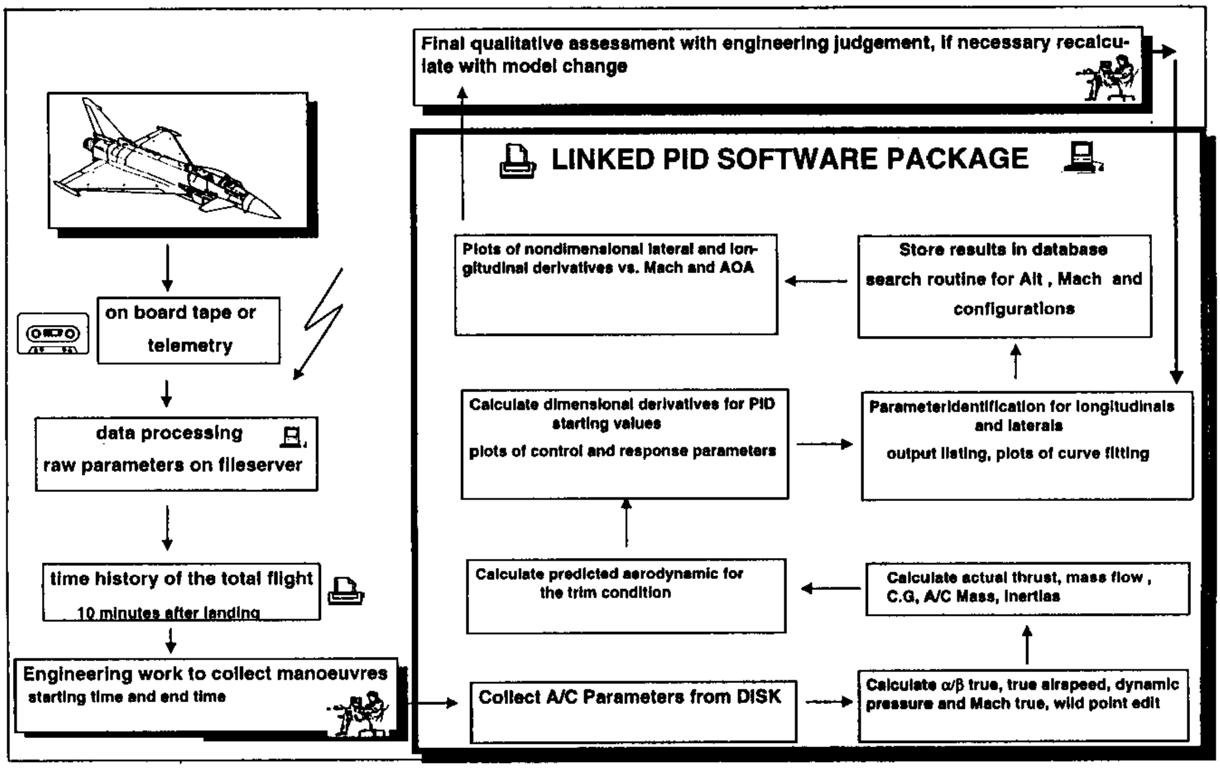


Fig. 5 Overview of Aerodynamic Parameter Identification Process

3 Representative Results

In the following some representative results for each of the described procedures above will be given. All results are from recent testing on EF2000. Since it is a military project analysis results are generally classified. Therefore certain information, which may be of interest to the reader, has been omitted.

3.1 Flight Dynamics Simulation Check (FDSC)

A typical result of FDSC analysis is given in Fig. 6. Part a) of it gives the measured traces for the pilot's inputs. The manoeuvre under consideration is a wind up turn to the left. Part b) shows the comparison of flight measured and simulated variables of the longitudinal motion. Generally very good agreement could be achieved, except for the Mach number, where some deviations can be observed. This may be due to an unsufficiently accurate modelling of the engine, at the time the Mach number curves start to deviate the pilot made an input via the throttle. Part c) shows the comparisons for the control surface positions. Finally part d) gives the leading edge position as well as two control law parameters, the integrator output and a calculated AOA value, which is used for scheduling purposes. The increasing deviation between measured and simulated traces towards the end of the manoeuvre is due to the cumulation of small starting errors during the integration process of the flight mechanical equations. Nevertheless the still very good agreement for all curves gives an indication of the high fidelity of the available model.

a)

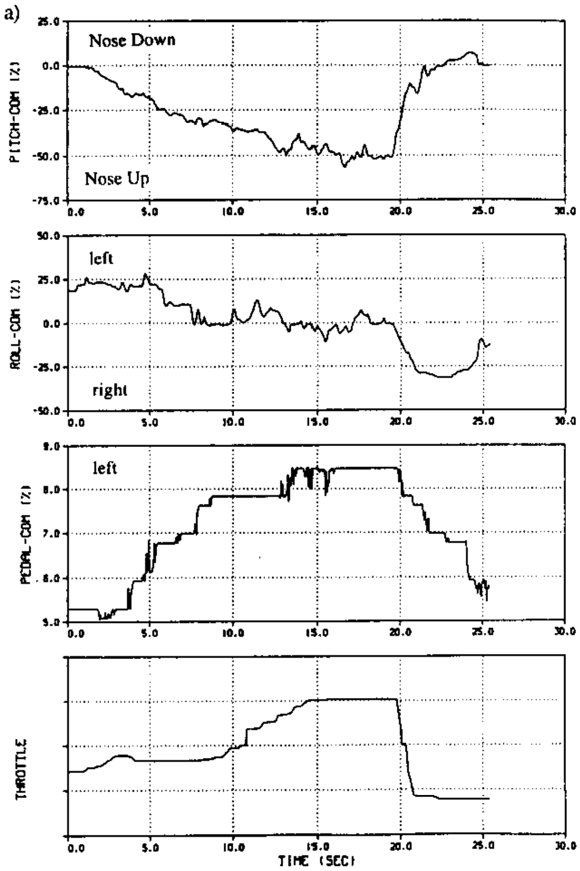
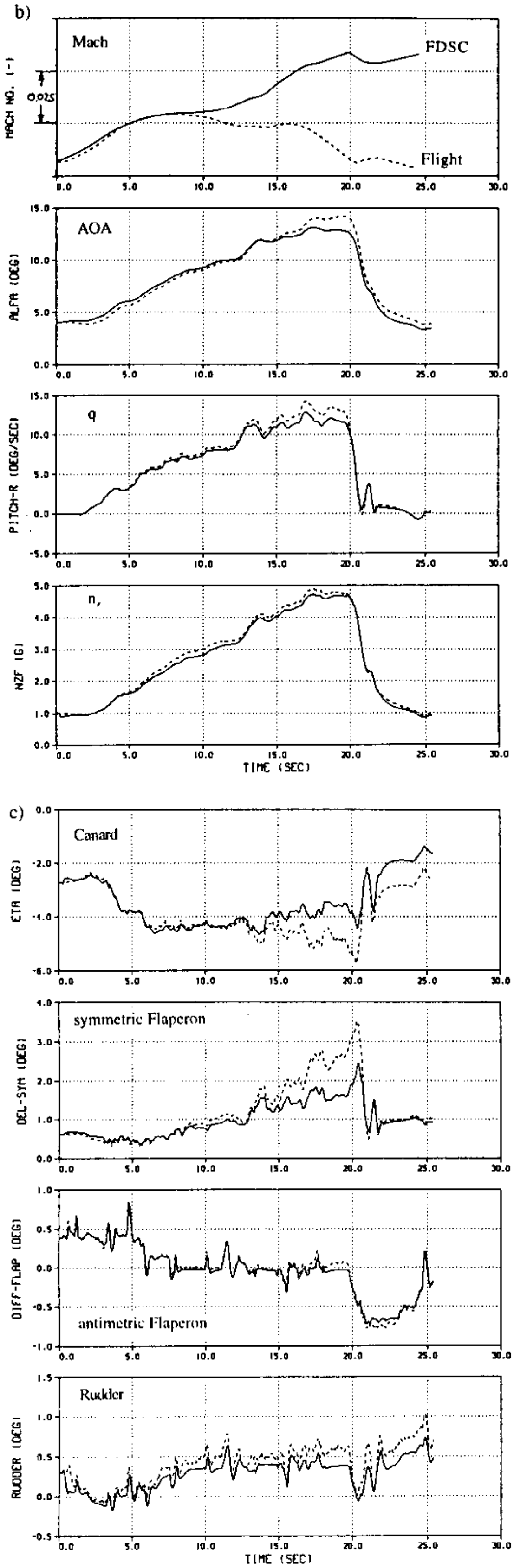


Fig. 6 Results of Flight Dynamics Simulation Check



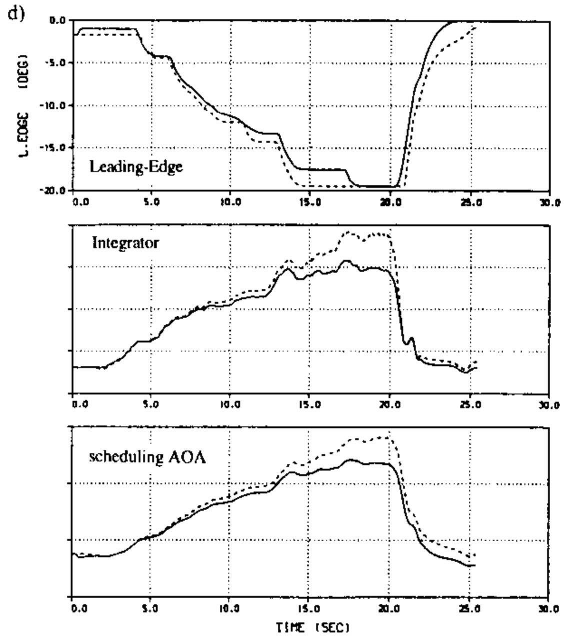


Fig. 6 Results of Flight Dynamics Simulation Check

3.2 Low Order Equivalent System (LOES) Analysis

The illustration of the LOES analysis will be given with a pitch 3211 manoeuvre. Fig. 7a gives the time history of the stick input. The signal has been filtered with a non-recursive low pass filter in order to improve the fidelity of the analysis result. Filtered and unfiltered signal are given in Fig. 7a, the difference is hardly visible, nevertheless filtering has a significant influence on the results. Fig. 7b gives the system response, the solid line the filtered, measured pitch rate and the dashed line the LOES calculated response. For this example a very simple approach was choosen with only a 4th order transfer function for numerator and denominator. Nevertheless with this simple model already a very good agreement has been achieved. A summary of the resulting Eigenvalue evaluation is given in Fig. 8 for the Short Period of the longitudinal motion. The result is an indication of the already very good handling qualities of EF2000 in this early stage of development.

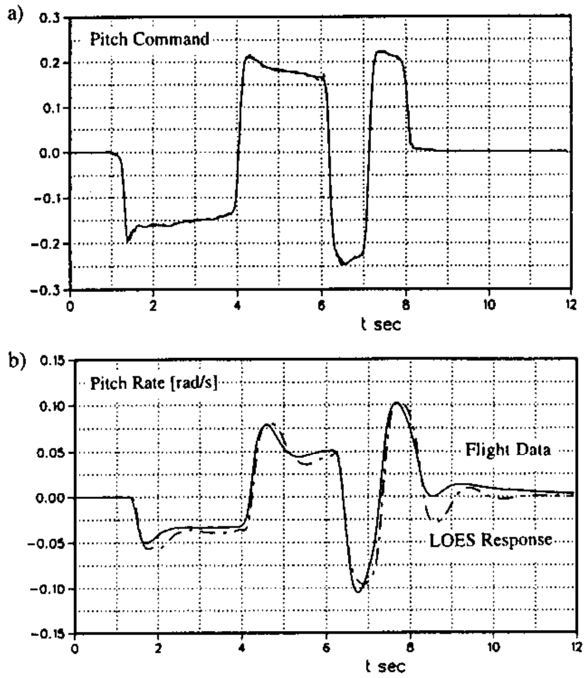


Fig. 7 Time Domain Results of Low Order Equivalent System Analysis

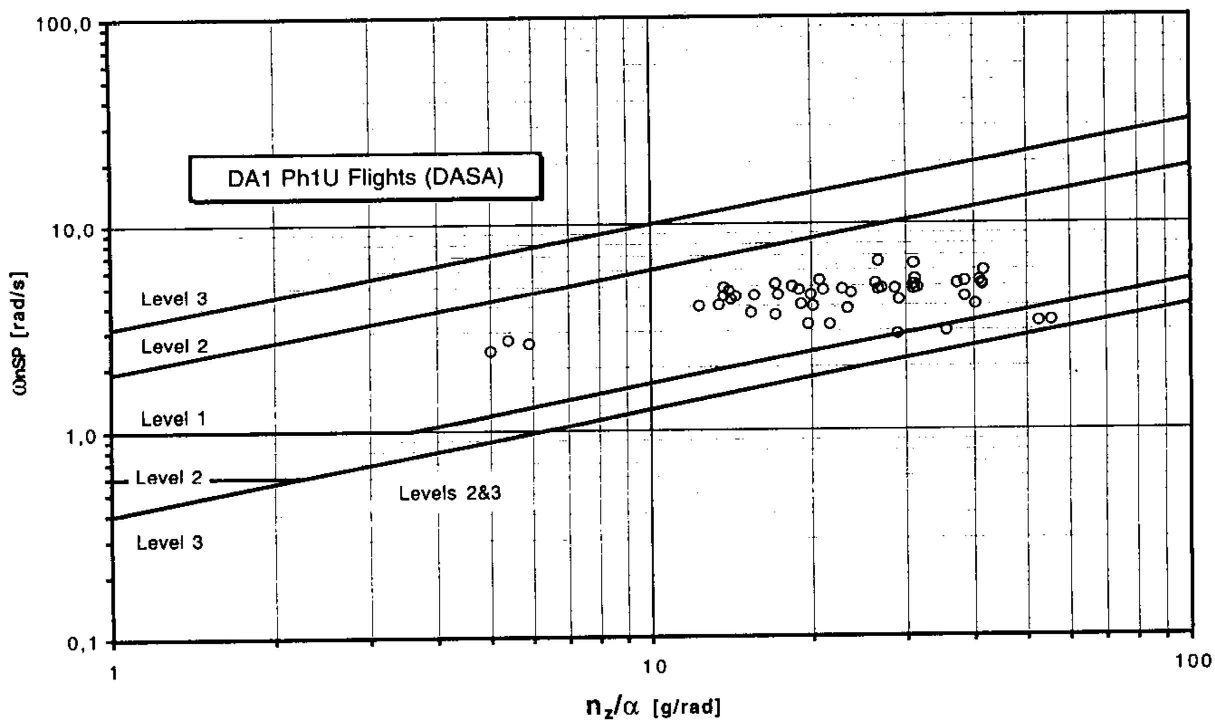


Fig. 8 Summary of Frequency Domain Results of Low Order Equivalent System Analysis (Short Period)

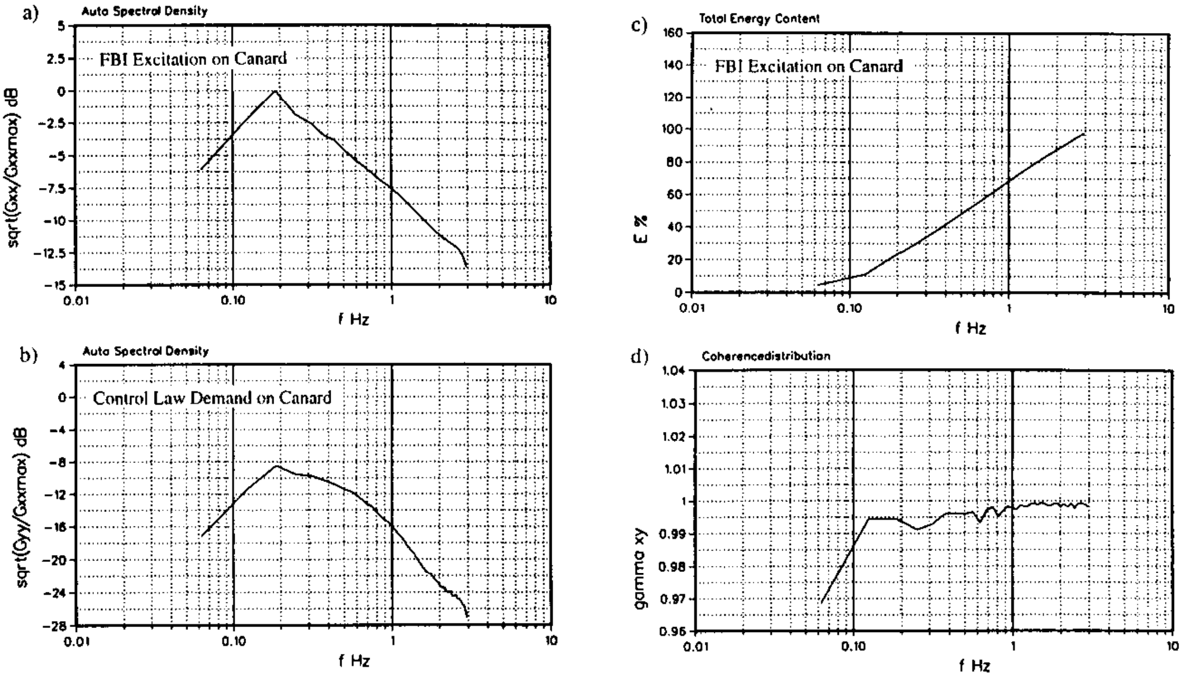


Fig. 9 Frequency Domain Analysis of FBI Excitation Signals

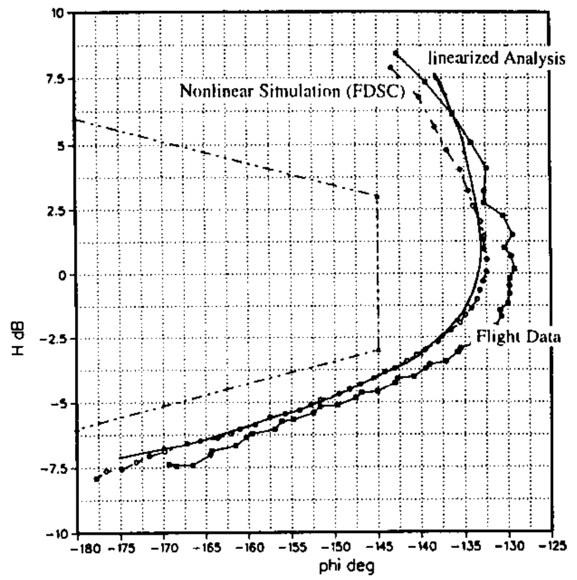


Fig. 10 Open Loop Stability Margins at the Bottleneck

3.3 Frequency Domain Analysis

3.3.1 Control Law Stability Evaluation

An example of FBI signal evaluation is given in Fig. 9 for FBI excitation at the canard command path, measured in flight on DA2, see also Fig. 3. Figs 9a and 9b show the spectra of the FBI excitation and the resulting control law demand, both spectra are normalised with the peak value of the FBI excitation spectrum. In addition Fig 9c gives the cumulation of energy in the excitation, also as a function of frequency, showing a linear distribution up to the maximum frequency at 3 Hz. The coherence function shown in Fig. 9d gives an indication on the validity of the resulting transfer function. It is the better the closer it gets to '1'. Finally Fig. 10 depicts the entire analysis result, showing the control law stability margin at the bottleneck, as derived with Eq. 6. Flight measured results have been derived from DA2 data with DASA analysis tools and are marked with the squares. Corresponding nonlinear simulation data have been produced with the described FDSC tool at DASA flight test and are marked with the circles, wheras the linearised analysis results come from DASA flight mechanics and are given as a solid line. The linearised data has been derived from an analytic control law model and not with Eq. 6. For this particular case a very good agreement between both predicted curves can be observed. A comparison between flight data and simulated data indicates that the predicted stability margin is closer to the stability boundary, thus indicating more stability in flight than with the model.

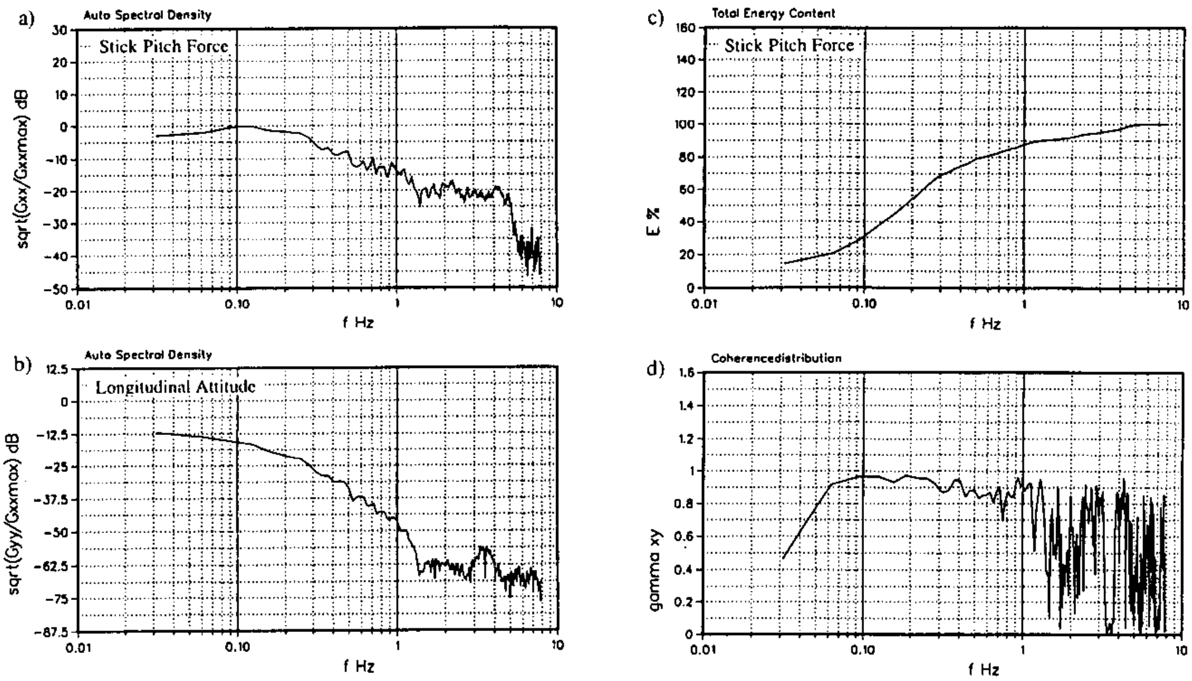


Fig. 11 Frequency Domain Analysis of Pilot Produced Frequency Sweep

3.3.2 Aircraft Pilot Coupling Evaluation

Aircraft pilot couplings criteria have been investigated in flight on DA1 with pilot produced frequency sweeps on the stick. This is a difficult task for the pilot especially for 'higher' frequencies, e.g. f>1.5 Hz. The resulting spectrum of the stick force signal is given in Fig. 11a. One can see that the distribution of energy is not as even as for the synthetic FBI excitation given in Fig. 9a. The spectrum of the corresponding system response, the aircraft's attitude, is given in Fig. 11b. The energy cumulation of the exciting stick force spectrum is given in Fig. 11c and one can easily see that most of the applied energy is already present for frequencies below 1 Hz. This has consequences on the quality of the resulting transfer function, which is already indicated in Fig. 11d with the results of the coherence distribution. For frequencies above 1 Hz only very poor coherence values can be observed. Nevertheless these results are tested against an aircraft pilot coupling criterion given by J. C. Gibson, Ref. 6. The result is given in Fig. 12. The resulting transfer function shows a very uneven trace, which has to be attributed to the above given arguments on energy cumulation and coherence distribution. For large phase lags the level 1 boundary is calculated from the slope of the measured transfer function. Since this is not so smooth, the slope calculation via numerical differentiation for this special case is questionable. Thus the result does not necessarily mean that the given boundary is hurt. It is expected at DASA flight test that these results will improve considerably once FBI signal excitation will also be available at the pilot's stick. In this context it should be noticed that the Gibson criterion is well suited for online analysis purposes.

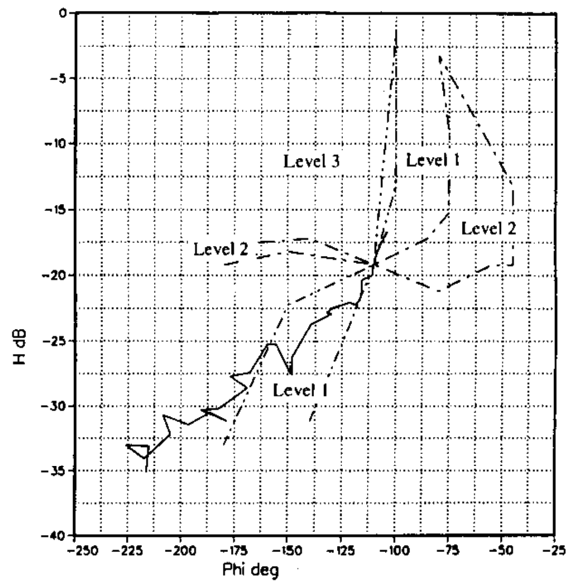


Fig. 12 Aircraft Pilot Coupling Criterion

3.4 Aerodynamic Parameter Identification (APID)

The presentation of results will be concluded with some typical APID results. Time histories of a pitch 3211 manoeuvre are given in Fig. 13. Fig. 13a gives a comparison of measured AOA (solid line) with the corresponding flightpath reconstruction result (dashed line). Figs 13b and c give the excitation via the control surfaces canard and symmetric flaperon, wheras Fig. 13d gives the measured load factor. Figs. 13e to h

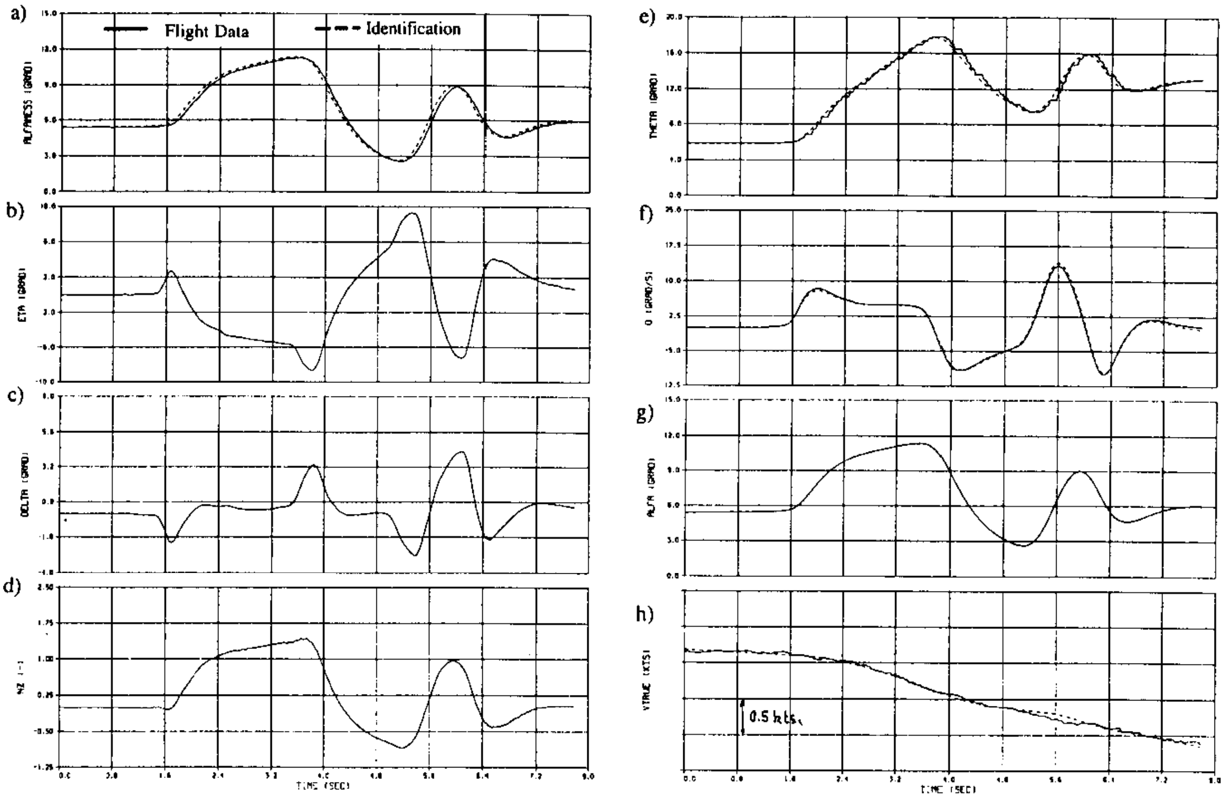


Fig. 13 Time Histories of Aerodynamic Parameter Identification Results

give the comparisons of measured state variables (solid lines) and 'identified' state variables (dashed lines). Identified state variables in this context means outcome of a simulation which uses as aerodynamic derivatives the results of the APID process. Good agreement of results in Figs. 13e to h is a necessary requirement for good APID results.

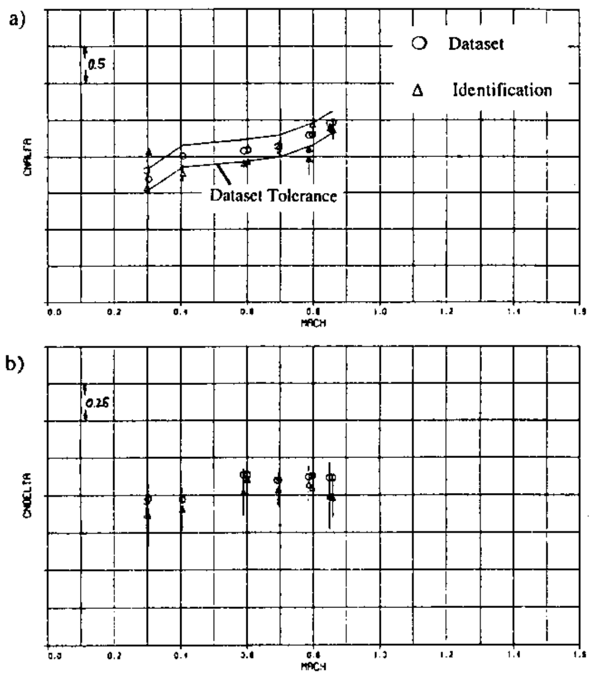


Fig. 14 Summary of Aerodynamic Parameter Identification of Longitudinal Aerodynamic Derivatives (Normal Force)

Some representative results for the longitudinal motion are given in Fig. 14 for the normal force coefficients $c_{N,\,alfa}$ (part a) and $c_{N,\,delta}$ (part b) and in Fig. 15 for the corresponding pitching moment derivatives, here also results for pitch damping c_{mq} (part c) are given. The figures give identified results as triangles together with 5σ deviation bounds as solid vertical lines. Predicted values as derived from the data set are given as circles, with respect to these circles data set tolerances are given as solid horizontal lines. The diagrammes reveal a very good coincidence between identification results and predictions, again indicating the high fidelity of the used model.

For these calculations the effectiveness of the canard was fixed due to a linear dependancy between canard and flaperon deflection. It is expected to improve this situation once the FBI will also be used for APID purposes, then the linear dependancy between canard and flaperon deflection can be disturbed, thus both effectivenesses could be identified.

Finally Fig. 16 gives a summary of further evaluations of the APID results. The identified derivatives have been used to calculate flight mechanical properties. As an example this figure gives the identified value of the stability margin during the tests.

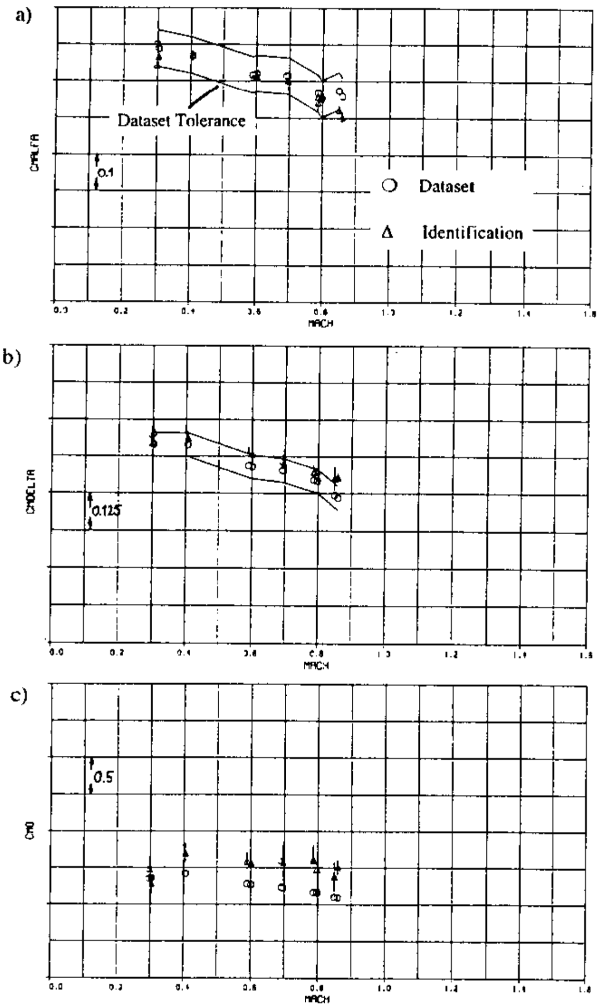


Fig. 15 Summary of Aerodynamic Parameter Identification of Longitudinal Aerodynamic Derivatives (Pitching Moment)

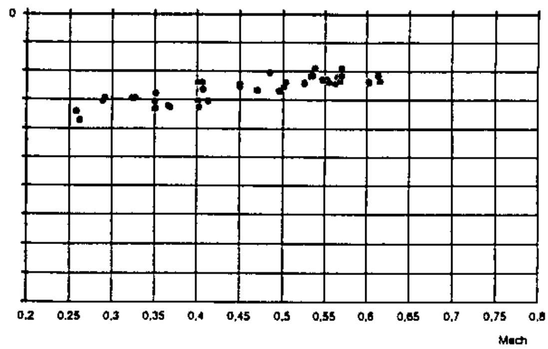


Fig. 16 Stability Margin as a Result of Aerodynamic Parameter Identification

4 Summary

EUROFIGHTER 2000 will be the future fighter aircraft for the air forces of Spain, Italy, United Kingdom and Germany. Currently the development flight test evaluation of this aircraft is under way. Flight test tasks are shared between partner companies. The present paper emphasises on analysis methods for flight mechanical and aerodynamical evaluation suitable for a very agile highly unstable fighter aircraft at DAIMLER-BENZ AEROSPACE flight test centre at Manching. Methods are summarised and illustrated with some representative results.

One major topic is the analysis of the augmented aircraft. Analysis methods in the time domain as simulation of flown manoeuvres and in the frequency domain as Z-transformation and Fourier analysis methods for system stability evaluations are presented. For the unaugmented aircraft DASA's aerodynamic parameter identification method is presented. It resembles a unique equation decoupling approach to cope with the problems arising from the analysis of unstable aircraft.

For the presented analysis methods some representative results are given. These results demonstrate the analysis capabilities of these methods. It is also shown that EF2000 flight testing can rely on an already high fidelity aerodynamic model. This gives confidence for the flight testing tasks.

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