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AEROELASTIC INVESTIGATIONS AS APPLIED TO AIRBUS AIRPLANES

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Abstract

The work breakdown for the aeroelastic development and certification of an Airbus aircraft reflects the multinational cooperation for the whole design and manufacturing. The work steps to get the Aeroelastics Certification are presented. A detailed description of every work step cannot be given, because that would exceed the scope of this paper. Therefore, only the latest developments in the domains of transonic unsteady aerodynamics, aeroservoelasticity, flutter and structural optimization, as applied to Airbus aircraft, are presented.

The design of aircraft today requires many interdisciplinary procedures. This is particularly valid for aeroelasticity, because several different disciplines like structure, aerodynamics, control technique and others are concerned. Besides the examples shown, e.g. structural optimization, unsteady aerodynamics, and aeroservoelasticity, a prospect is given for interdisciplinary optimization procedures performed independently by the disciplines participating.

1. Introduction

The aircraft of the Airbus family have been developed and manufactured within a multinational cooperation. Such multinational cooperation requires a special arrangement of responsibilities. Like other so-called "non-specific" design activities, the whole aeroelastic work for an Airbus aircraft series is shared among a prime partner and level 2 partners. Nevertheless, the theoretical and experimental aeroelastic work for the design as well as for the certification is dominated by the prime partner. This responsibility has been rotating between Aerospatiale and Deutsche Airbus for the different Airbus aircaft series. In this context, Deutsche Airbus is aeroelastic prime partner for the A330/340 series. The input data for aeroelastic calculation e.g. geometry, stiffness and mass distribution or FE-models, aerodynamic data, and control laws for the Electronic Flight Control System (EFCS) have been made available by the prime partner responsible for the aircraft component or the system.

2. Procedure to get Aeroelastics Certification

Although the aeroelastic procedure is well known it seems worthwhile to describe the sequence in time of the necessary aeroelastic tasks which have to be performed to get the certification (Fig. 1).

Since for Airbus aircraft static aeroelatics does not play such an important role in the aeroelastics certification procedure it has not been mentioned in Fig. 1. Static aeroelastic investigations must ensure that there is no reversal speed for any control surface, and no divergence speed inside the certification envelope. The reversal problem for outbord ailerons has been solved by fixing the aileron or cancelling the signal input on the actuator in the critical region. The divergence speed is no problem for sweptback lifting surfaces.

On the left-hand side of Fig. 1 the calculations are listed which are necessary to get flutter predictions for a certain project. In the predevelopment phase or for a feasibility study of an aircraft these flutter results may show flutter problems. In this case, design changes must be found in order to improve the flutter behaviour of this project, meaning that flutter calculations have to be performed with design changes which seem to solve the problem suitably.

If the available design changes do not solve the existing flutter problems on the project, the necessary flutter improvements might be provided by structural reinforcements. The numerical optimization methods offer effective means to define the reinforcement distribution both within the framework of a pure flutter optimization and a structural optimization process. Active Control Systems (ACS) e.g. Damping Augmentation Function (DAF) offer the possibility of increasing the damping values of certain modes. The ground vibration test (GVT) is an essential part of the aeroelastics certification procedure in Europe. The GVT results are used to adjust the theoretical structural model. This adjusted theoretical structural model is used for all further calculations including the certification calculations.

During the flight vibration tests (FVT) the aircraft flutter behaviour is verified. Also, the FVT is the last opportunity to detect not predicted flutter cases, and its results provide means to adjust the aerodynamic model.

In this paper the procedures of all mentioned disciplines cannot be treated as in the paper [1]. Therefore only the application of the following disciplines on Airbus aircraft is given for the improvement of aeroelastic design and also for the certification procedure.

- Unsteady Aerodynamics
- Flutter Optimization
- Aeroservoelasticity

Additionally, prospects for the determination of aircraft functions are given which can only be found optimally by an interdisciplinary consideration among several disciplines with equal importance on the result.

3. Unsteady Aerodynamics

For design flutter calculations of Airbus aircraft, linear unsteady airloads such as Doublet Lattice (D.L.) and Kernel Function methods have been used for a long time. In the transonic region, however, at least for wings with supercritical profiles which Airbus aircraft have been equipped with, flutter calculations using linear unsteady airloads may lead to nonconservative flutter results, because of a phenomenon generally described as transonic dip. Therefore several improvements have been made:

1. Adjustment of D.L. airloads to match steady measured local lift curve slopes and aerodynamic centres.

2. Correction of D.L. pressures by means of quasi-steady pressure distributions, as proposed by Garner [2], and improved by Dau [3].

3. Calculation of unsteady airloads by higher order aerodynamic theories (TSP, Full-Potential, Euler) taking into account boundary layer effects by viscous-inviscid interaction.

Fig. 2-4 show a comparison of wind tunnel data with results of Dau-Garner for the Aeroelastic Model Program (AMP). Unsteady pressure distributions, as well as flutter calculation results, are in excellent agreement with the experimental results. It should be mentioned that even the ascending leg of the transonic dip is well represented.

For many industrial applications unsteady airloads may be calculated precisely enough with the Dau-Garner Method, which uses measured pressure distributions to correct D. L. results. Transonic effects as well as viscous ones are taken into account by this method, so that excellent results may be obtained as shown in Fig. 2-4. Therefore this method has been applied with good success to the design and certification flutter calculations of Airbus airplanes. Fig. 5 shows the influence of the transonic effects on flutter calculation results for the Airbus A 340. For comparison D.L. airloads are shown with the same M number.

Fig. 6 shows the diverse methods for the calculation of 3D unsteady airloads by solving higher order inviscid aerodynamic equations, which may take into account viscous effects by coupling Integral and Finite-Difference (F.D.) methods. The coupling procedures may be divided into in weak and strong viscous-inviscid interaction schemes. Neglecting of boundary layer effects leads to inaccurate steady and unsteady airloads mainly because of the poor prediction of shock strength and shock position. Therefore higher order methods must at least take into account the boundary layer displacement thickness in addition to the geometrical profiles. the papers [4] and [5] give the methods and their effectiveness which have been developed and used by Deutsche Airbus.

Most of the methods for determining transonic airloads are time marching procedures integrating from one time step to the next, while the boundary conditions are prescribed by an arbitrary motion of the lifting surface. The strong interaction methods simultaneously solve the governing equations of viscid and inviscid flow at each time step.

In contrast to these nonlinear time marching procedures, frequency domain methods treat only sinusoidal motions of the lifting surfaces. For this type of approach the fundamental equations may be time linearized with the assumption of small amplitudes, separating the mean steady flow from the unsteady one. Integral as well as F.D. methods exist for solving these time linearized methods.

If nonlinear effects become important, e.g. with increasing amplitudes, correction methods and time linearized methods are no longer valid. Such types of flow can only be calculated by the time marching codes mentioned. Unlike in the subsonic region, where a harmonic motion induces harmonic unsteady airloads, the airloads in the transonic speed range are no longer harmonic, but only periodical. This is mainly due to the unsteady shock motion (Fig. 7). The higher harmonics of the pressure distribution become more pronounced with increasing vibration amplitudes (Fig. 8). This dependence was measured in the AMP experiment at various spanwise sections.

The flutter calculation is usually based on the modal method. The vibration modes used are the calculated or measured natural modes of the aircraft. With some small neglections the structural equations of motion may be transformed into an eigenvalue problem, nonlinearly dependent on the reduced frequency. This classical flutter calculation method is only valid as long as the harmonic motion of the aircraft in a natural mode induces harmonic airloads. But with amplitude the resulting shock motion becomes more and more important for the unsteady airloads. Then the flutter calculation has to be performed in a way similar to the procedure used in the time marching aerodynamic codes, i.e. a time domain flutter calculation has to be carried out by a simultaneous integration of aerodynamic and structural equations of motion. This type of flutter investigation is called flutter simulation, and takes into account:

- the full dependence of the airloads on amplitudes
- the higher harmonics
- the influence of growing and decaying amplitudes on the aerodynamics

Details of such a method are given in [6]. Fig. 9 shows a comparison of the classical flutter calculation with the flutter simulation. The classical flutter calculation results have been obtained by taking into account only the first harmonic of the calculated airloads of the viscous TSP method. Since there is no difference between the results of the flutter simulation and the flutter calculation, the contribution of nonlinear effects are small enough to be represented by the flutter calculation approach.

On Airbus aircraft the unsteady transonic airloads applied in flutter calculations can be calculated with sufficient accuracy by correction methods, i.e. pronounced nonlinear effects which would influence the flutter results have not been observed.

But it seems important that airload and flutter calculation methods, which take into account the real physical transonic effects, are available if such phenomena become important on a project. Then the still existing shortcomings of those airload calculation methods might not be so important unlike the advantage that the principal physical effects can be considered.

4. Aeroservoelasticity

The Airbus A 320, A 330 and A 340 are equipped with an EFCS and with electrically controlled actuators for the ailerons and elevators. The rudder actuators are controlled mechanically from the stick, and electrically from the yaw damper servo actuators (Fig. 10). The electrical input signals for all the actuators are calculated by flight computers, and are based amongst others on acceleration and rates, measured at certain structural points of the aircraft. Within this calculation defined control laws are used. The measured signals are converted by analog-digital converters into digitalized data, and vice-versa the calculated response data into analog signals. A principal sketch for the EFCS is shown in Fig. 11. The control laws are defined such that the handling qualities of the aircraft are optimal. Thus, it seems obvious that the control laws used in such a system not only influence the handling qualities of the aircraft, but also the loads and the flutter behaviour.

In the classical flutter calculation, the displacement of the a/c structure is represented by a set of N natural modes. To keep the number N of the structural modes used in a flutter calculation of an aircraft including the EFCS in the same order as without the EFCS, additional unit-angle-rotation modes of the control surfaces have to be added, at least one for each control surface. That means the response of a fly-by-wire aircraft is represented by a set of mode shapes:

$$\psi(x,t) = \sum_{i=1}^{N} \varphi_i(x) q_i(t) + \sum_{i=N+1}^{N+n} \varphi_i(x) q_i(t) \tag{1}$$

where $\Phi_i(x), i=1,\dots,N+n$, are the N mode shapes of the associated conservative system and the n rigid control surface rotations, and $q_i(t), i=1,\dots,N+n$, are the generalized coordinates. With the series (1) the flutter stability equation of a fly-by-wire aircraft can be given with the following equation:

$$\left\{ s^2 M + sD + K + \frac{1}{2}\varrho v^2 \, Q(Im(s)) + \varphi_P^T H(s) \varphi_M \right\} q = 0 \tag{2}$$

The first 4 terms of equation (2) describe the flutter stability of the classical system. The last term of the equation contains the functions and quantities of the flight control system and the actuators, i.e. M, D, K, Q: matrices of the generalized masses, dampings, stiffnesses and unsteady airloads; Φ_p matrix for generalizing the physical discrete forces; Φ_M measuring matrix and H (s) matrix of the transfer functions, defined as:

$$F(s) = H(s) y \quad \text{with} \quad y = \varphi_M q \tag{3}$$

with F(s) actuator force acting on the aircraft. The transfer functions describe the relation between forces and displacements. When the transfer functions have been established by calculation or measurement, the equation (2) can be solved in the same way as a classical flutter equation. The recommended flutter solution method is the method of Vogel [7] and also the method of Hassig [8]. With that the aeroservoelastic stability equation of an aircraft is fully described. In addition to the classical flutter equation, the unit-angle-rotation of the control surfaces and the transfer functions of the flight control system and the actuators are necessary.

However, potential instabilities of controllers and actuators cannot be obtained by this method, because the respective degrees of freedom are included but not analysed. To check those instabilities as well, the equations in the state space including the equations for controllers and actuators have to be applied as used by the control engineers. These methods have been described by e.g in [9]. Fig. 12 obviously shows the influence of the EFCS on flutter for the A 340 aircraft at an early development stage. By changing the gains and by the introduction of filters with low-pass and notch character the influence on flutter has to be and can be minimized.

As shown the aeroservoelastic equation requires linear transfer functions for the systems used, and linear strain stress relations for the structure of the aircraft. Usually, however, the control laws depend nonlinearly on the rates and accelerations of the aircraft, the filter response depends nonlinearly on the input signals, and limiters limit the responses. In addition the main parts of the EFCS work on a digital basis, other parts on an analog basis. That means the sampling rate for signals defines the resolution of the feedback input signal. The calculation time of the computers for the control signals leads to time delays for these signals.

That means the control laws have to be linearized for certain signal amplitude ranges in the aeroservoelastic calculation, and time delays must be translated in phase shifts of the signals.

All the nonlinearites induced in and by the EFCS may be better covered by a simulation with hardware in the loop. For this simulation the hardware is the EFCS, while the elastic motion of the aircraft which produces the input signals for the EFCS is calculated by a digital computer. Such a simulation is not yet possible within industrial limits. Today, the calculation speed of the computers only covers the possibility of calculating the response of a rigid aircraft in correlation with the hardware parts.

Active control systems (ACS) are probably very simply added to a fly-by-wire aircraft, because the necessary computers, the bus and the electrically controlled actuators exist. Fig. 13 shows the dynamics of a ride comfort system for the lateral movement of the fuselage controlled by the rudder and the yaw damper servoactuators already mentioned. This system had been planned at a certain development stage of the A 340. Since the valve levers of the rudder actuators are controlled by a rod, structural nonlinearities and hysteresis effects have to be considered. Details are given for such ride-control-systems in [10]. The nonlinearities were implemented in the programming of the dynamic model by simulation procedures and transformations using the simulation language ACSL (Advanced Continuous Simulation Language).

The effectiveness of an ACS is highly dependent on the failure likelihood of such a system. In [10] the requirements for certification of a "Flutter Damping Augmentation System" were described. The A 320 is equipped with a "Load Alleviation Function".

5. Flutter Optimization

If principal design changes do not lead to a flutter free aircraft, the necessary flutter improvements might be provided by structural reinforcements. The numerical optimization methods [11] offer effective means to define the reinforcements distribution over the aircraft or its component. By a sensitivity analysis the effectiveness of the reinforcements of skin, span or stringer elements (the so-called design variables) are determined. These sensitivity calculations have to be performed for the different iteration steps of the optimization process. For the formulation of the aim of the optimization process, damping constraints for hump shaped damping as well as flutter speed constraints for damping curves with steep gradients may be used (Fig 14). The application of the flutter optimization has been given for several examples on Airbus aircraft [1], [12]. Flutter optimization only, however, can provide reinforcements of the structure to avoid an exceeding of allowed stress levels. Therefore it is supposed that simultaneous stress and flutter optimization is more appropriate to get an overall minimum weight solution for the structure. Within the framework of an AGARD S & M Panel workshop entitled "Integrated Design Analysis and Optimization of Aircraft Structures" a simultaneous stress and flutter optimization for the A 340 wing was established by British Aerospace (BAe) and DA [13].

In this work an FE-model of the wing, fixed at the wing root rib, was used for the determination of stresses and their gradients. The stress optimization model was defined by seven dimensioning load cases and a total of 5072 stress constraints (principal stress). Semi models representing a four engined A/C series, different in fuselage length, constrained by symmetric and antisymmetric boundary conditions applied on the plane of symmetry were used to investigate dynamics. The aeroelastic optimization model covers critical symmetric and antisymmetric flutter modes for each of the two aircraft variants in different payload and fuel conditions. This resulted in 24 aeroelastic constraints. The top and bottom surface as well as the front spar of the wing, broken down into 21 design variables, were released for optimization. To elaborate the salient features of constraint introduction, 2 different methodologies were under consideration:

Step 1 Optimization with stress constraints only.

Step 2 Based on the result of 1 (lower bounds of design variables are the result values of design variables of 1) introduction of flutter constraints.

Step 3 Introduction of stress - and flutter constraints simultaneously.

Result of step 2 to be compared finally with result of step 3.

Several optimization schemes were applied. The results shown in Fig. 15 were achieved by Sequential Convex Programming (SCP) as strategy, Modified Method of Feasible Direction (MMFD) as optimizer, and with a polynomial line search. The optimization with stress constraints only provided a weight reduction of 768 kg per aircraft side. The simultaneous stress flutter approach lead to 169 kg weight saving compared to sequential stress flutter approach. This is the salient feature of this result. That the stress optimization only provided the most favourable results is taken for granted. The optimization program used is an in-house tool of DA called SIMOPT, Simultaneous Optimization under Static and Aeroelastic Constraints.

6. Aeroelasticity as part of the design in an interdisciplinary consideration

The aeroelastic work for the design of an aircraft is dependent on the results and the progress of other disciplines and cannot be achieved independently of the requirements of certain other disciplines. With progressing design process the input data for the aeroelastic calculation become more precise, but the possibility for design modifications of the aircraft for the improvement of its aeroelastic behaviour decreases considerably. Modifications at a time schedule, for which the design of the aircraft is more or less frozen, possibly impair the aircraft performance.

Taking into account input data precise enough to get flutter predictions appropriate to assess the overall aeroelastics situation of an A/C, this should ideally be directly fed back into the design process.

This way is considered to be unrealistic because such a valuation is not possible before the theoretical model has been adjusted to the ground vibration test results, and additionally the final definition of the electronic flight control system (EFCS) is known. During the design process the discussion arising for optimum weight and reduction of development risks can partly be prevented by starting an interdisciplinary structural optimization run, taking into account manufacturing, stress, and flutter constraints assigned to the current stage of theoretical models. The gain hereby is to avoid already recognizable problems like flutter or low damping caused by frequency couplings or frequency neighbourhood, thereby not exceeding stress levels and achieving manufacturable design under weight optimality. Furthermore this result can be provided at low cost compared to the situation study of parameters for all participating disciplines. Because the EFCS can influence flutter and the loads of an A/C, its phase and filter constraints should be introduced in future into the optimization process with the aim of obtaining excellent handling qualities and suitable effects on loads and flutter. At least, optimization taking into account constraints in an interdisciplinary sense reduces development risks considerably.

For an A/C design which embodies optimal attractiveness, interdisciplinary cooperation must be initiated to provide a basis for design decisions on time, taking all important interdisciplinary mutual effects into account. A methodology for this was proposed by Sobieszczanski-Sobieski [14]. By means of an analysis providing total derivatives the effects of design changes on behaviour variables (stress level, damping, etc.) are visualized. Furthermore this analysis, repeatedly made following the design stage, can be used to find the optimal solution by means of mathematical optimization tools. Engineering supported by this methodology may provide the way to reach product optimality for future tasks.

7. Conclusion

The procedures to get the aeroelastics certification for Airbus aircraft are given in part. The transonic unsteady aerodynamics in the flutter calculations for Airbus aircraft have been covered by matching the D.L. airloads with steady measured local lift curve slopes and aerodynamic centres, or by correction of D.L. pressures by means of quasi-steady pressure distributions, proposed by Garner and Dau with sufficient precision. Nevertheless methods have been prepared for the calculation of aerodynamic forces in the transonic speed range based on higher order aerodynamic equations and under consideration of the boundary layer. The influence of the EFCS on flutter for fly-by-wire Airbus aircraft was considered. To minimize this influence, gains had to be reduced and filters added. An appropriate weight saving can only be achieved by a simultaneous stress and flutter optimization. An optimal aircraft design can only be achieved on time by integrating some of the aeroelastic work in an interdisciplinary optimization process.

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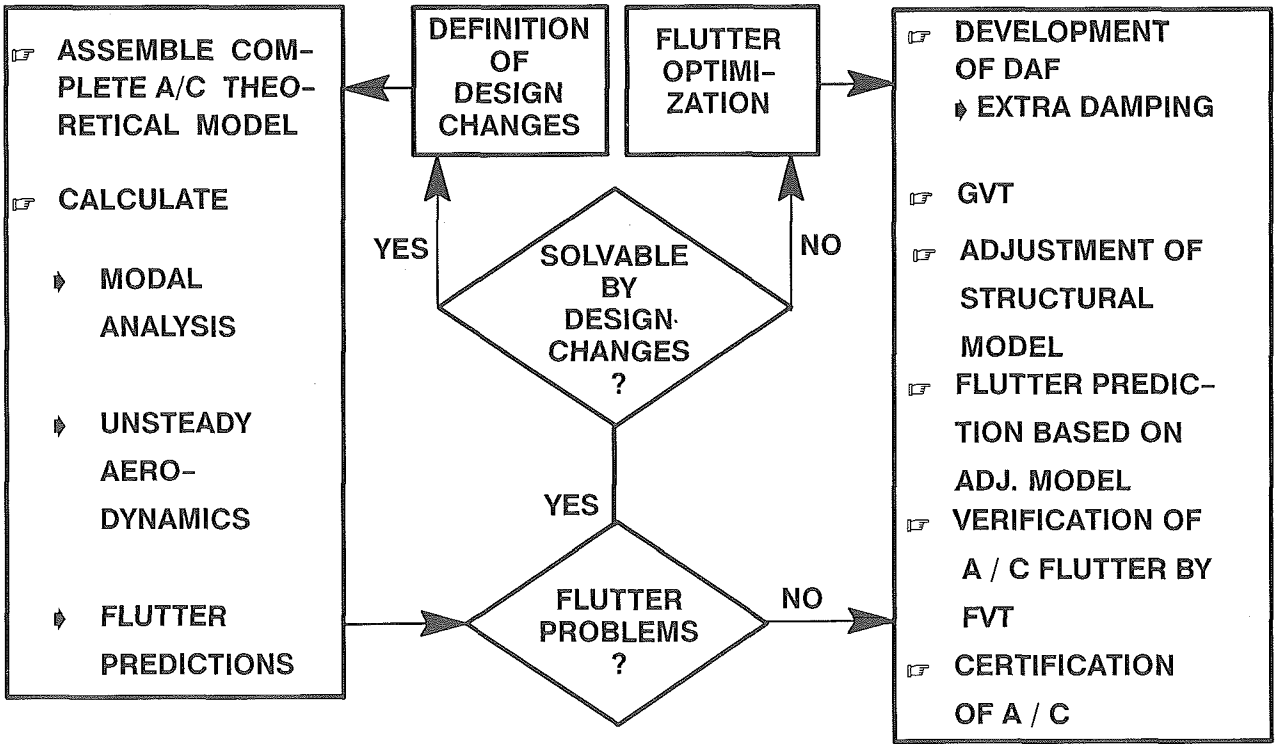


Fig. 1 Procedure to get A/C Aeroelastics Certification

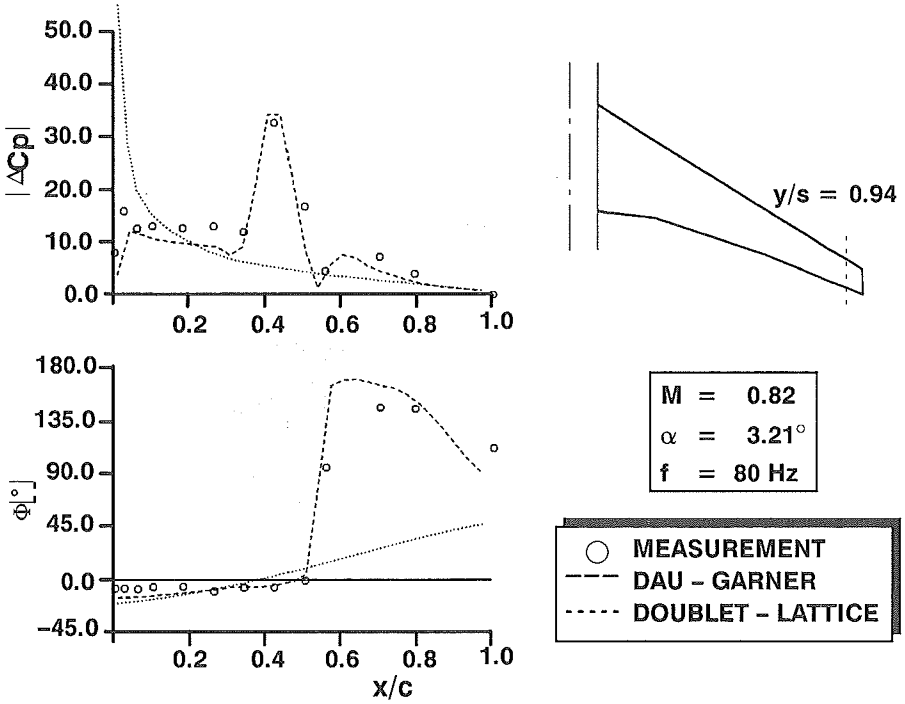


Fig. 2 Comparison of Measured and Calculated Unsteady Pressure Distributions

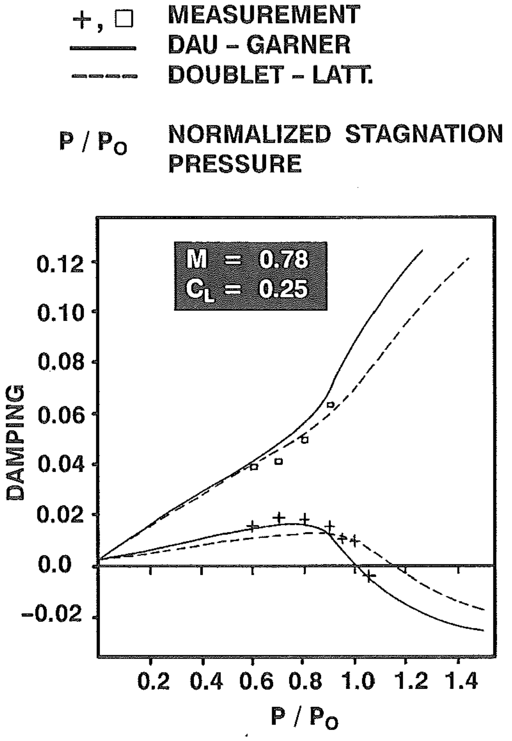


Fig. 3 Damping Development of a Flutter Model Test compared to Calculation Results

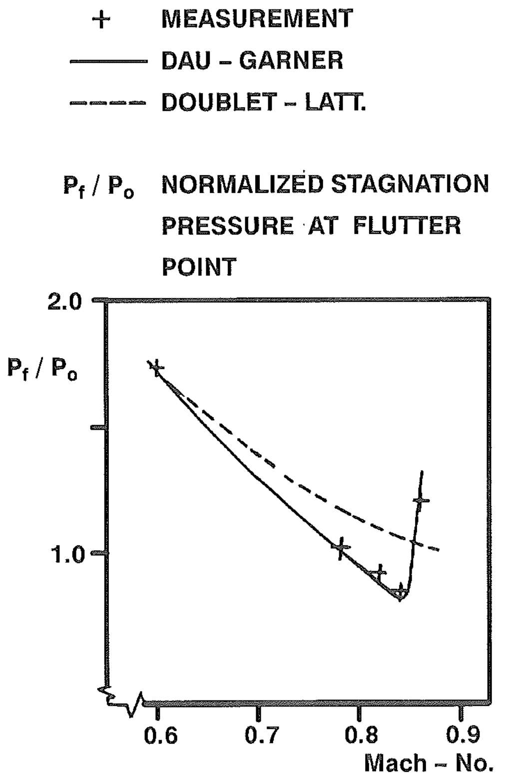


Fig. 4 Transonic Dip of a Flutter Model

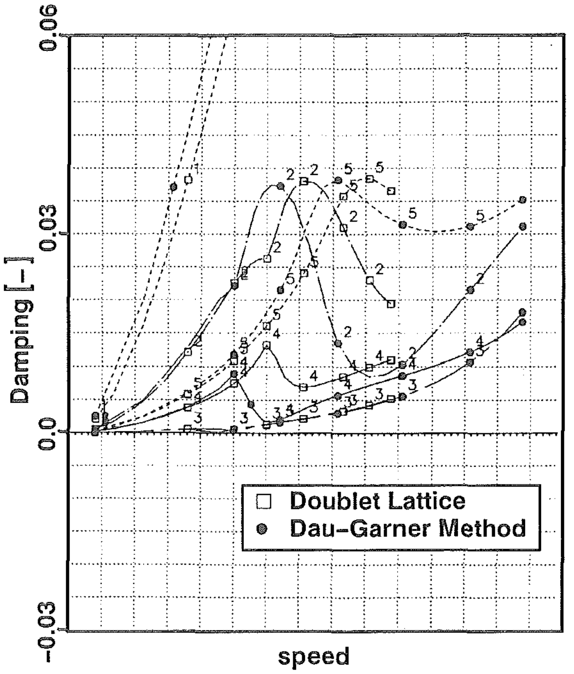
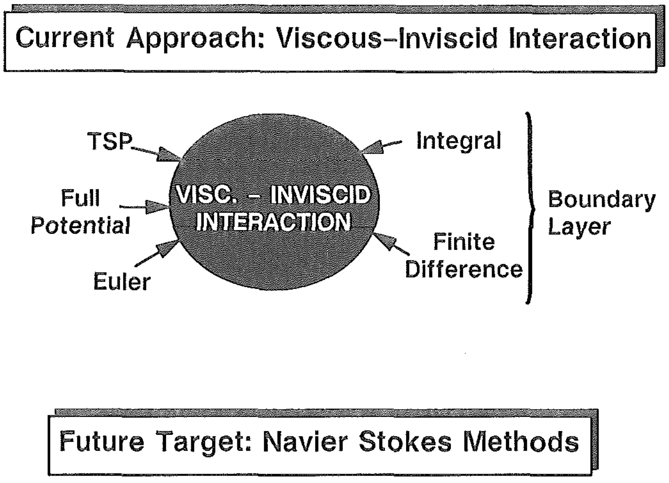


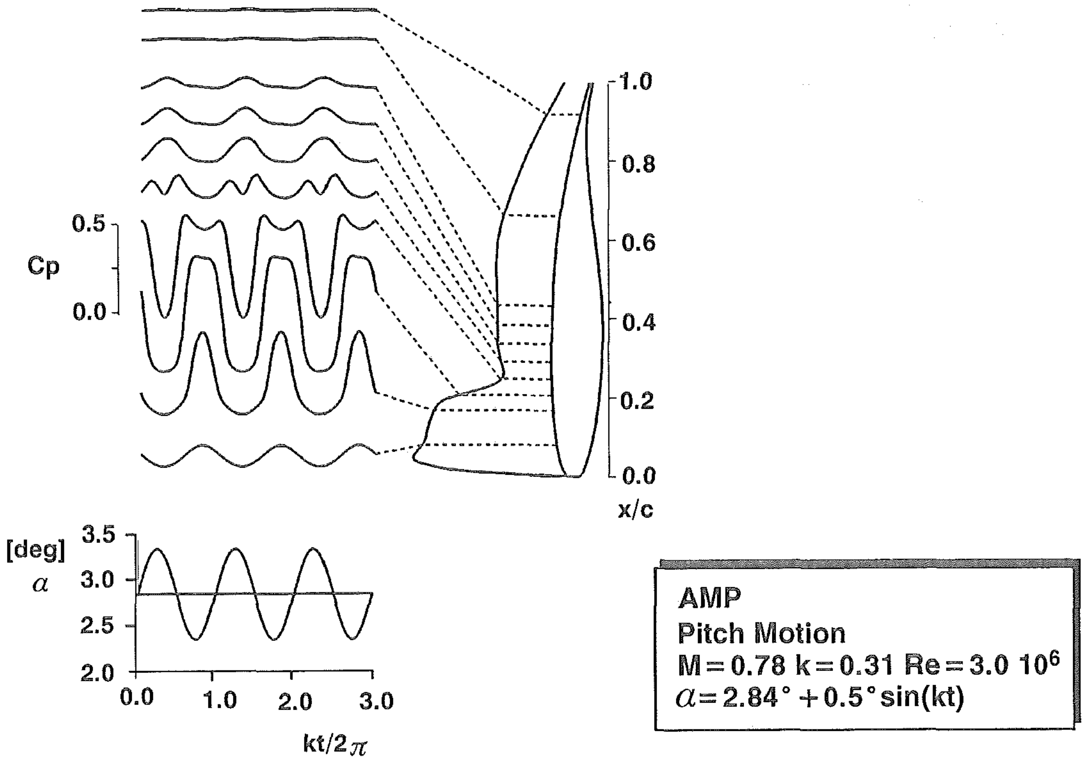
Fig. 5 Influence of Transonic Correction for Airbus A340



Current Approach: Viscous-Inviscid Interaction

Future Target: Navier Stokes Methods

Fig. 6 3D Viscous and Inviscid Aerodynamic Methods



AMP
Pitch Motion
$M=0.78$ $k=0.31$ $Re=3.0\ 10^6$
$\alpha=2.84°+0.5°\sin(kt)$

Fig. 7 Time Histories of Upper Surfaces Pressure Coefficients

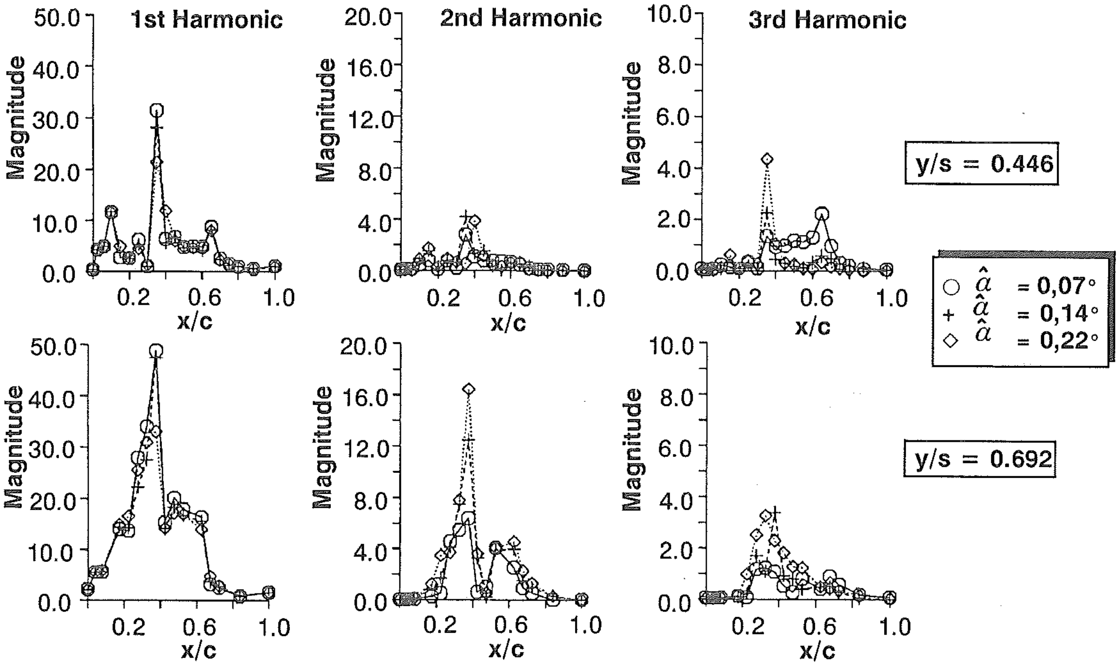


Fig . 8 Influence of Higher Harmonies with Increasing Oscillation Amplitudes

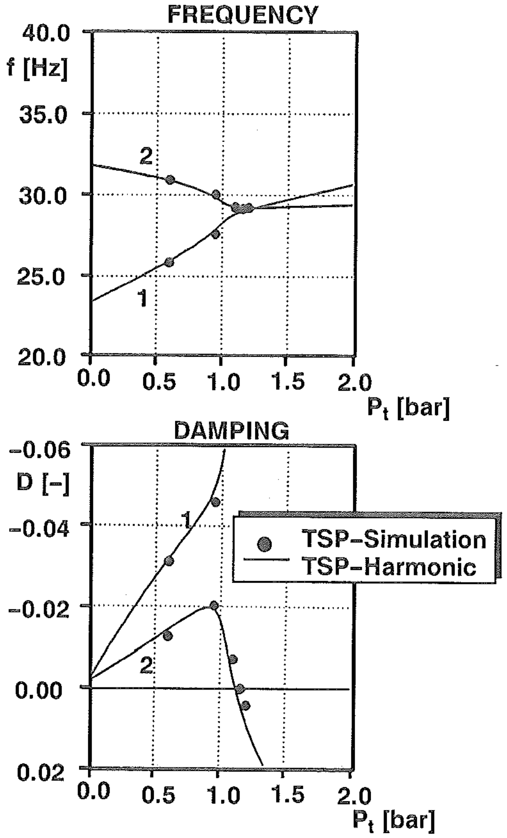


Fig. 9 Comparison of Flutter Calculation with Flutter Simulation; 2 DOF's, AMP, $M=0.78, \alpha=2.84°$, $Re=3.0 \cdot 10^6$

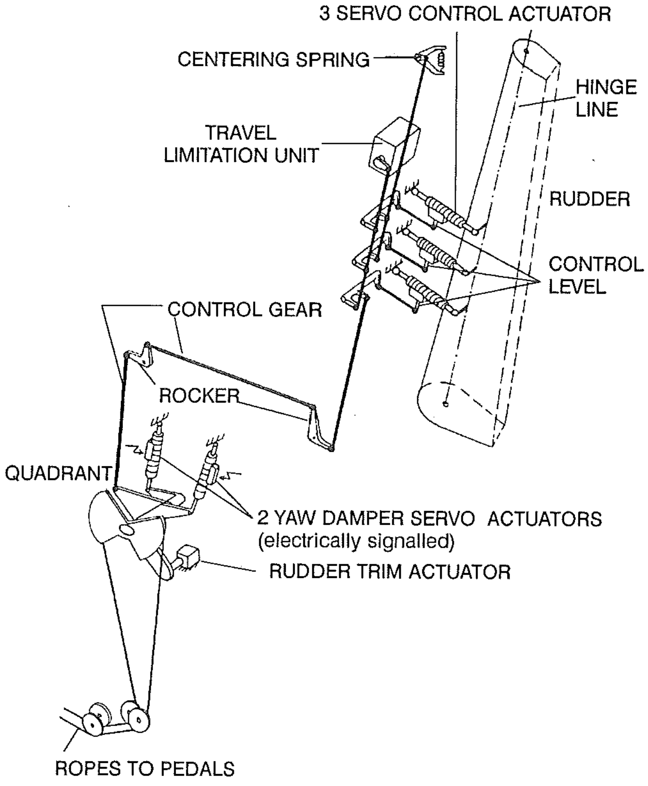


Fig. 10 Rudder Control

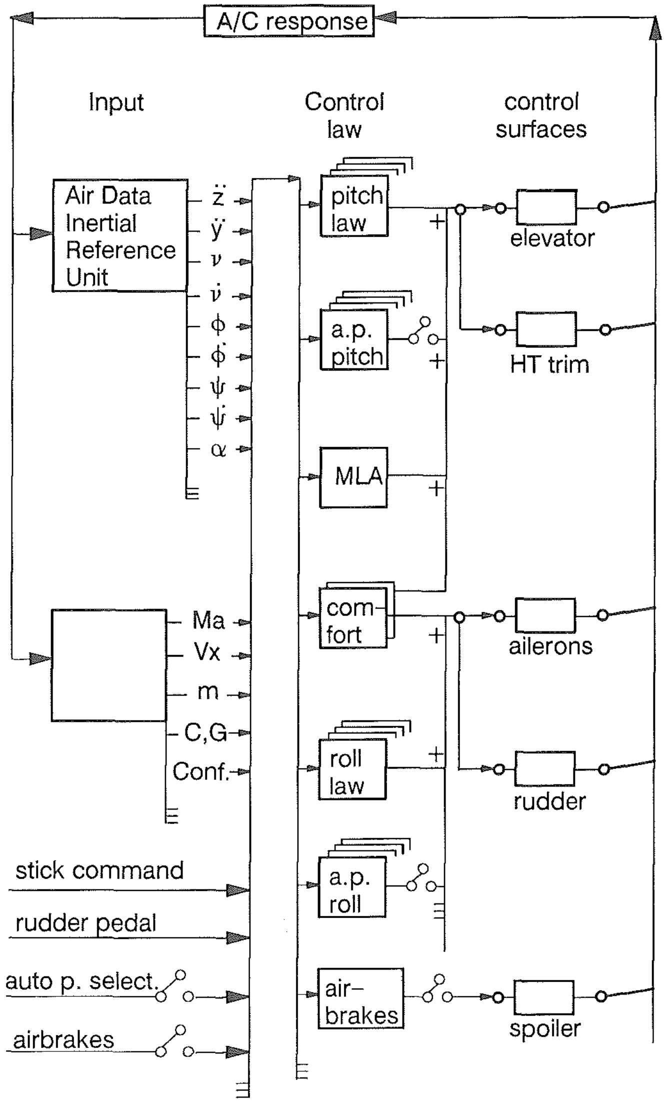


Fig. 11 Simplified Electronic Control Circuit without: coupling, monitoring, redundancies

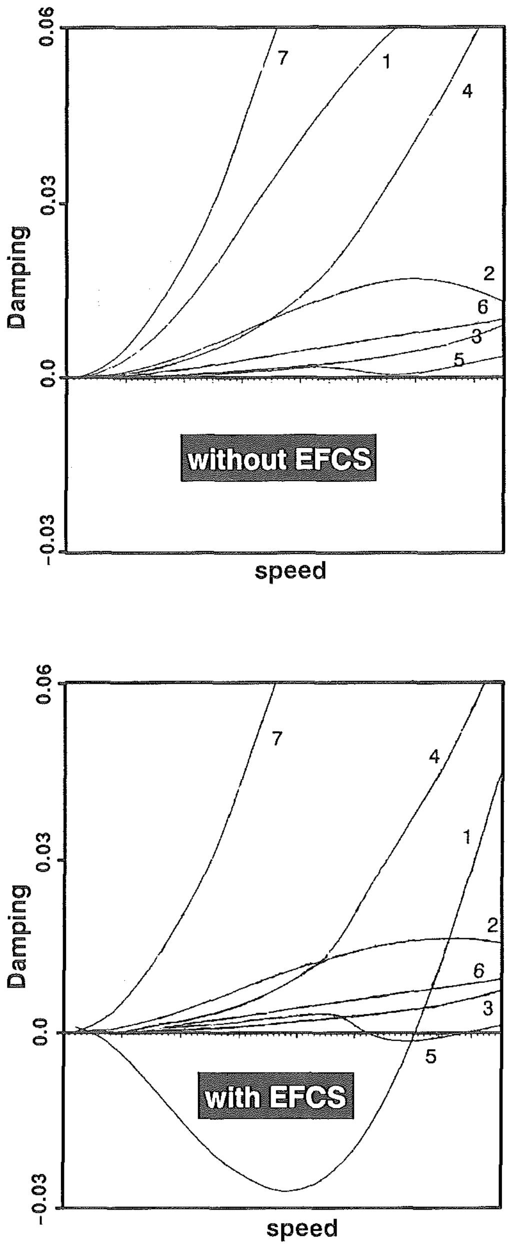
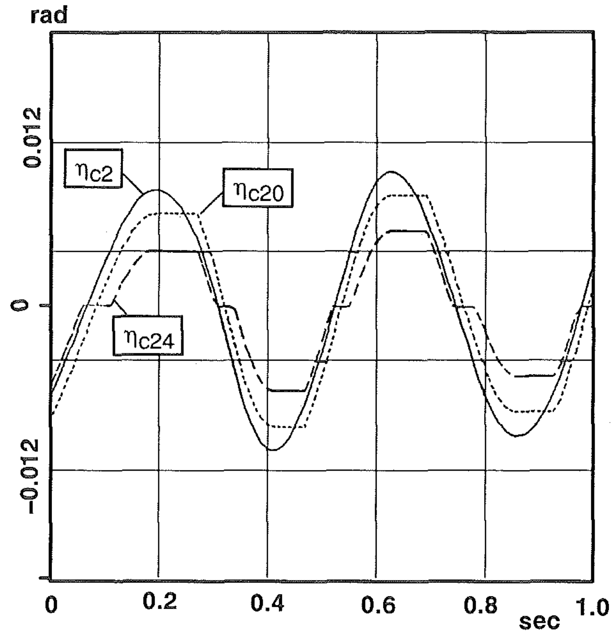


Fig. 12 Comparison of Flutter Calculation Results with and without the Effect of EFCS



η_{c2}: position of yaw damper servo actuator
η_{c20}: command affected by hysteresis
η_{c24}: position of valve levers at rudder actuator

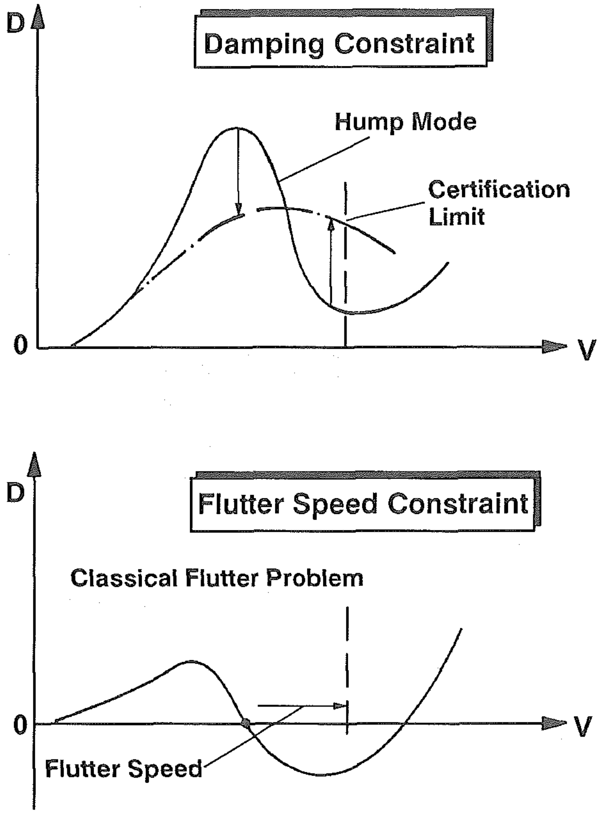


Fig. 13 Dynamics of control gear

Fig. 14 Damping and Flutter Speed Constraints

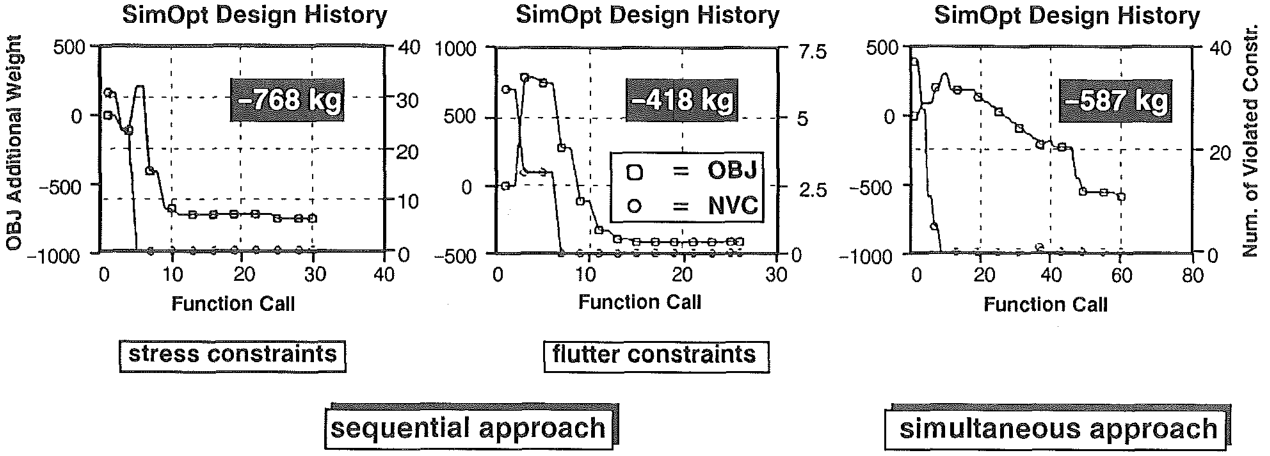


Fig. 15 Simultaneous Optimisation in Comparison with the Sequential Approach