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ADVANCED AERODYNAMIC WING DESIGN FOR COMMERCIAL TRANSPORTS - REVIEW OF A TECHNOLOGY PROGRAM IN THE NETHERLANDS.

N. Voogt
Aerodynamics Department
Fokker B.V.
Amsterdam
The Netherlands

J.W. Slooff
Head, Computational Aerodynamics Dept.
National Aerospace Laboratory
Amsterdam
The Netherlands

ABSTRACT

Since the early seventies a transonic technology base has been established in the Netherlands building on earlier theoretical and experimental research done at NLR on shock-free transonic airfoils. Subsequently, as part of an advanced short/medium range transport technology program, a procedure for the aerodynamic design of transonic wings was develed along with computational methods,and experimental verifications were made.
The paper will describe the evolution of computational tools and aerodynamic design procedures. Some typical examples will be shown of airfoil and wing design studies.

1. INTRODUCTION

During the last decade transonic* wing technology has been a widely studied subject. This has, not in the least, also been the case in the Netherlands, which, at present, has a tradition of twenty years of R&D experience in transonic flow (fig. 1).

Although these Dutch developments have certainly not been untouched by international contacts and cooperation it is felt that they contain a number of fairly unique aspects. It is the purpose of this paper to review some of these.

In the early seventies, after a considerable period of research in transonic flow (Pearcey[(1)], Nieuwland & Spee[(2)], Whitcomb[(3)]), the potential benefits of a new generation of transonic airfoils with low wave drag had clearly been demonstrated. At the same time aerodynamic design problems had come within reach of the rapidly advancing field of computational aerodynamics. In the Netherlands such developments triggered a technology program with the objective to bring the available knowledge and experience on shock-free transonic airfoils in a form directly applicable in industrial projects for short/medium range transport aircraft.
The foundations for this technology program had been developed at NLR since the early sixties by the pioneering work on shock-free airfoils by Nieuwland and Spee and the development of powerful computational tools (Loeve et al[(4)], Boerstoel[(5)]).
By 1973 these elements could be combined into an aerodynamic design procedure[(6)] and design excercises for transonic wings were started subsequently.

From the outset it was realized that such direct application oriented research and development could only be successful in every way with sufficient input from industry with respect to the numerous engineering aspects that constrain wing design in practice. For this reason the technology program was executed in close cooperation between NLR and Fokker; NLR providing theoretical and experimental expertise on transonic flow as well as computational and experimental means, while the Fokker contribution included configuration design and optimization through applied computational aerodynamics and assisted by general aeronautical engineering experience. The program was administered by the Netherlands Agency for Aerospace Programs (N.I.V.R.).

In the following we will first present a brief overview of the contents of the complete technology program. Subsequently we will focus on the main topics of formulation and validation of an aerodynamic design procedure for transonic transport-type wings and the establishing of a transonic technology base. Finally, an outline is given of some recent extensions of the design and analysis capabilities, involving highly automated computational aerodynamic systems, illustrating possibly unprecedented diagnostic capabilities.

2. GENERAL OUTLINE OF TECHNOLOGY PROGRAM

Setting out from knowledge acquired during the sixties, on basic theoretical and experimental research on transonic shock-free airfoils, the main objectives of the aerodynamic technology program were

a) utilizing emerging capabilities in computational aerodynamics, to turn this knowledge into a practical procedure for the aerodynamic design of wings for advanced short/medium range transport aircraft
b) to establish the expanded boundaries of the design space - offered by the new transonic technology - in terms of wing lift, drag, pitching moment, cruise Mach number and geometry, while taking into account the limitations arising from
   * geometrical constraints associated with wing volume (such as for fuel and landing gear storage), high lift devices, engine/airframe integration, manufacturing aspects and structural strength and stiffness required in connection with steady and unsteady aeroelastic effects.
   * aerodynamic constraints associated with high speed and low speed stall characteristics, high speed dive, buffet onset, control effectiveness, aeroelastic effects, engine/airframe integration.

In order to meet these objectives the technology program covered a large number of subjects, amongst which the following can be distinguished:

- formulation, validation, refinement and extension of an aerodynamic design procedure for transonic wings with low wave drag utilizing the latest available computational tools.
- design, computational and experimental (windtunnel) evaluation of transonic shock-free airfoils of various types.
- design, computational and experimental (windtunnel) evaluation of several high speed wingbody configurations with varying aspect ratio,

* "supercritical" in U.S. terminology

sweep angle, design lift coefficient and Mach number, spanwise and chordwise loading and pressure distributions.

- design and windtunnel testing of high lift devices for several different transonic shock-free airfoils and of complete 3-D low speed, high lift configurations.
- scale effect studies for both high speed and low speed, high lift configurations, including high Reynolds number 2-D airfoil tests (upto Re = 30 $\ast$ 10^6) and 3-D half-model moderate Reynolds number tests (upto Re = 9 $\ast$ 10^6).
- computational and windtunnel investigations on engine nacelle shaping and positioning, including jet interference simulation.
- formulation and validation through windtunnel testing of a computational procedure for predicting the unsteady airloads and flutter characteristics of wings in transonic flow.
- investigation of aileron effectiveness through windtunnel tests on airfoils and wing configurations equipped with various aileron types (including investigations on "buzz" phenomena).
- assessment of steady aeroelastic effects for various flight conditions as a function of wing torsion and bending moment levels and wing geometry.
- general configuration optimization studies with the objective to determine how the increased design space offered by the transonic shock-free technology can be utilized best for specific design goals.

Apart from the aerodynamically oriented subjects listed above the complete technology program also included aero-acoustics, structures and materials and advanced flight test instrumentation systems. In the remainder of this paper we will focus on some of the aerodynamic subjects. In particular we will discuss the aerodynamic wing design procedure, its validation and some of its applications; these being the subjects with which the present authors have been involved most directly.

3. FORMULATION, VALIDATION AND APPLICATION OF AN AERODYNAMIC DESIGN PROCEDURE FOR TRANSONIC FLOW.

3.1. General description of design procedure

The aerodynamic design philosophy underlying the design procedure developed in the context of the technology program sets out from the standpoint that the pressure distribution in a more direct sense than the geometry determines the aerodynamic characteristics of a wing. It is further based on the assumption that the design as well as the off-design characteristics of a wing of given planform are uniquely determined by the pressure distribution (or isobar pattern) at one, suitably selected "design condition". As indicated in figure 2 the design problem can then be resolved into three steps:

I. choice of the design or "target" pressure distribution
II. determination of the wing (section) geometry that generates the selected target pressure distribution.
III. estimation of the off-design aerodynamic characteristics of the resulting geometry.

The choice of the target pressure distribution is determined by the design requirements. At this point engineering "art" comes in through the physical insight of the design team and the available experience in correlating "design" pressure distributions with off-design characteristics.
The determination of the geometry of the wing sections that is to generate the target pressure distribution is, in principle, purely a technical problem that can be solved if appropriate tools are available. It requires methods for the solution of the "inverse" problem of aerodynamics.

The estimation of the off-design characteristics requires aerodynamic analysis codes supplemented with empirical rules. The purpose of the latter being to correlate calculated pressure distributions and / or boundary layer characteristics with phenomena determining buffet onset, maximum lift, etc.

After satisfactory completion of the computational design cycle the process proceeds to experimental verification by means of windtunnel testing.

3.2. Airfoil section design studies

Because transport aircraft generally utilize high aspect ratio wings several aspects of transonic shock-free wing aerodynamics were investigated through 2-D airfoil studies, in particular during the earlier stages of the technology program.

Transonic airfoil technology has in the Netherlands been built upon the ability to design airfoils with a shock-free design point by means of hodograph theory (Nieuwland(7), Boerstoel(5)).
With the Boerstoel hodograph method in particular it is possible to generate a large variety of airfoils with different types of shock-free recompression for given free-stream Mach numbers and lift levels. An important additional degree of freedom in design is offered by the possibility to modify large subsonic parts of such "hodograph" airfoils to better suit engineering requirements without spoiling the low-drag properties of the basic shock-free flow (Loeve and Slooff(8)).
For this purpose a 2-D version of the subsonic, inverse panel method of (9) was availabe.*
High speed off-design characteristics were estimated by means of several versions of the Bauer - Garabedian - Korn - Jameson (BGKJ)codes(10), supplemented with empirical rules.
Low speed (maximum lift) properties could be predicted by means of the NLR CLMAX code (unpublished in-house work, featuring free streamline modeling of separated flow). For the computational aerodynamic assessment of high lift devices the NLR MAT2D code(11) is available.

Windtunnel facilities utilized for 2-D airfoil experimental verifications include:

for high speed:

- NLR Pilot Tunnel	(Re $\leqslant$ 2.5 $\ast$ 10^6)
- Lockheed Georgia CFF	(Re upto 30 $\ast$ 10^6)
- NLR HST	(Re upto 12 $\ast$ 10^6)

* More recently a 2-D inverse transonic program system has been developed at NLR.

for low speed (with high lift devices):
- NLR LST 3x2 (Re $\leq 3.6 * 10^6$)
- NLR HST (Re upto $8 * 10^6$).

Main purpose of the airfoil design studies was to establish a technology base of relations between design pressure distributions and off-design characteristics and to assess the effects of geometrical and aerodynamic constraints. A general indication of the design pressure distribution parameters studied is given by fig. 3. In the following we will briefly discuss some specific examples.

Figure 4 provides an example from investigations on the parameters governing compressibility drag creep, the effect of the upper surface local Mach number level in particular. The figure reflects the general experience that the higher the local Mach number in the (shock-free) supersonic zone, the higher the drag creep (as well as basic drag level). On the other hand, the airfoil with the higher Mach number level can, of course, be appreciably thicker and/or can carry more lift. Which combination should be preferred depends on the specific design application and must be determined through optimization studies.

An example of study on the effects of variations in leading edge geometry on low speed $c_{l_{max}}$ is given in fig. 5. It should be noted that the different leading edge geometries result from different choices for the transonic design pressure distribution in the nose region with otherwise comparable high-speed aerodynamic and geometric characteristics. The figure illustrates the importance of being able to design for various types of pressure distribution. It also illustrates the fact that low Reynolds number $c_{l_{max}}$ data alone may provide misleading information with respect to high Reynolds numbers.
Note that the compressibility stall limit depends strongly on the free-stream Mach number.

For completeness it is mentioned that the CLMAX code utilized to contruct fig. 5 distinguishes three types of stall. One of these is the familiar trailing edge type of stall in which turbulent flow separation, starting at the trailing edge, spreads forward. In the other two cases flow conditions near the leading edge provoke local separation which then spreads instantaneously downstream.
When this happens, significant rear separation may already be present. In the leading edge type of stall separation may be either shock-induced or may be caused by excessive local pressure gradients behind the suction peak. In the latter case the (turbulent) separation is generally preceded by a laminar separation bubble followed by turbulent reattachment (v.d. Berg en Oskam[12]).
An example of the effect of imposing a geometry constraint on the design pressure distribution and the resulting geometry is illustrated by fig. 6.
The figure shows two designs, one without and one with a constraint on the maximum trailing edge angle. Clearly the thicker trailing edge region is much more attractive from the structures point of view. In the windtunnel experiment no significant adverse effects of this modification could be established.

An example from a study on the effects of pitching moment constraints is reproduced in fig. 7. The two airfoils were designed for the same design c_l and Mach number but for different levels of pitching moment. In this particular case the penalty to be paid for the pitching moment constraint was a loss of thickness of 2 percent in terms of t/c.
On the other hand the (viscous) drag of the constrained (thinner) airfoil was 6 percent less. Windtunnel tests confirmed that there was no significant difference in off-design performance.
Here again, optimization studies should indicate which of the two airfoils is suited best for a specific design goal.

Airfoil design studies of the type described above are very suitable for establishing trends in possibilities and limitations offered by transonic shock-free technology for high aspect ratio wings. However, fully 3-D wing design studies are required if one wishes to learn how precisely to exploit the favourable effects of three-dimensionality and how to avoid the undesirable ones.

3.3. Wing design studies

The design procedure for wing-body configurations in transonic flow is essentially an extension of its 2-D equivalent. It implies finding the sectional geometry of a wing which, in the presence of the body (and, if required, other parts of the configuration with fixed geometry) and subject to geometric constraints, will generate - at the design condition - a prescribed pressure distribution. The latter should be chosen such that drag at the design condition is minimized. The required off-design characteristics should, in addition, be met by the resulting wing geometry. With proper control over 3-D effects as provided by fully 3-D inverse methods these off-design characteristics may be related to the pressure distributions (and their spanwise variation) of 2-D shock-free airfoils.
The latter form the basis for the 3-D target pressure distribution.

The inverse problem of determining the wing geometry which produces the required pressure distribution is non-linear and must be solved iteratively. At the time when the design procedure was set up, no computational methods for 3-D transonic flow were available for design purposes and the transonic inverse problem was solved by using a program system [9] for subsonic flow with compressibility corrections in conjunction with a concept of equivalent subsonic pressure. The function of the latter is to relate the prescribed transonic target pressure distribution to an equivalent subsonic one. A detailed description of this approach is given in ref. 6.

An important feature of the inverse method of ref. 9 is that it allows control over geometrical characteristics so that unrealistic or structurally unattractive geometries can be avoided.
Without such control an aerodynamically suitable target pressure distribution will, in general, not lead to a suitable geometry. We will return to this point later.

For the estimation of the off-design characteristics of the resulting 3-D configuration in subsonic flow the NLR Panel Method[4], supplemented with boundary layer computations[13] have been available for some time. More recently aerodynamic procedures for transonic flow and low speed $C_{L_{max}}$ prediction have become available for use on a routine basis.

For the experimental part of the wing development studies, the NLR HST transonic windtunnel has been the main testing facility with a Reynolds number capability of upto $3.6 * 10^6$ for complete models and upto $9 * 10^6$ for half model testing. Low-speed tests of complete models including high-lift devices were also done in the NLR HST, then used as a low speed pressure tunnel ($Re \lesssim 3 * 10^6$).

The first validation of the design procedure was obtained for a wing-body configuration with a 20° swept wing of aspect ratio 8, designed for a Mach number of .75 and a liftcoefficient of .45. A target isobar pattern with uniform upper surface level but with a spanwise variation in chordwise shape - chosen in relation to off-design requirements - was specified over most of the wing span, with the exception of the root and tip regions. The flow in the tip region was kept subcritical and a curved planform leading edge was applied. Two separate approaches were followed for the inner wing design. In one of them subcritical flow was specified at the wing root. In the other case supercritical flow was allowed up to the wing root.

During these first inner wing design studies spanwise variations in pressure distributions were explored on various planforms [14]. The investigations resulted in inner wing geometries with substantial thickness. They were defined in combination with the same outer wing which had a thickness/chord ratio ranging from 15% near the wing tip to 16% on the inner end. The inner wing with the subcritical root had a curved leading edge and an 18% thick root section whereas the one with supercritical root flow had a straight leading edge and 17% t/c at the root.

In the subsequent windtunnel experiments good agreement for both configurations was found at the experimental design condition (fig. 8) between the measured and "shock-free" design pressure distribution. The weak shock waves shown in the experimental pressure distribution reflect the general observation from 2-D tests that pure shock-free flows are seldom realized in practice. This, however, is not a problem; the important fact is that the wave drag is low (or even negligible) and this was indeed realized in the experiments. Note that the different inner wing designs both show a shock-free flow at the wing root and have lead to only small differences in the outer wing pressure distribution.

An important further degree of freedom in the 3-D design process exploited during the inner wing studies is offered by the possibility to manipulate flow conditions near the wing root by means of wing-body fillet shaping. As illustrated by fig. 9 and confirmed by windtunnel experiments, specially shaped fairings can substantially improve the velocity distribution on a significant part of the inner wing. This option can be utilized in two ways: either for additional inner wing isobar control with the geometry fixed or for additional geometrical design space with the isobar pattern fixed.

A typical 3-D aspect of the design process, encountered during the inner wing studies, is that near the wing root the inverse problem is ill-posed, i.e. small differences in target pressure distribution may lead to large differences in geometry. An example is shown in fig. 10 where a given target pressure distribution is approached through two, significantly different, but equally unacceptable, geometries. In the inverse method of (9) the problem is solved by adding explicit geometrical requirements to the inverse method and solving the resulting over-determined problem in a weighted least squares' sense. In this way a suitable geometry can be obtained in only a few iterations at the cost of a minimum deviation from the target pressure distribution. While such a solution may represent a nuisance for the computational aerodynamicist, because it hinders convergence of the iterative inverse cycles, it may provide an unexpected additional degree of freedom for the airplane designer. The problem is how to exploit this freedom.

After the first validation of the design procedure wing design studies were continued for configurations with various wing planforms, covering a range in aspect ratio between 8 and 11 and from 16° to 23° in sweep angle: design conditions were varied in Mach number and in liftcoefficient (up to 0.6). Altogether some 10 different basic high speed configurations plus 6 additional variants were designed and tested. Figure 11 shows an example of a wing of aspect ratio 11 and a sweep of 16°. It has a thickness ranging from 16% in t/c at the root, through 15% at the kink station to 12% near the wing tip. The design condition is $c_L = .45$ at $M = .75$. As illustrated by the pressure distribution at the design point shock strengths are, again, well under control.

The 3-D wing design studies mentioned above included, a.o. the following subjects:

- assessment of various tip shapes and tip isobar patterns
- aerodynamic and geometric effects of spanwise variations in upper surface target velocity <u>levels</u>, as well as of further variations in chordwise <u>shape</u> in particular in relation to off-design characteristics
- aerodynamic and geometric consequences of variations in both spanwise and chordwise loading in relation to design (drag) as well as off-design characteristics.

Although the results of the wing design studies described above were generally successfull (as illustrated, e.g. by figs. 8 and 11) the main lacking element in the original design procedure was, of course, a computational method for 3-D transonic flows. As will be discussed in the next section, this gap was bridged in the later stages of the technology program.

4. FURTHER DEVELOPMENTS IN COMPUTATIONAL TOOLS FOR AERODYNAMIC ANALYSIS.

The capability to apply transonic technology successfully has recently been expanded through the development of comprehensive computer program systems and procedures for transonic and low speed aerodynamic analyses. In the latter case the 2-D CLMAX code mentioned in section 3.2. and the 3-D NLR PANEL code are combined to provide a means for estimating the low speed maximum lift of wing-body configurations (fig. 12). In this combination the level of c_{Lmax} for $Re \rightarrow \infty$ is determined by means of the 3-D PANEL code in combination with a compressibility stall criterion. The variation with Reynolds number is determined through application of the 2-D CLMAX code to a number of span stations. Results of early applications of the procedure for two different wings tested in the course of the technology program are presented in fig. 13.

For transonic flow the XFL022 NLR SYSTEM [15] has become available. This is a computational aerodynamic information system based on a numerical simulation of the compressible potential flow about wing-body configurations. As indicated in fig. 14 the system comprises a modified version of the Jameson - Caughey FL022 code[16], the NLR PANEL code[4] and the NLR 3-D boundary layer code BOLA[13] as well as several auxiliary routines. The system is capable of providing detailed information with respect to pressure distributions, boundary layer characteristics, lift, various components of drag (including trim drag for given tail surface characteristics), pitching moment and buffet onset. It is operational on the NLR - Fokker computer network and on the CDC Cybernet 176 and 170-750 computers. On the latter a complete run covering the c_L - Mach number plane with 20 to 25 data points can be executed in 48 hours through-put time.

Figure 15 illustrates the pressure prediction capability of the system, which is significantly better than that of the original FL022 code, for one of the wing-body combinations designed and tested during the technology program. The drag analysis capabilities are demonstrated by figs. 16 and 17. These show an example of the break-down of the total drag into the various components distinguished by the SYSTEM as a function of c_L and Mach number. Information such as contained by figs. 16 and 17 has proved invaluable in drag minimization studies.

Analytical capabilities of the type described above have proved to represent complementary means of great importance, relative to windtunnel testing, in aerodynamic analysis and design. It is the authors' experience that their availability greatly enhances the chances for optimal application of transonic technology.

5. CONCLUDING REMARKS.

An outline has been given of an aerodynamic technology program in the Netherlands executed in close cooperation between Fokker and NLR. Main objectives of the program were the formulation and validation of a computational procedure for the aerodynamic design of high aspect ratio wings with transonic flow typical for short/medium range commercial transport aircraft and the establishing of a transonic technology base.

As main achievements of the technology program the following can be listed:

- a well-proven and readily applicable procedure for the aerodynamic design of high aspect ratio wings, based on an "inverse" approach. A unique feature of the latter is the possibility to exercise explicit control over the geometry while approaching the "target" pressure distribution as closely as possible.
- extensive experience in relating target pressure distribution to (off-design) aerodynamic characteristics, obtained through numerous 2-D airfoil and 3-D wing design studies and windtunnel verifications, including assessment of high Reynolds number characteristics.
- possibly unique capabilities for the computational analysis of wing-body configurations in subsonic and transonic flow, including a.o. unprecedented diagnostic means for drag minimization studies.

It is felt that this program has yielded a transonic technology base of substantial extent that can be utilized in application to transport type aircraft configurations over a wide range of design conditions.

6. ACKNOWLEDGEMENTS.

The authors wish to stress the point that the work reported here has been accomplished together with a large number of colleagues at both Fokker and NLR, their own contributions merely being limited to the formulation and application of the computational design procedures. They are particularly indebted to Prof. Blom of Fokker for his confidence in the matter and for sharing parts of his vast experience in aircraft design.

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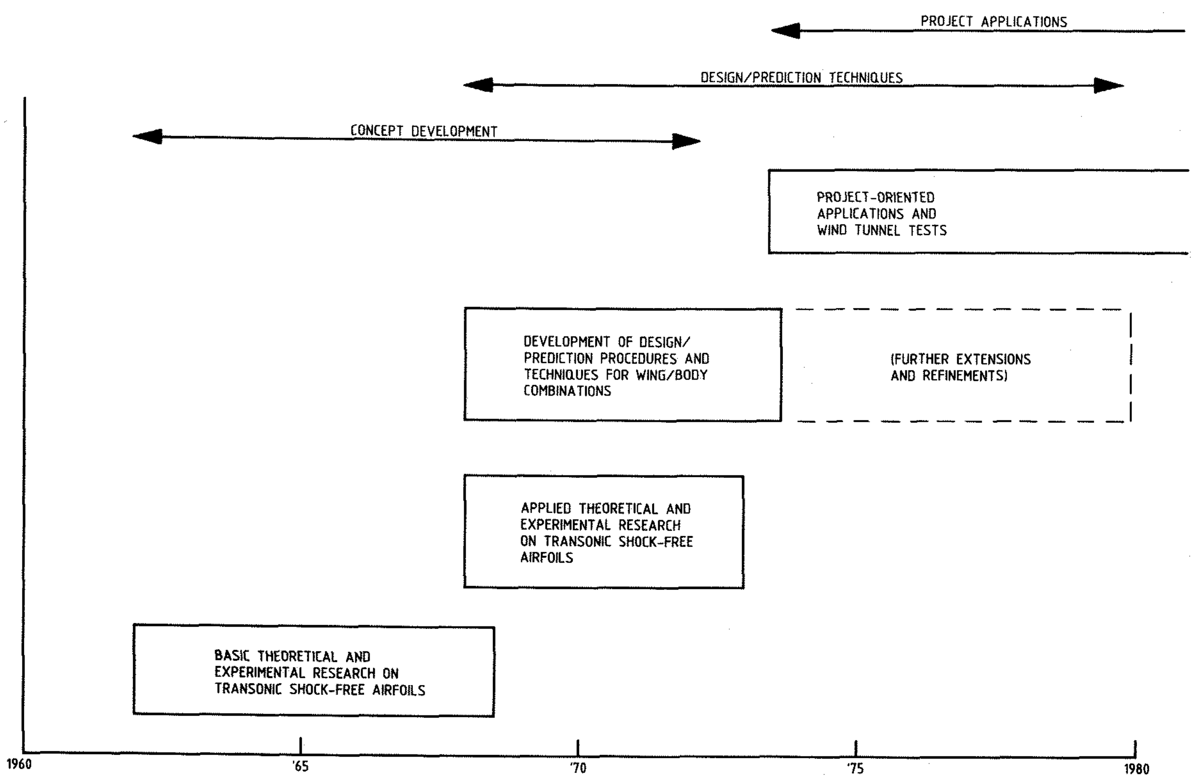


FIG. 1 DEVELOPMENT PHASES OF THE TRANSONIC TECHNOLOGY PROGRAM

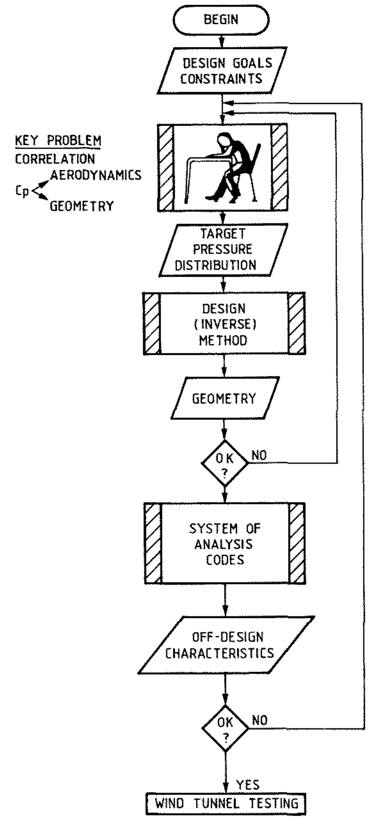


FIG. 2 FLOW DIAGRAM OF AERODYNAMIC DESIGN PROCEDURE

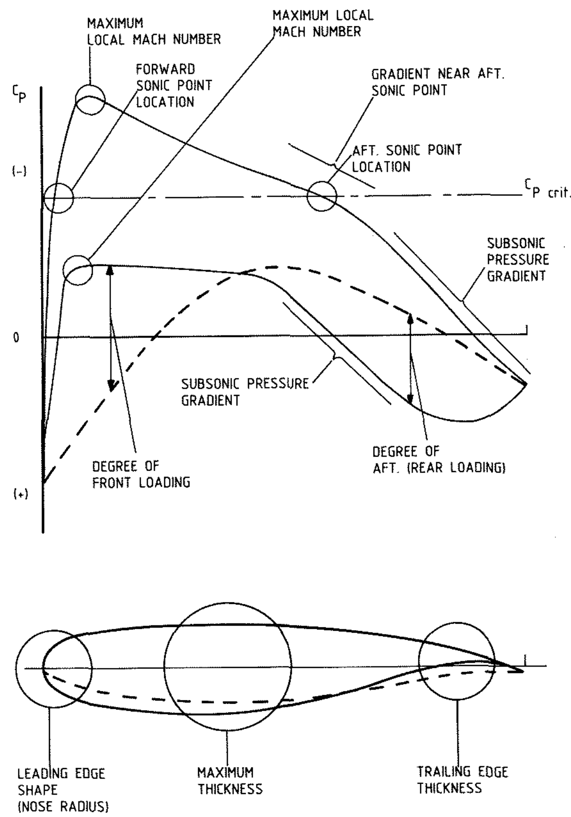


FIG. 3 SIGNIFICANT DESIGN PRESSURE DISTRIBUTION PARAMETERS FOR OFF-DESIGN CHARACTERISTICS

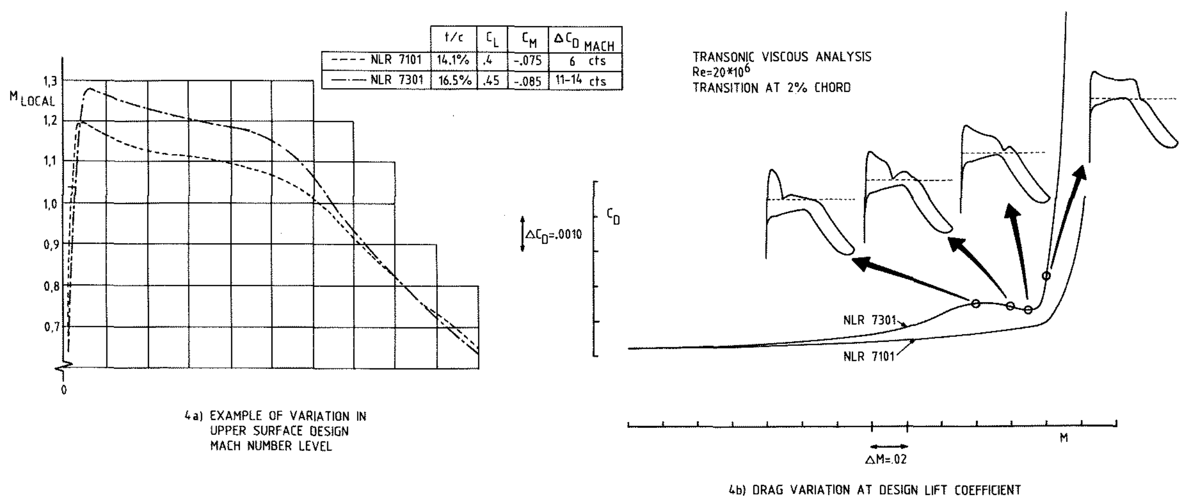


FIG. 4 EFFECT OF UPPER SURFACE LOCAL MACH NUMBER LEVEL ON DRAG CREEP

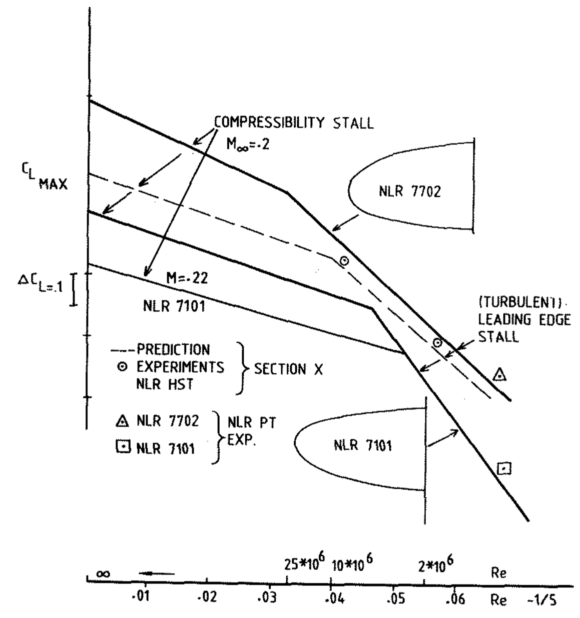


FIG. 5 PREDICTION OF CL MAX RANGE FOR DIFFERENT NOSE SHAPES

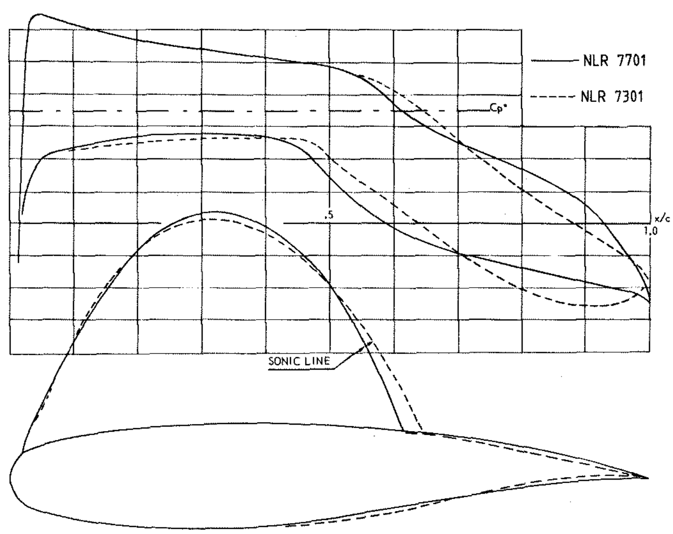
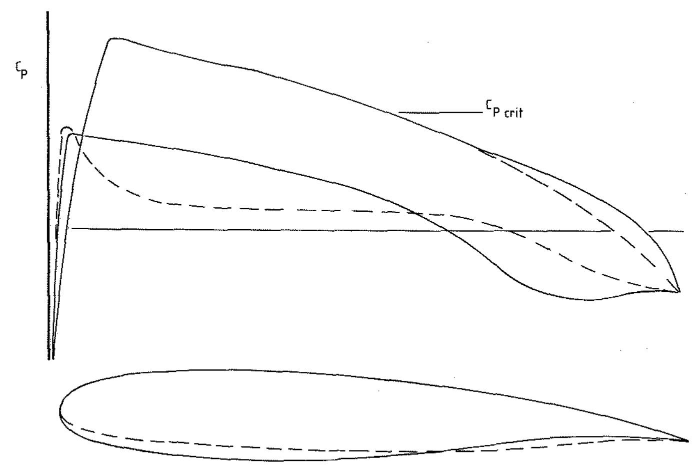


FIG. 6 EFFECT OF A CONSTRAINT ON THE TRAILING EDGE ANGLE



△ C_m	△ t/c	△ C_D	△$C_{L\,BUFFET}$	△ $C_{L\,MAX}$	
.045	-.02	-6%	0	0	——— NLR 7702
					— — — NLR 7703

FIG. 7 EFFECT OF A PITCHING MOMENT CONSTRAINT AT CONSTANT DESIGN CL AND MACH NUMBER

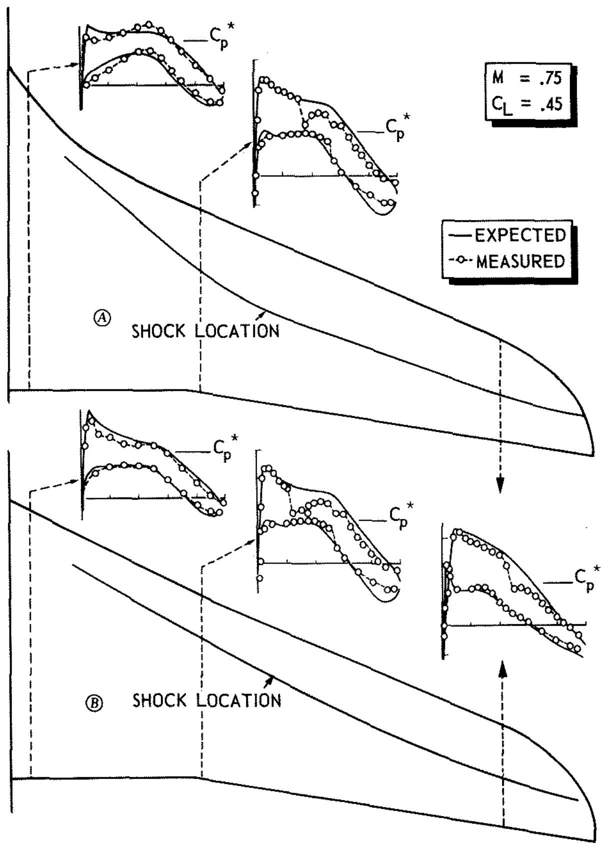


FIG. 8 COMPARISON OF MEASURED AND EXPECTED TRANSONIC PRESSURE DISTRIBUTION FOR WINGS WITH ASPECT RATIO 8

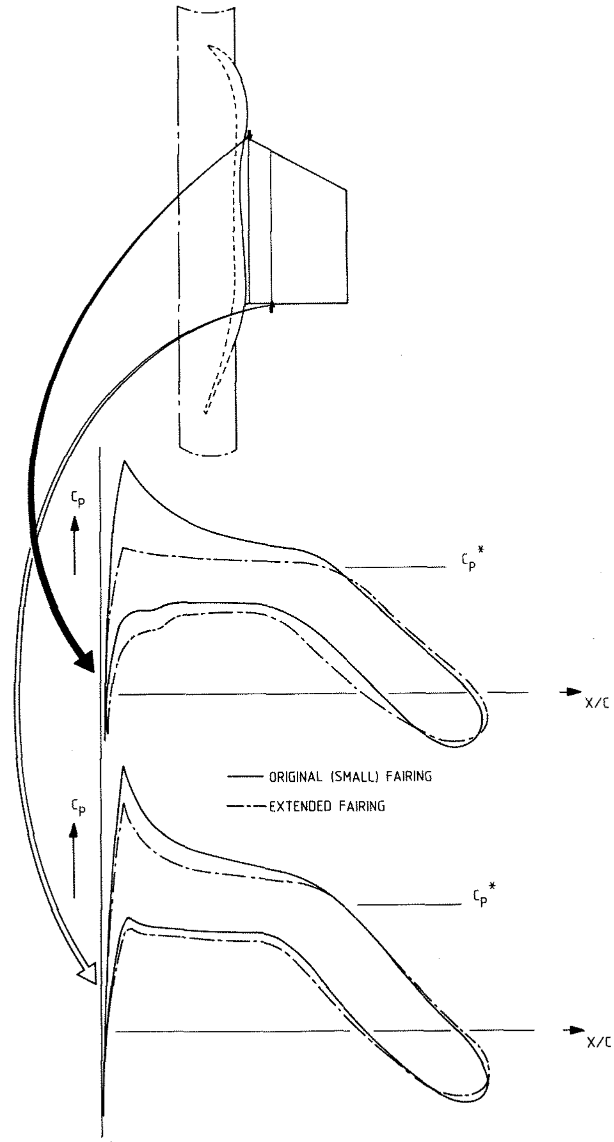


FIG. 9 EFFECT OF EXTENDED FAIRING ON INNER WING PRESSURE DISTRIBUTION

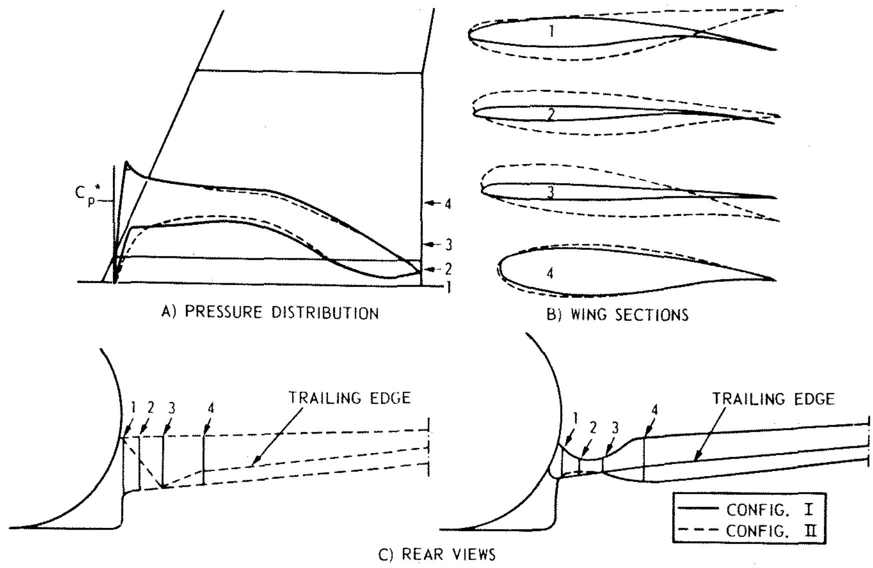


FIG.10 EXAMPLE OF WIDELY DIFFERENT GEOMETRIES PRODUCING ALMOST THE SAME PRESSURE DISTRIBUTION

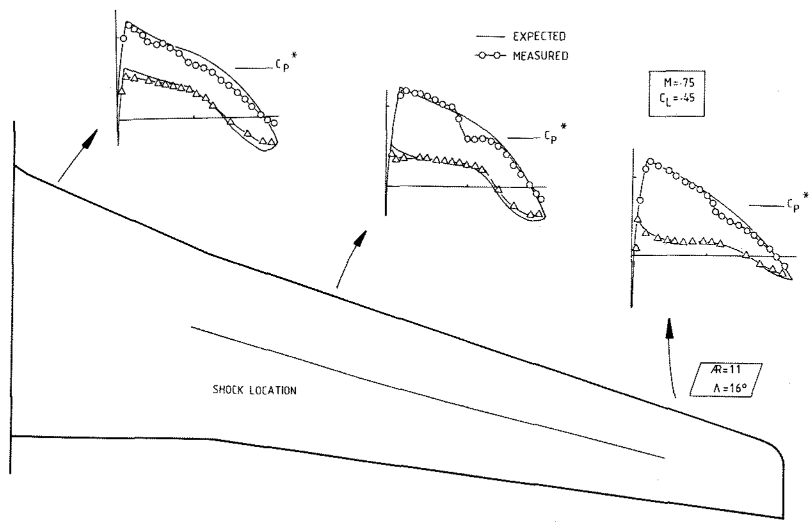


FIG.11 COMPARISON OF EXPERIMENTAL AND EXPECTED TRANSONIC PRESSURE DISTRIBUTION FOR A HIGH ASPECT RATIO WING

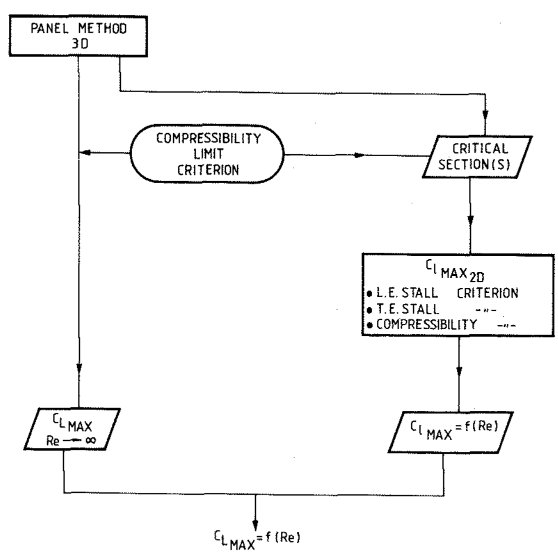


FIG.12 LOW SPEED CL MAX PREDICTION PROCEDURE

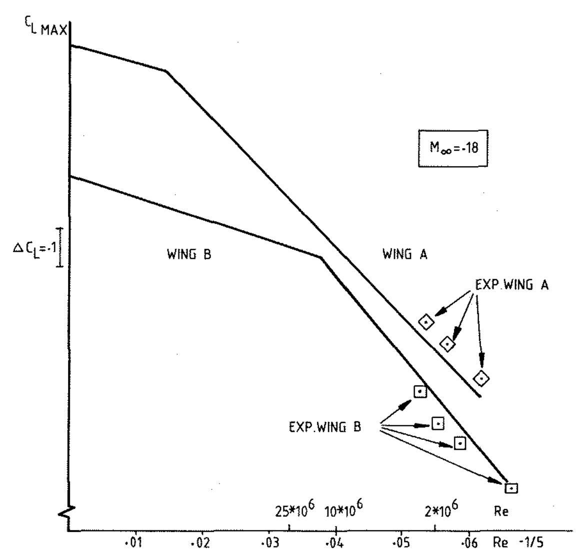


FIG.13 COMPARISON OF PREDICTED AND MEASURED LOW-SPEED CL MAX

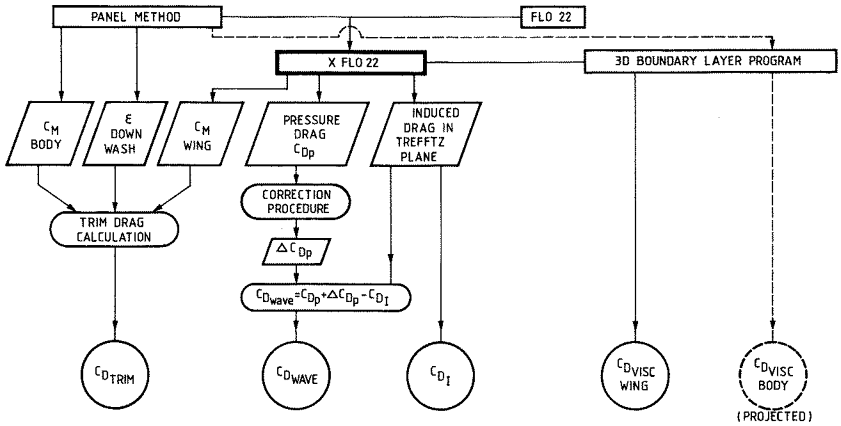


FIG.14 WING-BODY DRAG ANALYSIS BY X FLO 22 SYSTEM

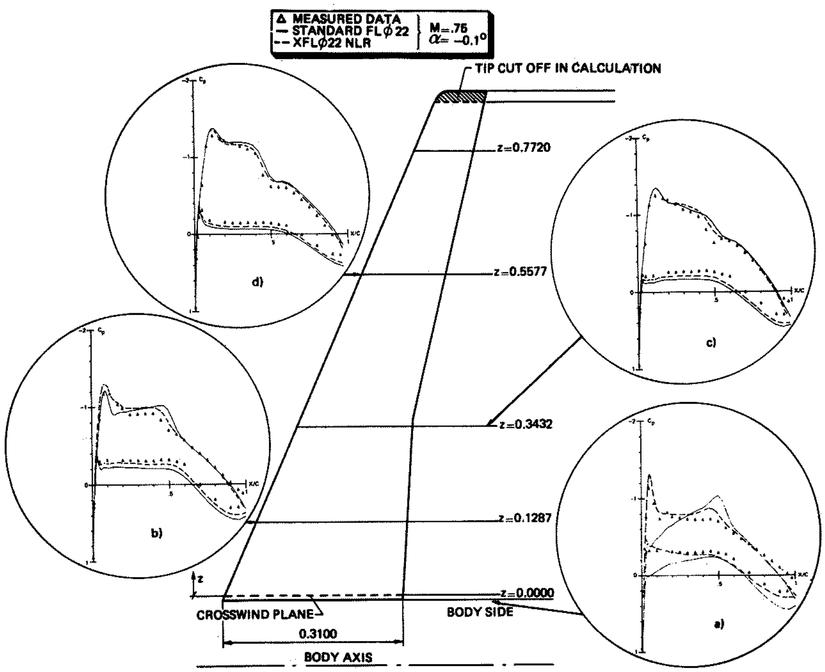


FIG.15 BODY PLUS FILLET EFFECT SIMULATION IN FLO 22 BY X-WIND FROM PANEL METHOD

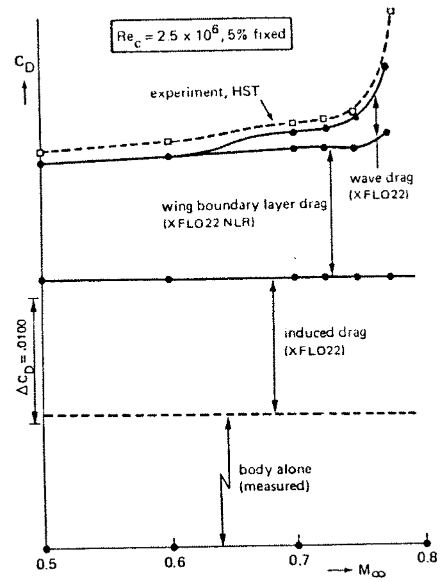


FIG.17 DRAG CORRELATION AT CONSTANT LIFT

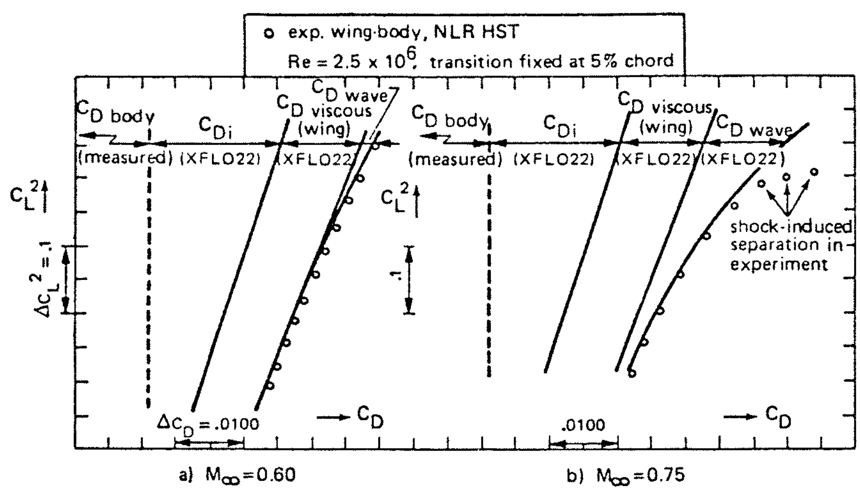


FIG.16 DRAG CORRELATION AT CONSTANT MACH NUMBER