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EFFECTS OF THE AIRFOIL CHOICE ON ROTOR AERODYNAMIC BEHAVIOUR IN FORWARD FLIGHT

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1. FOREWORD

A few years ago, reviewing the progress made in rotor aerodynamics (Ref. 1) , P. YAGGY and I. STATLER noted that, if numerous studies were made for the operational evaluation of specific configurations or concepts, the volume of analytical research work required for the understanding of basic phenomena was relatively small.

This problem still stands today, at a moment where the usual questions ("How can the finalization of a prototype be facilitated by calculations ? " "At the preliminary project stage, how can a rotor aerodynamic behaviour be evaluated with some degree of accuracy ? ") are covered by a more fundamental question : "Have we taken full advantage of all the potential capabilities of the conventional rotor formula ? "(Ref. 2). It is to be admitted that such a situation is acute at a period when the aerospace industry is making great efforts to develop "new formulas" for rotorcraft.

If this field of research still conceals elements of quasi-mysterious complexity, some new facts have appeared during the last few years :

- from the fundamental research aspects, some modest progress has been made in the establishment of mathematic models of airfoils and rotors aerodynamics. This improvement is due, partly, to the larger capacity of modern computers allowing the use of more sophisticated theoretical models, including less restrictive assumptions.

- as regards to the applications, the composite blade technology (now well-developed) allows, without problem, a large choice of airfoils, plan forms, thickness and twist values - Unfortunately, often theories cannot offer a precise guidance for these choices.
  Therefore, an important effort is to be made to bring the fundamental knowledge to the level reached by technology.

The purpose of this paper is to describe briefly the capabilities and limits of airfoils and rotor aerodynamic calculation methods at present applied by AEROSPATIALE. These methods are used to define the general criteria for the choice of airfoil and examine, through bi-dimensional tests, the performance of some conventional airfoils.

Tests on rotor models show not only how important the choice of an airfoil may be, but also the limits of the conventional selection procedures.

2. THE ROTOR AERODYNAMIC FIELD

2.1.- General considerations and basic parameters

The definition and adaptation of an airfoil to a given type of mission and for a specific aircraft, require the most accurately available knowledge of the rotor aerodynamic field and airfoil operating envelope.

This is true, particularly, for general research work where the improvement of the "Engineer's Art" may be attempted through a systematic analysis procedure and the study of the various elements making-up the aerodynamic problem.

In this field, problems are of two kinds :

- First, parameters determining the rotor aerodynamic behaviour are numerous, different and interdependent. Often, it is difficult to study their individual effect and practically impossible to classify them by order of relative significance.

- Also, the establishment of a mathematic model is affected by the above difficulties : the problem can not be treated fully in all its complexity and it is never known which component is to be neglected in an attempt to simplify the problem. Further, it is necessary to adopt mathematic models consistent with physical reality and to know how to identify, then discard, problems associated with digital resolution.

One of the first difficulties, having a fundamental character, is the strong coupling existing between Aero-dynamics and Dynamics. The aeroelastic characteristics of rotor heads and blades will be, in various ways, part of the forced responses and instability problems and affect the airfoil operating conditions. The ´branch modes´method allows the aeroelastic condition of the structure sub-assemblies to be characterized (Ref. 3 and 4) . Hence it is possible to study the isolated rotor suitably positioned in the flow.

The mathematical model and the type of resolution may depend on the kind of problem it is concerned with (stable flight or manoeuvres, periodic response or instability). But, in all cases, the best model will be that associating, most closely, the aerodynamics and dynamics.

On the subject, ´´the acceleration doublet´´method, developed by ONERA, realizes in the linear field, for a stable flight, a complete coupling with analytical resolution without iteration between blade loads and responses (Ref. 5 to 8).

The particular importance of blade aeroelastic characteristics in the airfoil operating envelope is shown on figure 1. It is obvious that the conclusions drawn for a ´´rigid blade´´are a rough approximation only.
The corresponding experiences, made by AEROSPATIALE in the MODANE ´´S 1´´wind tunnel, with rigid blade rotors having a low ´´LOCK´´number represent imperfectly the in-flight responses.
However, they allow the neglect of dynamic problems and the study of purely aerodynamic phenomena even in severe and unusual conditions (Ref. 9).

In a perfect fluid, the aerodynamics depend on two significant parameters : the induced downwash distribution and the unsteady processes.

The variable downwash distribution is due to load variations in azimuth and along the blade span.
It is evidenced by a complex vortex system, which may create strong interactions according to the configuration. The knowledge of this distribution has been very much improved by the transfer from momentum based theory (ref. 10) to the vortex theory, at first *with uniform loading and infinite number of blades (ref. 11),* then, more realistically, by taking the individual wake of each blade into account (Ref. 12).

The final concept of a rigid wake (Ref. 13) seems to be sufficient for the forward flight, where, due to the rotor tilt and rapid ´´blowing´´of its wake, the distribution is slightly affected by the exact wake geometry. This is not true in hovering flight and at low speed, when the rotors, particularly if they are highly loaded, are greatly affected by the near-by wake (Ref. 14).

Unsteady processes result from the periodic modulation of speeds in amplitude and direction which is caused by the rotation and blade flapping and cyclic controls.

The acceleration doublet method, developed by ONERA (Ref. 15 and 16) and used by Aerospatiale, endeavours to take these various parameters into account. The ´´lifting problem in a perfect fluid´´is schematized by representing the blade as a set of doublets moving in an arbitrary manner, and resolving, through a collocation process, the integral equation linking the speed potential to the load spatial distribution and its time history. The impact of sophisticated aerodynamics on the airfoil operating range is shown in figure 1. The differences are significant, even in linear calculations, comparatively to a bi-dimensional theory with constant downwash.

The simplification introduced by the use of a ´´lifting line´´is penalizing at high speed and at blade tip. It would require either the introduction of additional terms in the schematization (ref. 17) or the passage to the lifting surface.

This last solution is presently being developed and will also include the study of problems associated to moments.

The last major item is the strongly non linear character of the rotor under limit operating conditions, raising not only schematization problems but, also, numerical difficulties.

The dynamic stall is one of the most penalizing rotor limitations. In spite of the progress made in the study of rotor steady and unsteady boundary layers (Ref. 18 and 19), sophisticated theories cannot yet be coupled with the rotor aerodynamic diagrams in a inviscid fluid. Therefore, it is necessary to resort to semi-empirical methods (Ref. 20 and 21) and introduce non-linearities, as corrections, in linear theories (Ref. 22).

2.2. - Airfoil operating range

With rotor aerodynamics more or less properly schematized, the airfoil operating range may be defined. A linear formula permits the determination of the ''ideal operating range'' of the ''asymptotic rotor'' which must be the aim for improving the efficiency of the actual rotor. The use of profile aerodynamic coefficient modelized characteristics (C_L max, C_D) permits the parametric study of their effect on the rotor behaviour and, from these, deduce the desirable airfoil features (Ref. 23).

The natural limitations in forward flight are the transonic troubles for the advancing blade and the stall of the retreating blade (Fig. 2).

While rotor aerodynamics is mainly unsteady and three-dimensional, it is generally thought that the start for any study is the improvement of the airfoil bi-dimensional characteristics in steady conditions.

The requirements outlined depend upon the applications and objectives sought (Ref. 24 and 25). However, ''average'' requirements may be determined for blade working sections.

- In hovering : it is difficult to determine accurately the airfoil operating range which is strongly affected by the twist value adopted. A large twist value (with an almost uniform distribution of downwash) improves the ''figure of merit'' to the prejudice of the vibration level in forward flight.
  With the usual twist values, Aerospatiale's present objectives are, for $C_L = 0.6$ and a Mach number between 0.5 and 0.6, a drag reduction with a ''lift/drag'' ratio improvement of about 20 - 30 per cent relative to the NACA 0012 airfoil. An improvement for larger C_L is of some interest only in case of solidity ratio or rotational speed reduction.
  In order to decrease the effects of blade vortex interactions, a drag divergence of $\Delta C_L = 0.2$ is requested with respect to the NACA 0012 airfoil, for $0.55 < M < 0.65$.

- For the advancing blade, it is necessary to push back the drag divergence Mach number, at zero lift, to reduce the advancing blade significant drag on fast helicopters and simultaneously allow a chord reduction and an increase of the present rotational speeds on slower aircraft. Currently, the aim is to increase, by 0.05, the drag divergence Mach number at $C_L = 0$ relative to the NACA 0012 airfoil, with a comparable drag level below the divergence and a C_D moderate increase beyond ($C_D = 0.012$ for $C_L = 0$ at $M = 0.85$).

- For the retreating blade, the rotor capabilities, particularly in manoeuvers or in altitude, are bound to the C_L max. While in this area advantage is taken from unsteady effects, again of ΔC_L max $= 0.3$ relative to the NACA 0012 airfoil is currently searched for in the $0.3 < M < 0.4$ range.

  It is also necessary to have the best C_L possible at $M = 0.5$ for sections located at 0.7 to 0.8 R approximately which are highly loaded at high speed when the blade is in forward and rear positions.
  Airfoils having in this area a too small aerodynamic damping, in unsteady mode, should be avoided.

- The moments and their evolution with the Mach number constitute a major rotor limitation, mainly when cambered airfoils and blades with low torsional stiffness (Ref. 25 and 26) are adopted.
  Even in less critical configurations moments have a significant bearing on pitch link loading and, therefore, on the control linkage service life, on control loads with servo-controls ''off''(on light helicopters) and finally, on load factor limitations (Servo-control reversibility).
  For $0.6 < M < 0.8$, condition $|C_{mo}| < 0.01$ is mandatorily required and we hope to obtain condition $|C_{mo}| < 0.005$ with a ''Mach tuck'' exceeding the drag divergence Mach number.

  Finally the relative position of the pitch axis aerodynamic centre and blade C.G. has a certain significance in dynamic problems. It is desirable to have a stable aerodynamic centre and a rear C.G. In this field, we require, in the blade envelope (C_L, M), variations amounting to 1 per cent approximately for a mean aerodynamic centre located between 25 und 28 per cent.

3. Bi-dimensional aerodynamics of airfoils

3.1. Computation method in 2 D steady

Most of the computing programmes used in Marignane, have been developed by the Aerospatiale Airplane Division.

In *incompressible* fluid, (Fig. 3), a singularity distribution allows the proper determination of the parietal field in perfect fluid. A displacement thickness correction may be introduced to take the viscous effects into account. The laminar and turbulent boundary layer is determined by the Karman integral relations according to a process roughly similar to that of R. MICHEL (Ref. 27).
The natural transition is punctually performed according to MICHEL's criterion. The computation allows the pointing out of a laminar separation followed by a turbulent reattachment based on Owen and Klaufer's criterion (Ref. 28), with continuation of the computation. The turbulent boundary layer separation (which stops computation) is given by Nikuradse's criterion (Ref. 29). The airfoil drag is directly computed by integrating, on the one hand, the frictions (with use of Ludwieg and Tillmann law of friction (Ref. 27) in turbulent fluid) and, on the other hand, the pressures determined on the open airfoil with the addition of the displacement thickness.

In sub-critical compressible fluid (Fig. 3), *the Sell's method (Ref. 30) is based on a conformal transformation* associating the space outside the actual profile to the inside of a "unit" radius circle centered on an image located at the infinite of the physical plane.
Equations governing the subcritical flow of fluid are transformed to apply them to the inside of the "image" circle ; *the stream function is numerically determined* using centered finite difference scheme of the second order.
From the parietal field of pressures, it is possible to make a computation of boundary layer based on MICHEL's integral equations for the compressible boundary layer with the adiabatic wall (Ref. 27).

In super-critical flow (fig. 4), the GARABEDIAN and KORN method (ref. 31) is widely used. The complete speed potential equation is discretized using a mixed scheme of the NURMAN-COLE type in a plane transformed from the physical plane by a conformal transformation. The applicable limitations are the non-conservativity of scheme and the low shock assumption.
A thickness displacement correction is made through MICHEL's equations. Improvements were introduced by the Airplane Division so as to bring computation algorythms more in accord with the reality when passing through the shock and in the trailing edge area.

The incompressible inverse method of determining airfoils developed by Y. MORCHOISNE (Ref. 32) owes its qualities of precision and rapidity to two basic choices : on the one hand, that of a singularity method due *to its precision and on the other hand, that of a proper coupling between* the quantities to be computed and the given boundary conditions. The stream function in the field outside an initial airfoil is computed from the NEUMANN conditions on Ψ, the airfoil being computed from the DIRICHLET conditions on Ψ.
This singularity method was extended to the sub-critical or even the shock-free super-critical case (Ref. 33). *Starting from the fact that,* around a given airfoil, the compressible field or speeds may be obtained by combination of elementary fields (Vortex segments located on the airfoil and outside blocks of sources expressing the compressibility), the boundary conditions are processed as in the incompressible field. The Mach imposition along the airfoil gives, in practice, the distribution of compressibility sources with a good convergence, even in the presence of small shock.

3.2. Experimental evaluation of "conventional" airfoils

The new airfoil generation consists essentially of transonic airfoils defined, for rotating wings, by methods and concepts developed for fast subsonic airplane wings (Ref. 24, 25, and 34 to 37).
This generation was preceded by a family of airfoils based either on modifications of the NACA 0012 airfoil or on cambered NACA airfoil modifications. In this connection, the experimental characteristics of three conventional airfoils are examined hereunder :

- NACA 0012, basic airfoil
- BV 23010 - 1.58, a modification of NACA 23012, having a leading edge circle of a 12 per cent thick section, 10 per cent thickness. The airfoil was fitted with a 0° tab.
- SA 13109 - 1.58, with a "131" low cambered mean line, 9 per cent thickness and increased leading edge circle (corresponding to 12 per cent thick section).

These airfoils were tested in the Modane transonic "S3" wind tunnel within a representative range of the Reynolds number. Most tests were performed under a total pressure of pio= 1.7 bar corresponding to a Reynolds number of ($7 \times 10^6 \times M$) - For NACA 0012 and SA 13109 - 1.58 airfoils, some tests were carried out at $p_{io} = 1.2$ bar, without any significant effect on aerodynamic coefficients. These tests with perforated walls were completed by tests with solid walls in order to determine the corrections. These computations are currently being made and, therefore, the global results, shown for comparison, are "as read". Finally, drags were measured by splitting up the wakes.

3.2.1. Hovering flight operation

The polar diagrams at $M = 0.6$ show improved performance comparatively to the NACA 0012 airfoil for the other two airfoils (Fig. 5). For $C_L < 0.5$, the SA 13109 - 1.58 airfoil has a low C_D resulting from a low pressure drag level, lower than that of BV 23010 - 1.58 airfoil. However as soon as $C_L = 0.6$, the over-speed peak on the upper surface causes some reduction of performance (Fig. 6) and the drag divergence will appear at $C_L = 0.7$. Such is not the case for the BV airfoil which has a less significant overspeed peak resulting in a slower performance reduction at high C_L. Transitions, pushed back on upper surface and, principally, on lower surface, assist in providing a low drag for the BV airfoil.

On the SA 13109 - 1.58 airfoil, the C_{mo} value is zero and an acceptable moment evolution up to $C_L = 0.6$ is noted in spite of the fact that its aerodynamic centre is too much forward ; on the contrary, on the BV 23010 - 1.58 airfoil, the aerodynamic centre is stable and rigorously centered at 25 per cent, but the C_{mo} is unacceptable when the trailing edge tab is not bent up.

On the NACA 0012 airfoil, a very strong increase of the Reynolds number results in a higher drag level (further to the transition advancing) and in a lesser displacement of the aerodynamic centre at high lift values. The advancing of the lower surface transition point towards the leading edge thickens the boundary layer and reduces the assymetry of lower and upper surface boundary layers existing at a high Reynolds number. Finally, between $M = 0.55$ and $M = 0.65$, the SA airfoil has drag divergence characteristics near those of the NACA 0012 and lower than those of the BV airfoil (Fig. 9).

3.2.2 "Advancing blade" operation

Figures (7) shows the good transonic qualities of the SA 13109 - 1.58 airfoil with a drag which, while being slightly higher than that of the NACA 0012 airfoil at moderate Mach number, has a favourable evolution above $M = 0.8$, with, therefore, a drag divergence better than that of the BV airfoil (Figure 9). The moments evolution is also very satisfactory (Fig. 7), the BV airfoil being in unfavourable conditions when its trailing edge tab is not deflected.

According to Aerospatiale specifications, the S.A. airfoil satisfies transonic criteria for high speed flight.

3.2.3. "Retreating blade" operation

The results applicable to low Mach numbers are recorded (fig. 9) and show the excellent performances of the BV 23010 - 1.58 airfoil, with a very good C_L max. level and a very small drop between M= 0.4 and M = 0.5. Naturally, we have to take account of the influence of the trailing edge tab geometry on $\frac{\partial C_L}{\partial i}$ and on C_L max.
The moments evolution is satisfactory at low Mach numbers for these three airfoils.

Fig. 8 shows the unsteady performances of the SA 13109 - 1.58 airfoil at low frequency for C_L max and at high frequency for the aerodynamic damping. The CEAT S10 wind tunnel oscillatory rig airfoil has 0.4 m chord length.

4. Rotor applications

4.1. Comparative performances on rotor

The effect of airfoil characteristics on rotor behaviour has been evaluated, in the Modane S.1 wind tunnel, on a three-bladed 4 m diameter rotor fitted with rectangular blades having a 210 mm chord and an 8° theoretical twist. For one blade set a NACA 0012 airfoil was used and a tapered blade derived from the SA 13109 - 1.58 airfoil for the other (Ref. 38).
The tests were performed in terms of pitch at various rotor shaft tilts, the rotor not being fitted with a swash-plate.
The analysis of reduced lift values versus the reduced airfoil powers (figure 10) shows that both rotors have similar performances at low advance ratio and zero propulsion. The situation is different at very high advance ratio where the compressibility effects are very significant. These effects are felt only at an advancing tip blade Mach number of 0.92 - 0.94 for the evolutive rotor and at 0.85 Mach number for NACA 0012 rotor. The stall is also pushed back for a same Mach number.
However, these results indicate that, beside the natural trends, the airfoil selection and characteristics must be adapted to the type of problem investigated or to the performance range to be improved.

4.2. Limits of the conventional definition of rotor airfoils

While the definition of airfoils meeting "steady" bi-dimensional criteria allows the improvement of rotor performances, this mode of determination is limited by tri-dimensional and unsteady rotor phenomena. Figure (11) illustrates a significative comparison between bi-dimensional results obtained on a NACA 0012 airfoil in the Modane S3 wind tunnel and those on a rotor in the ONERA S2 Chalais wind tunnel by J.J. Philippe (Ref. 39). This is a tapered thickness two-bladed rotor on which the (0.9 R) section has the NACA 0012 shape.
The comparison is made for a "zero lift" case, at iso-Mach numbers. Two azimuthal positions are chosen for every Mach number allowing to find, for the 0.9 R section, the considered Mach number. The tri-dimensional effects are due to the aerodynamic field associated to the blade tip and to radial flows caused by the yaw angles.
Bi-dimensional chordwise pressure distributions are close to those met for $0 < \Psi < 90°$ at low Mach number (0.7) while, at high Mach number (0.83), they are nearer those for $90° < \Psi < 180°$. The supersonic flow areas are generally less extended and shock intensities lower when Mach-number increases than when it decreases. These phenomena were confirmed by computations based on a small perturbations method (Ref. 39 and 40).
These results show the significance of unsteady effects due to the speed modulation, even at iso-incidence angle.

5. Conclusion

The fundamental study of the airfoil selection effect on the rotor behaviour and the adaptation of such airfoils to specific flight conditions requires a thorough knowledge of the rotor aerodynamic field.
The rotor aerodynamic field is dominated by the strong coupling between the geometrical and aerolastic rotor characteristics and requires unsteady tri-dimensional aerodynamics limited in modelization by significant non-linearities.
However, steady bi-dimensional criteria allow the definition of new airfoil families. Computation methods are limited by stall problems at low Mach numbers and by transonic shock wave-boundary layer coupling.
The impact of these new definitions is variable according to the operating envelope and is complicated by the unsteady character of the rotor field.

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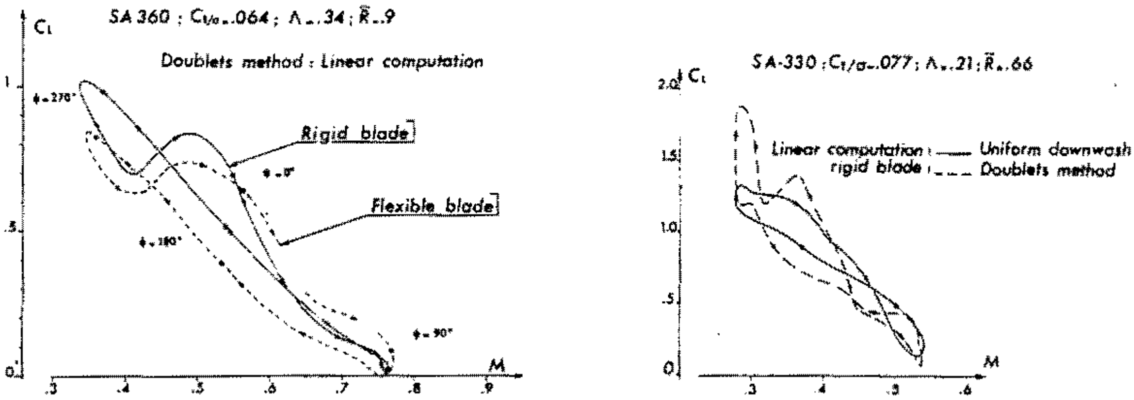


Fig. 1 : Influence of the downwash model and blade dynamic on the airfoil operating range

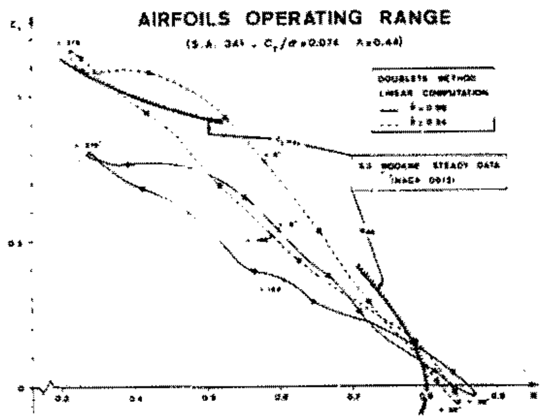
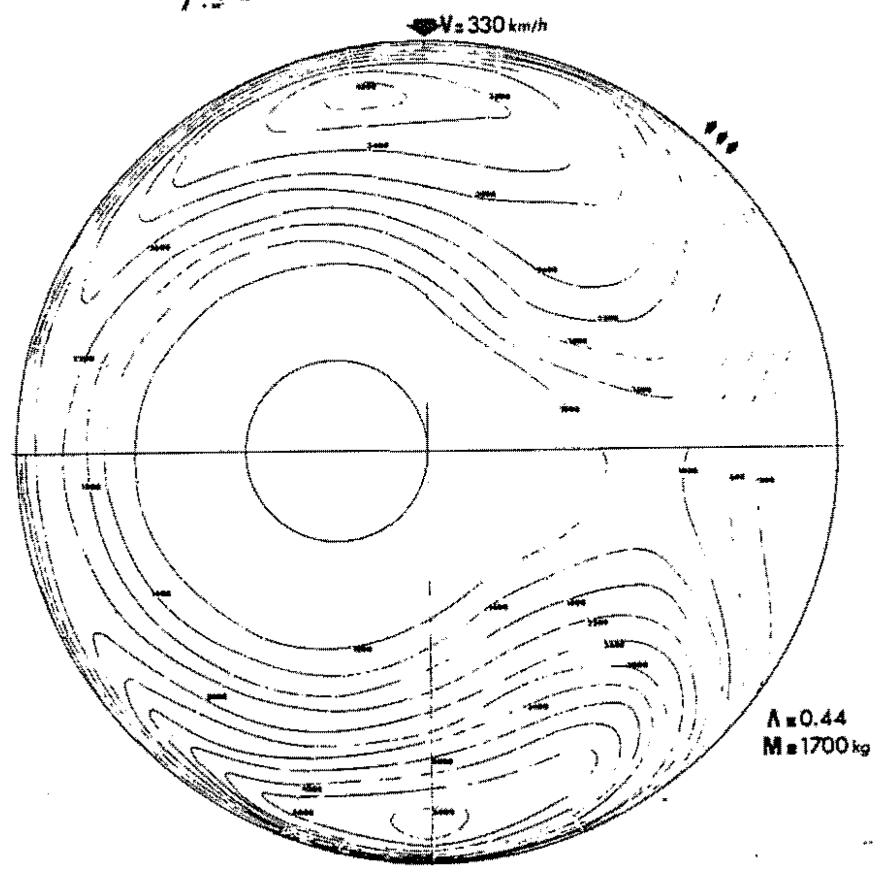


Fig. 2 : Classic limitations of the airfoil operating range



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High speed loads distribution (N/m)

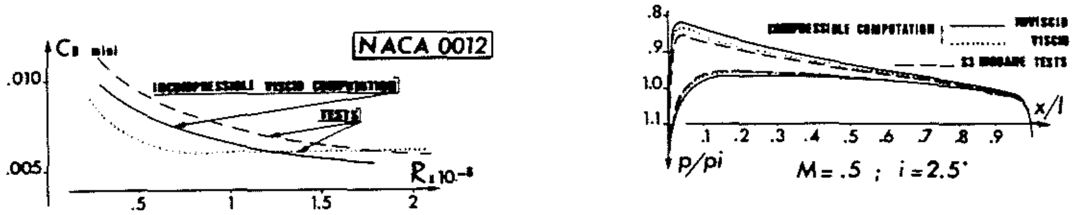

Fig. 3 : 2 D subcritical computations

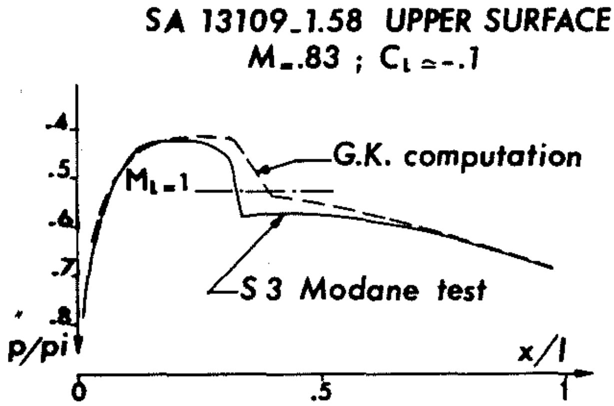

Fig. 4 : 2 D supercritical computations

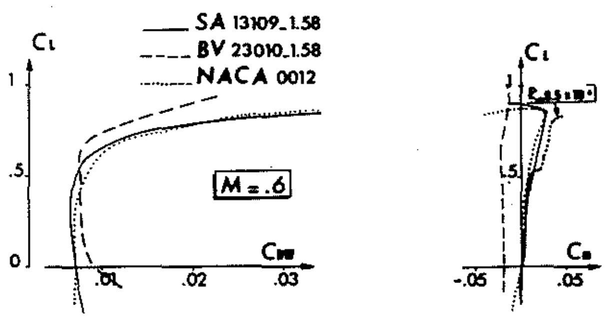

Fig. 5 : S. 3 Modane 2 D tests. Hovering conditions.

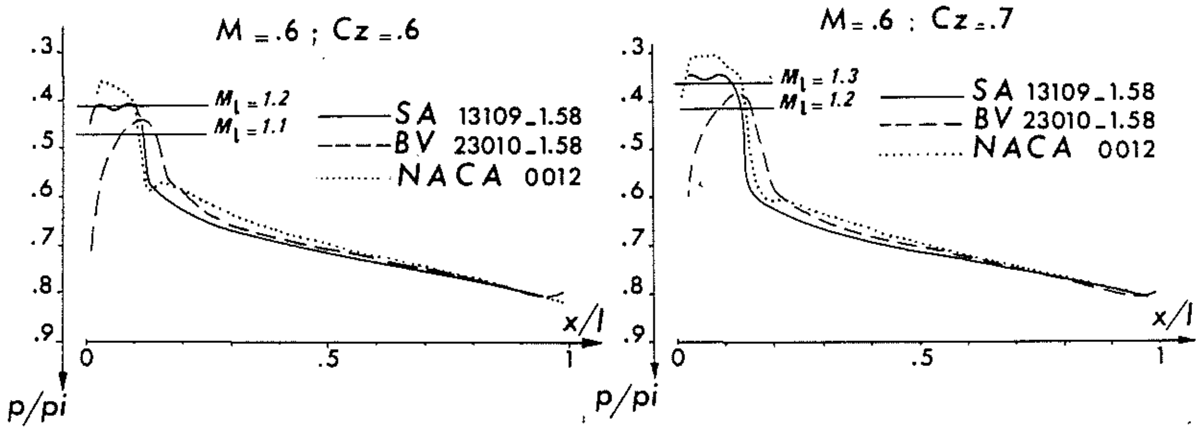

Fig. 6 : S 3 Modane 2 D tests. Upper surface pressure distributions for hovering conditions.

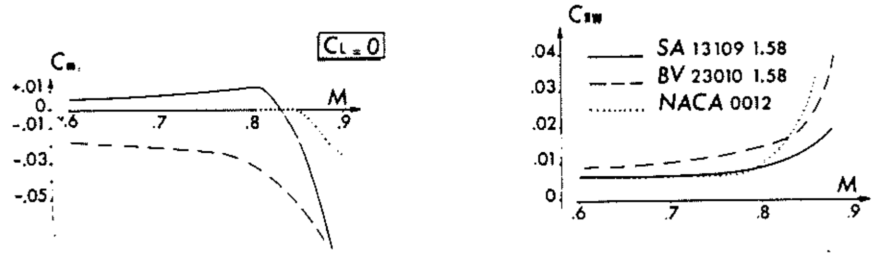

Fig. 7 : S 3 Modane 2 D tests. Advancing blade conditions

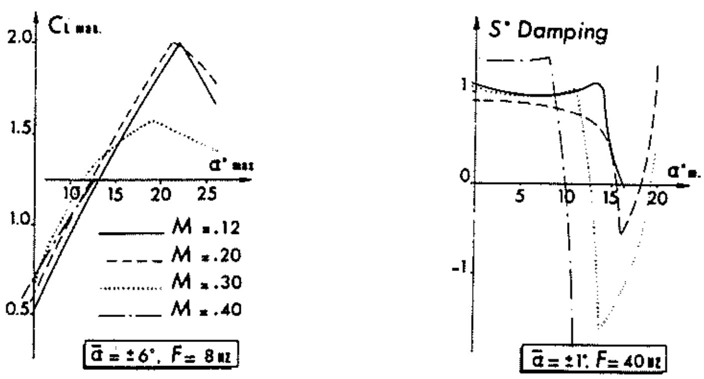

Fig. 8 : S. 10 Toulouse 2 D unsteady tests for SA 13109 - 1.58 Airfoil

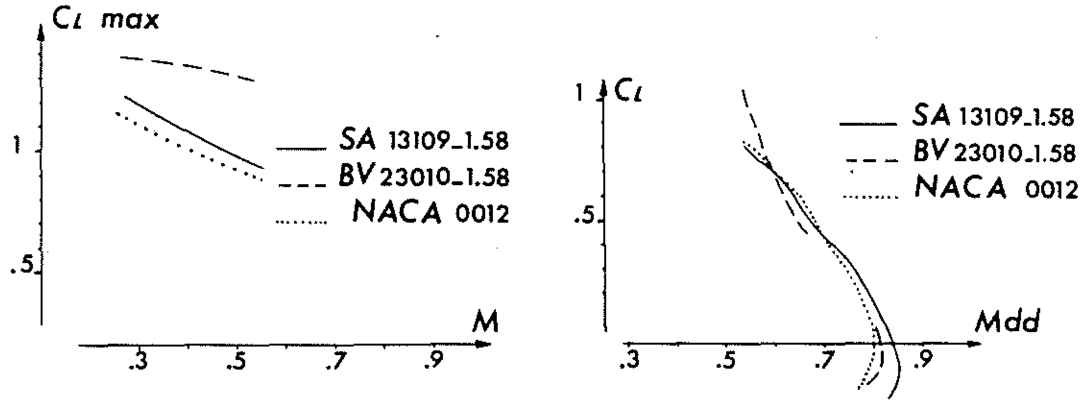

Fig. 9 : S. 3 Modane 2 D tests. Airfoils capability limitations

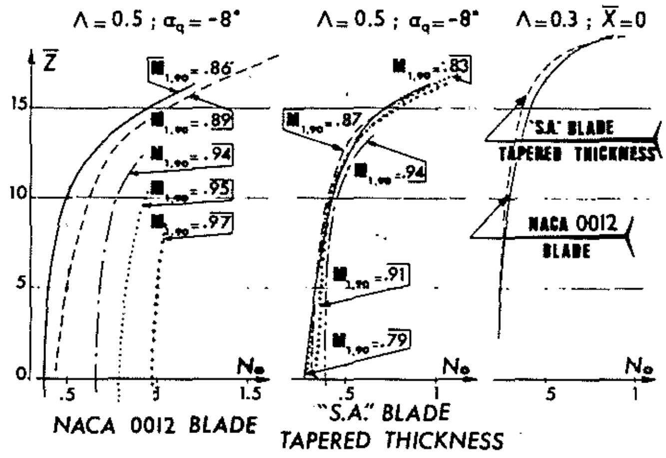

Fig. 10 : S. 1 Modane rotor tests

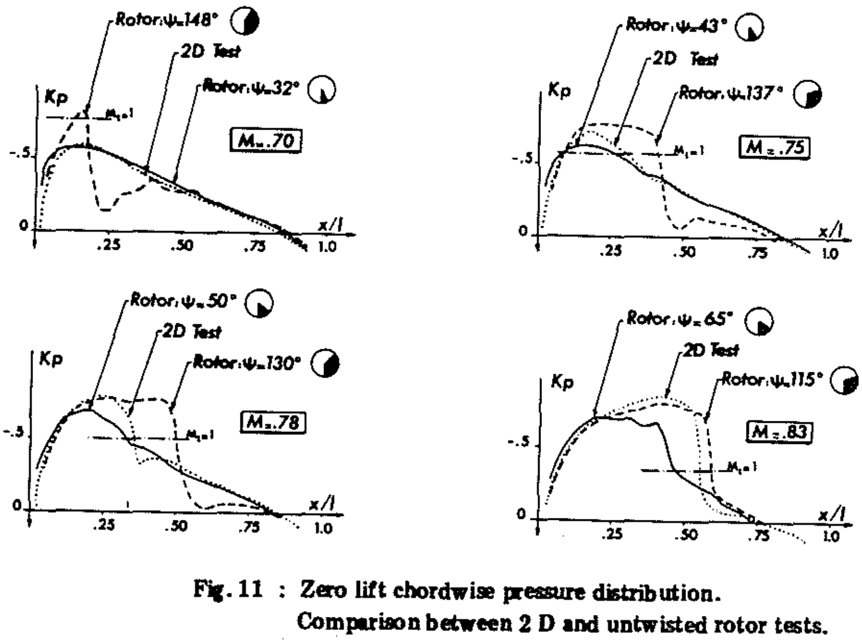

**Fig. 11 : Zero lift chordwise pressure distribution.
Comparison between 2 D and untwisted rotor tests.**