GENERAL LECTURES

Aeroelasticity Today and Tomorrow

G. COUPRY

Future Trends in Propulsion

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AEROELASTICITY TODAY AND TOMORROW

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Abstract

For the last fifteen years, aeroelasticity had to face a considerable challenge in the context of the general development of the aerospace industry. The presentation will look at this evolution in some of its aspects.

New problems have merged (response of flexible aircraft to turbulence, aeroelastic behaviour of supercritical wings, buffet prediction, forced vibrations of helicopters, compressor blade flutter...) while new tools have become available (powerful computers, composite materials, optimization procedures, active control technology...). Most of these tools are not yet completely in hand, but, in some cases, progress in their use can be foreseen ; for instance, in the field of unsteady aerodynamics, 3D transonic calculations and flow detachment analysis already exhibit promising results and will probably be available for industry within ten years ; on the other hand, the impact of active control technology on aeroelasticity is much more difficult to assess, as well as its influence on requirements.

Nevertheless unexpected improvements in any field or research may completely change the future of aeroelasticity and, for this reason, this concise survey of the state of the art will not lead to too precise conclusions.

Introduction

First of all I would like to thank the I.C.A.S. Committee for inviting me to deliver this General Lecture on Aeroelasticity Today and Tomorrow. May I say I am very proud to have this invitation, but also very anxious because the subject is quite broad and develops very rapidly. As most of the presentation will deal with the state of the art and the progress to be expected in the themes concerned with aeroelasticity, it seems useful to devote part of the introduction to a brief summary of past activity and to the fields of research subsequently addressed.

From 1936 until the sixties, the main concern of aeroelasticity was the flutter survey of airplanes with the tools existing at that time : ground vibration tests to measure the parameters of the natural modes of the structure[1-3] and very simple 2D unsteady aerodynamics to predict the flutter speed[4,5]. Since that period, finite element calculations and lifting surface theory, both supported by powerful computer have made it possible to derive a first evaluation of the risk of flutter at an early stage of the design.

The advent of new techniques, like composite materials, supercritical wings, active control... is the challenge that aeroelasticity has to face now, and is responsible for most of the research on advanced aircraft. On the other hand, for about fifteen years aeroelasticians became concerned with new problems (or old problems still unsolved) like aeroelastic instabilities in engine components or vibrations of helicopters... These problems have set up quite difficult matters of research that are far from being cleared up.

The author dares not to cover all the activities related with aeroelasticity. He will limit himself to a broad overview, with three headings :

- Structure,
- Aeroelasticity of aircraft,
- Aeroelasticity of helicopters and of engines.

I. The structure

The last fifteen years have been remarkable for the advent of finite element calculations and, more recently for the development of optimization methods and the proposal for new Ground Vibration Test (G.V.T.) techniques. Composite materials are opening tremendous possibilities, but are raising difficult problems that are still under discussion. We will address the two aspects of analysis and test.

I.1. Calculation

Classical finite element methods are well in hand and allow improved calculation of the static deformation, definition of the natural modes of the structure and improvement of the simplified beams models used at the first stage of the design. Several ten thousands of degrees of freedom are currently taken into account, thanks to very powerful computers. Figure 1 exhibits modelization of a fighter with 30,000 degrees of freedom.

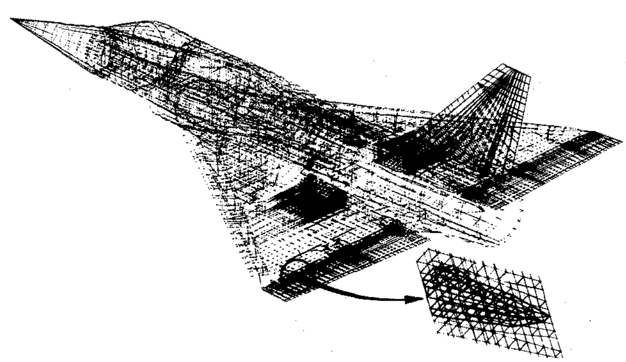

Figure 1. Finite Elements Calculation of a Modern Fighter.

Whatever the industrial succes of finite element calculations of metallic structures, this technique still presents shortcomings that are to be overcome if one wants to extend their usage. Let us list some of them :

- Damping, as it appears in aerospace structures, cannot be predicted by finite element calculations, which means that its value must be guessed to derive forced responses.
- Up to now, the joining of different parts of the structure (for instance wings and fuselage) is still difficult and imposes a tremendous number of degrees of freedom.
- Derivation of stresses from displacement calculations is well understood, but its application to industrial problems is not yet easy.
- Buckling (and postbuckling) of stiffened panels, and its influence on the natural modes of the structure is nowadays a matter of exploration.

Changing from metallic structures to composites has raised new problems.

Composite materials have offered the aerospace community remarkable possibilities, but they have led to completely new design methodology and to the necessity of solving accurately the difficult problem of determining their constitutive equations. In addition to the gain expected on weight, one of the main advantages of these materials is their suitability for optimization procedures, where the opportunity of arranging the successive layers provides the engineer with new possibilities[6-9] : one could claim that the field of structural optimization and aerodynamic tailoring was not really opened until these new materials appeared on the market.

As usual, these advantages have to be balanced with some difficulties :

Finite element calculations of a complete structure cannot obviously be achieved layer per layer, which needs integration along thickness. Such elements (at least orthotropic) are difficult to build and their constitutive equations are strongly dependent of the orientation of the plies ; they should be carefully tested before usage. Even so, the number of parameters to deal with in an optimization process is much too large, and most of the effort tends now towards the elaboration of "macroelements" (for instance stiffened panels) depending on a small number of degrees of freedom, and such that local stresses can be easily recovered at the end of the calculation. Figure 2 presents a "macroelement" representative of a stiffened panel.

In an attempt to reduce the number of degrees of freedom, Weisshaar, following Housner and Stein[10] proposed the introduction of a global stiffness parameter that describes "ben-twist" cross coupling as a function of the orientation and stacking sequence of symmetrical laminate plies with respect to a reference axis of the wing.

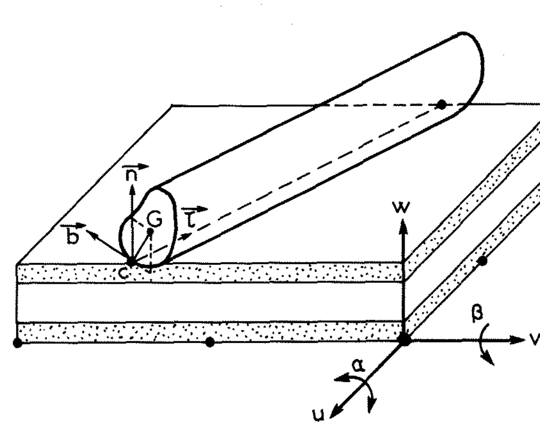

Figure 2. Macro-element Associated With a Stiffened Composite Plate (8 Nodes, 40 d.o.f).

I would not like to close this paragraph without evoking pioneer studies :

- Medium Frequency Range Calculations[11,12] (where the modal density is large and where the asymptotic theory cannot yet be applied) are now available and make it possible to compute forced response at much higher frequencies than those attainable by the modal approach. Figure 3 provides with an example of propagation of vibration calculated along a stiffened cylinder at medium frequency.

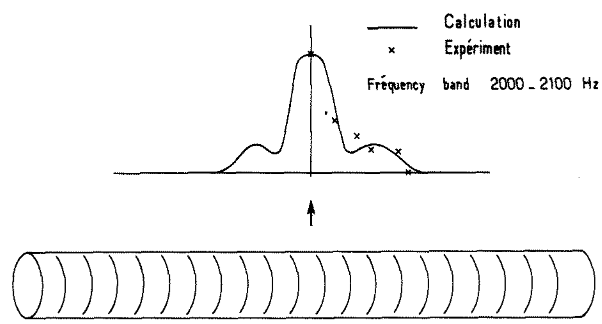

Figure 3. Energy Propagation Along a Stiffened Cylinder.

- Tentative studies to model the actual damping of structures by a random distribution of oscillators.

It seems that these two efforts will be key factors for progress in the near future.

<u>I.2. Ground vibration tests</u>

Since World War II and until the advent of efficient calculation techniques the Ground Vibration Test (G.V.T.) has been the sole means for determining the natural modes of structures otherwise described by too simple beam models at the stage of the design. Since the seventies new G.V.T. methods have been proposed, with more or less success, and the first steps have been made to narrow the gap that still exists between analysis and test.

All the progress in the G.V.T. methods is based on the opportunities offered by powerful minicomputers that can be moved easily from airfield to airfield. Using these facilities, one has the temptation of shortening the test duration by collecting simultaneously the data associated, by one way or the other, with different uncorrelated excitations. Fitting these experimental results with a theoretical linear model should provide the designer with a complete modal representation of the structure. This philosophy supports several methods that have been proposed during the last ten years[13-15].

This "black-box" methods have the shortcoming that they assume that the airplane is perfectly linear, which is not true in general and exposes the danger that non-linearities on one mode may pollute the results on other "good" modes through the fitting process. Nevertheless, this type of method is attractive and will presumably be the basis for progress in the near future, if associated with some means of chekcing rapidly the results.

In other respects, much can be expected from increasing the correlation between analysis and G.V.T. Up to now, we have the G.V.T. on one hand, the finite element calculations on the other hand, and the G.V.T. is mainly used to check the theoretical model and sometimes to correct it. Playing these two tramps altogether could lead to considerable progress in two ways :

- The results of the finite element calculation could help to determine the best configurations of excitation to be used in G.V.T.
- An automatic process, taking into account the results of the G.V.T. could make it possible to correct the theoretical model in such a way that it fits the experimental results ; an interesting approach to this problem has been proposed recently, where areas of errors in modeling are automatically located.

II. Aircraft aeroelasticity

From the sixties until now, the main problems of the aeroelastician were flutter prediction, calculation of static deformation and evaluation of the loads and of the response to turbulence. Linear unsteady aerodynamics (lifting surface theory or doublet lattice method in subsonic flow, box method in supersonic) were generally considered as sufficient, when supported by careful experiments in wind tunnel on rigid or flexible or dynamic models.

The advent of supercritical wings and of active control techniques, and the extension of the aircraft missions have drastically changed the situation.

II.1. Unsteady aerodynamics

As they fly close to the transonic domain, supercritical wings are very sensitive to the angle of attack, because of their thickness. That means that their static deformation in cruise conditions has a large effect on their efficiency and can be responsible for unexpected flutter.

In the late seventies, Ballhaus[16] proposed the algorithm of alternate directions that provides with cheap calculation cost the solutions of the small transonic disturbance potential flow equation. Later on, Angelini and Alii improved this 2D method[17] by deriving transonic equation and boundary conditions in a consistent way by the means of a variational principle.

This yields, in classical notation, the equation :

$$(1 - M_\infty^2 - \lambda \frac{\partial \phi}{\partial x}) + \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = K^2 M_\infty^2 \frac{\partial^2 \phi}{\partial t^2} + 2K M_\infty \frac{\partial^2 \phi}{\partial x \partial t}$$

where λ consistently stand for :

$$\lambda = (\gamma + 1) M_\infty^2 + 2(1 - M_\infty^2) \quad M_\infty^2$$

and to the boundary condition :

$$\frac{\partial \phi}{\partial y} = \mu \frac{\partial h}{\partial x} + K \frac{\partial h}{\partial t} (1 - M_\infty^2 \frac{\partial \phi}{\partial x} - K M_\infty^2 \frac{\partial \phi}{\partial V})$$

with

$$\mu = 1 - (1 - M_\infty^2) \frac{\partial \phi}{\partial x} - \frac{\lambda}{2} (\frac{\partial \phi}{\partial x})^2 - K M_\infty^2 \frac{\partial \phi}{\partial t}$$

this boundary condition is to be compared with the "classical one" :

$$\frac{\partial \phi}{\partial y} = \frac{\partial h}{\partial x} + K \frac{\partial h}{\partial t}$$

These unsteady equation and boundary conditions are derived with the assumptions :

$$K^2 \approx \delta^{2/3} \approx (1 - M_\infty^2) \approx \varepsilon << 1$$

where ε is the perturbation parameter.

In the early eighties, Leballeur[18] succeeded in coupling the inviscid transonic solution with a model of unsteady attached boundary layer. Figure 4 illustrates the results in steady flow by comparing calculations with boundary layer effects with inviscid calculations and with wind tunnel experiments of Tijdeman[20]. Figure 5 gives an example of unsteady calculations, with and without boundary layer.

Since this time, progress was made in two directions : extension to 3D transonic unsteady flow of the alternate directions method in inviscid flow, and first approach to take into account detached boundary layer in 2D flow[19]. On these two points much is still to be done, as illustrated by the fact that calculations of the influence of the angle of attack on the flutter speed still fail to explain the wind tunnel results. The analysis of unsteady detached boundary layers and their coupling with 2D inviscid flow is still a matter or research, though encouraging results have been obtained, where shock-wave-boundary layer instabilities are visible. Nevertheless, extension to unsteady 3D viscous flow will presumably not be available within the next ten years.

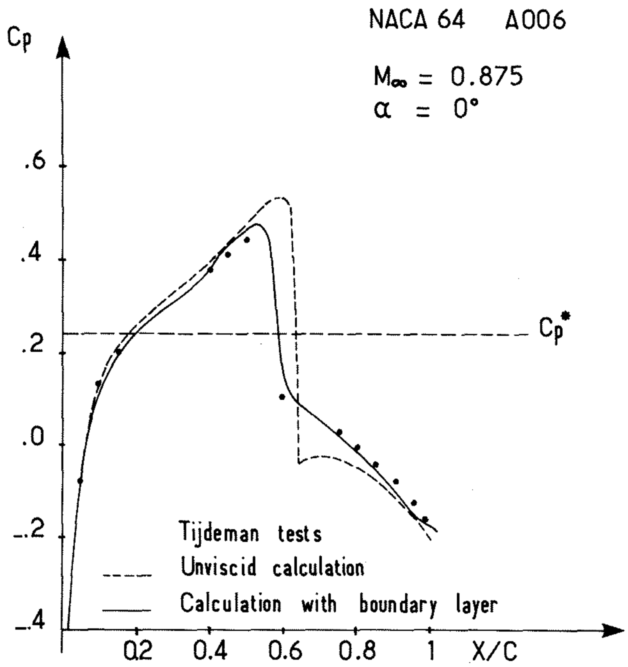

Figure 4. Steady Pressures :

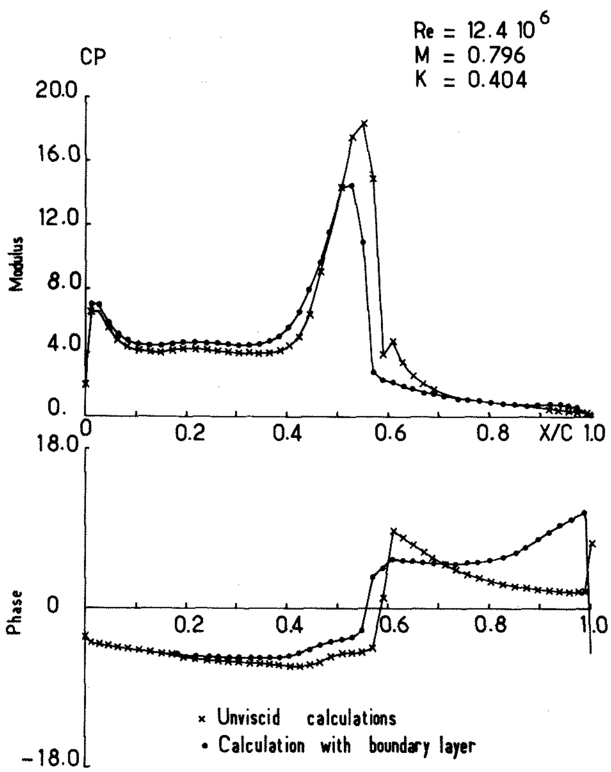

Figure 5. NACA 64 A010 :

In addition to the problems raised by supercritical wings, it became obvious during the last decade that unsteady air forces on the engine had a critical influence on the flutter speed of large transport aircraft. In the current state of the art, one relies on rough theories and on rough wind tunnel tests to evaluate this effect. Experimental work on sophisticated models of engine is to be completed next year, and theory should follow closely experiments.

At the end of this paragraph, one should note a new and important effort of many research establishments towards exact solutions of Euler equations.

II.2. Wind tunnel and flight tests

All the theoretical work has to be supported by wind tunnel tests and flight experiments to check the analysis or to replace it where it fails to predict the aeroelastic behaviour of the structure. For these reasons flutter models have been used during the last two decades, specially for military aircraft carrying stores in the transonic range, and to assess the effect of engines on large commercial airplanes. On the other hand, since the last few years, attention has been focused on the measurement of the static deformation of models in the wind tunnel, due to its possible critical influence on the flutter speed ; strain and optical techniques are used by now, but much is still to be done to make them industrial tools.

In the same way, careful experiments have to be carried out in wind tunnels to collect data that will be used as the foundation of the analysis of new phenomena ; accurate definition of the unsteady flow needs hundreds of pressure transducers and specialized minicomputers to reduce the data and make them easy to handle. Figure 6 illustrates the results for one of these experiments, where the unsteady pressure field induced on a supercritical wing by the oscillations of a spoiler is measured in detail.

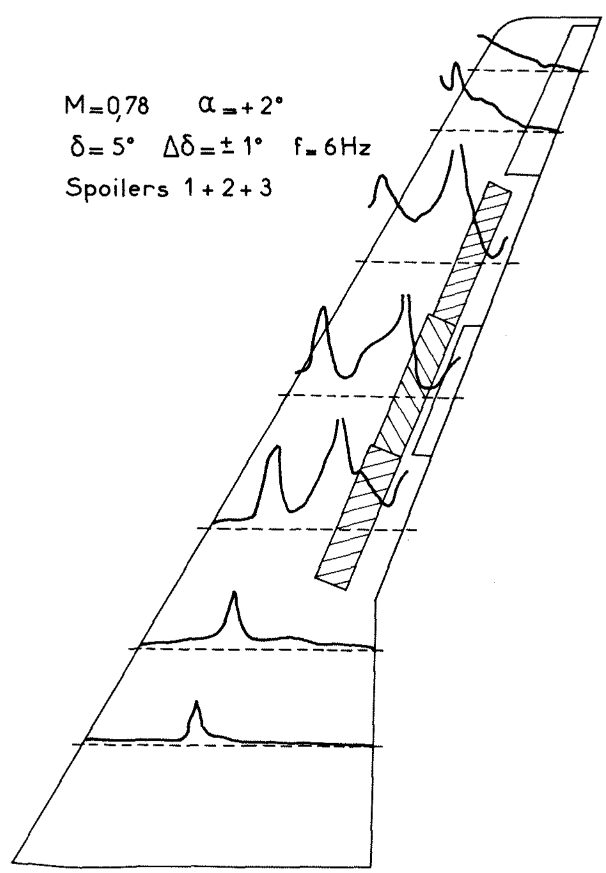

Figure 6. Modulus of The Pressure Field Induced By Spoilers Oscillations.

Once again, this experiment replaces a theory that does not yet exists, and one can only rely on experiments.

Flight test techniques are under significant development for two main reasons : the first one lies in the necessity for completing flight vibration tests during the opening up of the flight domain for safety and certification purpose ; the second one is due to the fact that most of the modern airplanes are equipped with fly by wire and automatic control, and that the open loop of the servoelastic system has to be checked in flight.

Bonkers and inertial exciters are still often used for the flutter survey of small or medium size aircraft ; nevertheless, they had to be replaced by some other type of excitation once attention was focused on the low frequency first modes of large commercial airplanes. By now, the difficulties due to this very low frequency excitation are solved by using tip vanes, actuated by hydraulic power, and which provide large lift forces. Figure 7 shows a tip vane installed on an Airbus A-310.

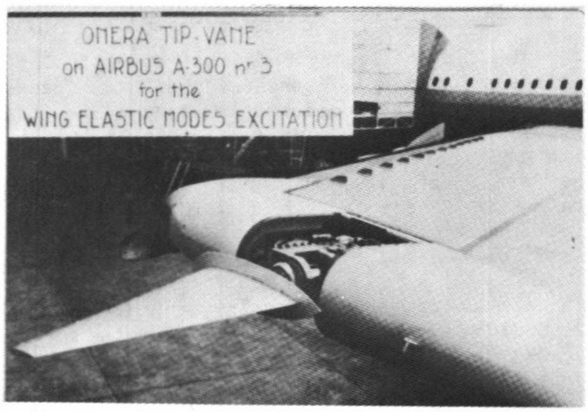

Figure 7. Tip Vane on Airbus A-300.

When concerned with active control, one has to measure in flight the transfer functions of many parameters to turbulence and to control inputs. This implies a need for a very complete set of equipment (accelerometers, gages, ...) and a large data acquisition system. In addition, the data reduction needs to be made very carefully (for instance by imposing through the fitting process that all the transfer functions have the same poles), in order to help improvement of the aeroelastic model of the aircraft. Unfortunately, comparison between flight test results and analysis is often (not always) disappointing, which means that research is still needed in this domain. Figure 8 presents the transfer function of wing tip acceleration to oscillations of a spoiler as measured in flight on an Airbus A-310.

II.3. Impact of active control

Since about ten years owing to the development of hydraulic techniques (actuators can now achieve angular velocity of 80°/s) and to improvements in electronic and micro-computers, active control methodology invaded nearly all aspects of aeronautical engineering : fly by wire, flight mechanics, ...) ; it now lays siege to aeroelasticity..

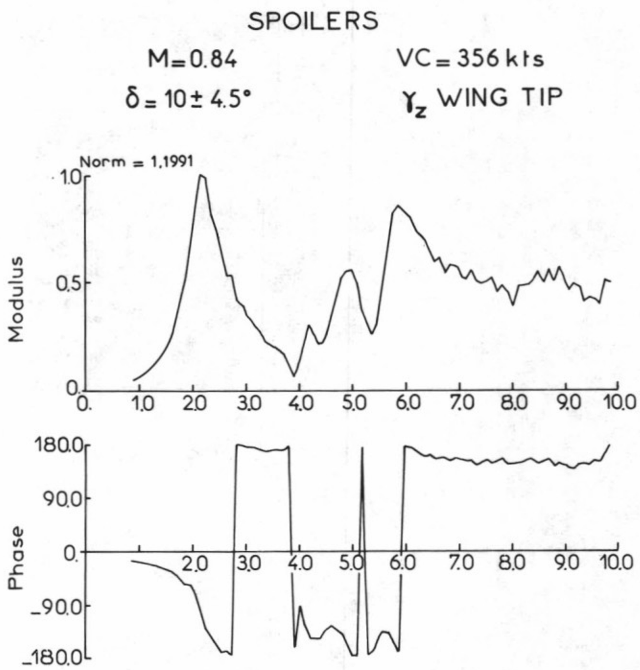

Figure 8. Wing Tip Response to Spoiler Oscillation.

At the end of the seventies O'Connell[21] and the staff of Lockheed California Company succeeded in designing a load control system for the extended span L1011, which reduced significantly the highest loads, and that was certificated by FAA.

Nowadays, in the search for extra economies, the trend is still to increase the span and most of the modern large commercial airplanes in design (or about to fly) will be necessarily equipped with some sort of active load control ; in this respect, active control competes with structural optimization and aerodynamic tailoring and one should keep in mind that the next generation of aircraft will be designed by association of these two means.

Another endeavour is flutter suppression by active control for which the first application will presumably be on aircraft with stores flutter[22-24]. Numerous theoretical studies have been achieved and some flutter experiments have been carried out in wind tunnels in order to compare the different solutions ; AFFDL, ONERA and MBB have been leaders and are still active in this domain. Figures 9 and 10 provide the reader with the result of flutter suppression experiments in transonic flow of a half dynamic model of a fighter carrying three stores : a gain or more than 20% on the critical speed has been demonstrated.

Attempts were also made to check control laws in flight ; the system was proved to be sound but was not entirely successful.

New aeroelastic problems are now being addressed by active control :

- Penetration at high speed and very low altitude in a turbulent environment where vibrations of the airframe might upset the pilot and make him unable to fulfill his mission.

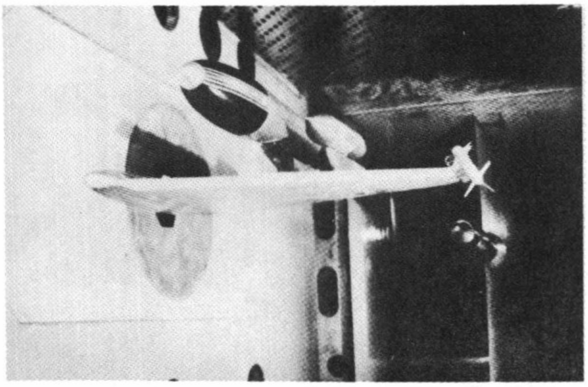

Figure 9. Dynamic Model With Stores in Transonic Wind Tunnel.

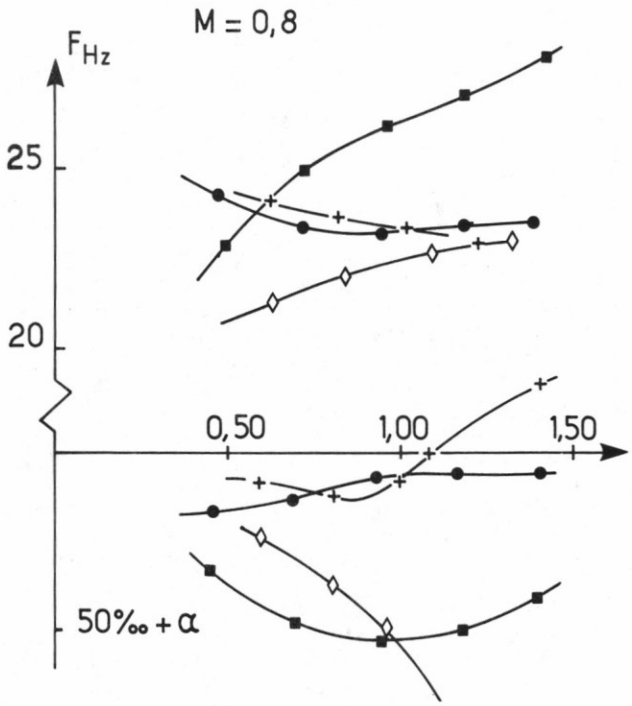

Figure 10. Flutter Chart of The Model :

Without control { + Mode 3 ; ◊ Mode 2 }

With Control { ■ Mode 2 ; ● Mode 3 }

- Buffet reduction of commercial airplanes by active control, providing a large aerodynamic damping of the first modes, has been studied and tested in wind tunnel, which is illustrated in figure 11.

III. Aeroelasticity of helicopters and engines

The importance of aeroelasticity on the behaviour of helicopters and engines was not really understood before the mid-sixties ; at that time the actual difficulties were clearly seen and became topics for research : an appropriate simplified theory was proposed to study the aeroelastic vibrations of helicopters,

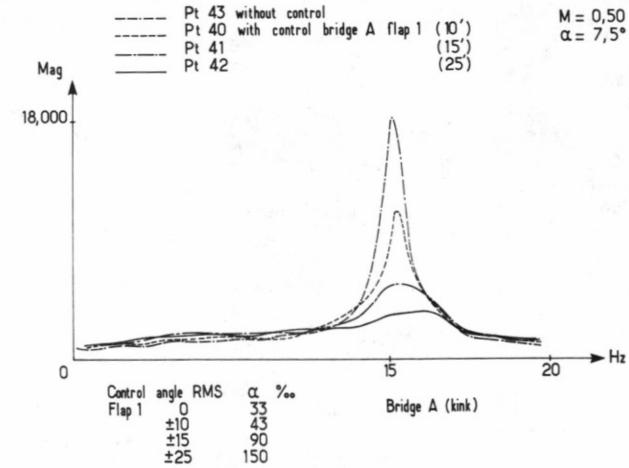

Figure 11. Buffet Reduction on a Supercritical Wing.

and instabilities of compressor blades were indisputably attributed to flow detachment, at least in the subsonic and transonic range.

III.1. Aeroelasticity of helicopters

At the beginning of the seventies the designers became interested to the aeroelasticity of helicopters ; the problem (that obviously existed before) became really annoying with the increase of the flight speed, due to the stall of the retreating blade and to transonic effects on the advancing blade ; it thus became an important factor in the competition of the companies.

The unsteady aerodynamics problem is very difficult to set up (and of course to solve), because the flow is periodic as well as the angle of attack of the blade. To our knowledge, one of the first attempts to estimate the unsteady air loads on a rotor was proposed in 1970 by Dat[25] ; it is based on a "lifting line" approach and it permitted the first consistent aeroelastic calculations. Figure 12 illustrates one of the first applications, where the lift calculated for one span location on the rotating blade as a function of the azimuth is compared with the result of wind tunnel test.

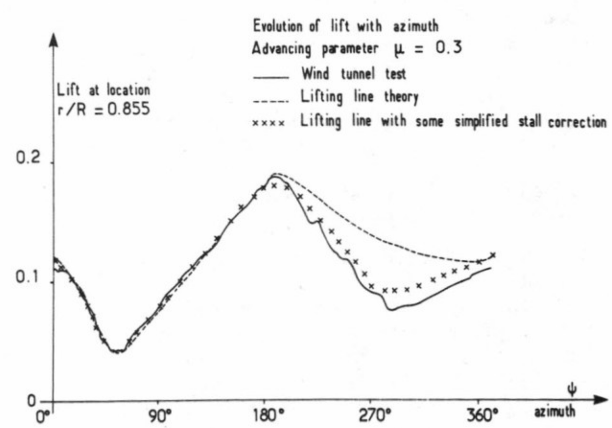

Figure 12. Evolution of Lift With Azimuth.

Such a simple theory has obviously its shortcomings (specially where the advancing ratio is large) and, what is more, yields tremendous calculations if coupling with structural modes is involved. Consequently, a special effort was needed in two directions : modeling of the stall of the retreating blade and derivation of new methods which could make easier the coupling of the flow and of the structure.

In 1979[26,27], an empirical model was proposed to represent the dynamic stall of an airfoil. The model is based on non linear differential equations for lift and moment, expressed as functions of angle of attack and of its two first derivatives. The model is consistent, on one hand, with steady stall, and, on the other hand, with the classical unsteady aerodynamics for small angle of attack. The coefficients of the differential equation have to be measured in wind tunnels, where the profile has a small harmonic oscillation around different large angles of attack corresponding to stall conditions. The efficiency of the empirical model is illustrated in figure 13 where comparison is made between the lift predicted by the model and experimental results for a very large harmonic oscillation around a steady angle of attack of 11°.

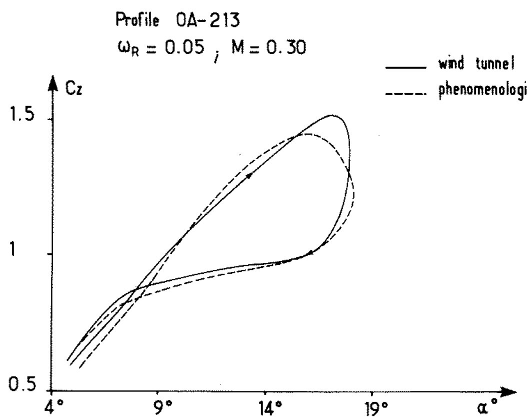

Figure 13. Lift For a Large Angle of Attack Excursion.

Nowadays, it seems that the empirical model provides a very good fit of all the experimental results on airfoils. Nevertheless, as only a small part of the retreating blade suffers stall, one needs to build a consistent approach for the complete rotor, that is some coupling between the linear lifting line theory and the 2D non linear stall model. By now, work is going on in this direction, with more or less success.

Using the lifting line theory, the prediction of the dynamic behaviour of the rotor (which involves coupling with the natural modes of the structure) is still possible, in the frequency domain (using large computers) if one is interested only on forced response ; on the other hand, time histories of vibrations or assessment of stability yields unacceptable computer time and cost and needs a new approach, as the "staggered method" evaluated by now.

III.2. Aeroelasticity of compressors

According to the good results obtained in aircraft flutter survey, the first attempts to understand the instabilities of compressors were based on the derivation of sophisticated linear theories that could take into acount the vibration of rotating blades and their aeroelastic coupling ; simpler linear unsteady theories were proposed for cascades[28,29]. All these approaches failed to predict the actual instabilities, except perhaps for low angle of attack in supersonic conditions.

At the beginning of the seventies, thorough experiments in cascades wind tunnels, where steady and unsteady pressures were measured on the central oscillating blade and on the next ones, made it clear that flow detachment at the leading edge was responsible for most of the phenomenon. Areas of instabilities are exhibited in the performance chart given in figure 14.

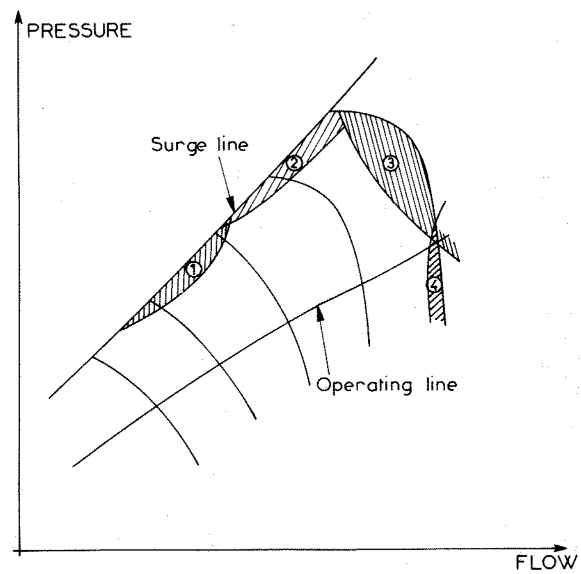

Figure 14. Performance Chart and Location of the Areas of Instability :
① Subsonic-Transonic Stall Flutter
② Supersonic Stall Flutter
③ Bending Supersonic Flutter
④ Torsion Supersonic Flutter.

From this time, and up to now, one has to relie on experiments in cascade wind tunnels to determine the direct unsteady air forces on the vibrating blade and those induced on the next ones. Starting from these results and taking into account the coupling between blades, one then can predict the instabilities of the actual compressor[30,31]. Figure 15 provides the reader with a comparison between the damping calculated by this way and the damping measured on the compressor.

In addition to this empirical aproach, a fundamental research is pursued ; it is based on the unsteady 2D boundary layer theory and on some rough modeling of the flow separation at the leading edge. The first results are promising, but much is still to be done and derivation of a design tool should not be expected before at least five years.

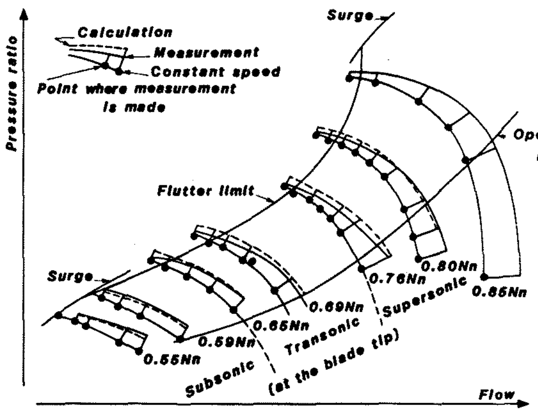

Figure 15. Performance Chart :
----- Theoretical Damping
——— Actual Damping.

Conclusion

Let us try now to describe what future looks like in aeroelasticity :

- 3D transonic and supersonic accurate calculations of unsteady inviscid flow will become available very soon, by the small perturbation potential and by Euler equations, thanks to new powerful computers ; at a further stage, the introduction of at least some viscous effects can be foreseen.
- On another hand, aerodynamic tailoring and active control are nowadays searching their way separately ; they will very probably merge into one design tool within the next ten years.
- But the greatest challenge is in the field of helicopters and engines, where the basic phenomena, which are no longer linear, have not yet been sufficiently understood and modelled... and one should keep in mind that even simple linear models yield unacceptable computation time ! Progress in this field depends on the derivation of relatively simple non linear models and on the proposal for new algorithms for the calculation of the coupling between flow and structure.

At the end of this presentation, the author feels frustrated : he intended to depict the main features of the activities in the field of aeroelasticity... and he knows that many topics have not been addressed, or have been addressed too succinctly. He is also aware that his presentation could be biased by an insufficient knowledge of what is going on in other research organisations. Nevertheless, he hopes that he has been able to make a bit clearer a very intricated domain.

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