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TRANSONIC AIRFOIL DESIGN FOR HELICOPTER ROTOR APPLICATIONS

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ROTOR AIRFOIL DESIGN

Despite the fact that the flow over a rotor blade is strongly influenced by locally three-dimensional and unsteady effects, practical experience has always demonstrated that substantial improvements in the aerodynamic performance can be gained by improving the steady two-dimensional characteristics of the airfoil(s) employed. The two phenomena known to have great impact on the overall rotor performance are: 1) retreating blade stall with the associated large pressure drag, and 2) compressibility effects on the advancing blade leading to shock formation and the associated wave drag and boundary-layer separation losses.

HOVER | FORWARD FLIGHT | MANEUVERS

GENERAL DESIGN OBJECTIVES

- MAXIMUM LIFT CAPABILITY AT LOW SPEED
- HIGH MACH DRAG DIVERGENCE
- NEAR ZERO PITCHING MOMENT
- LOW PROFILE AND COMPRESSIBILITY DRAG

ROTOR AIRFOIL DESIGN IS A MULTIPLE DESIGN POINT PROBLEM

CLASSIFICATION OF DESIGN PROBLEMS

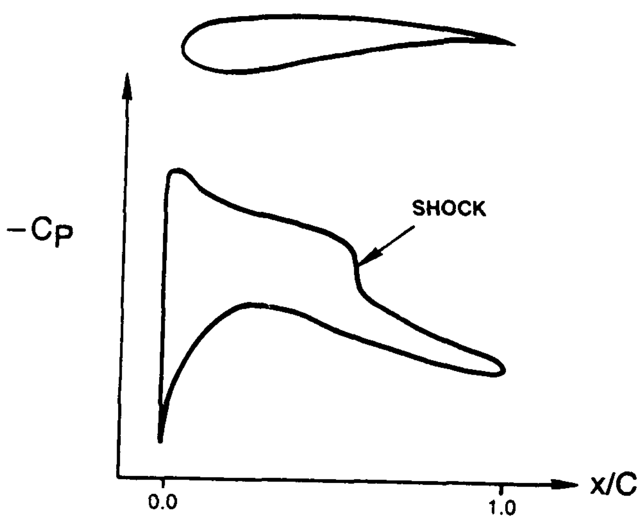
Two design problems are identified:

ITERATIVE DIRECT METHODS [1,2]: In these methods, direct solutions are sought with an airfoil geometry that is modified in an iterative process (either by the designer or through numerical optimization utilizing a set of geometric shape functions) to minimize the differences between the computed and the prescribed target pressures.

INVERSE METHODS [3-5]: Here a target pressure distribution is prescribed and the objective is to find the airfoil geometry that would yield the specified target pressure at design conditions.

The above two inviscid procedures have also been extended to allow for viscous effects through coupling with an integral boundary-layer formulation [6,7].

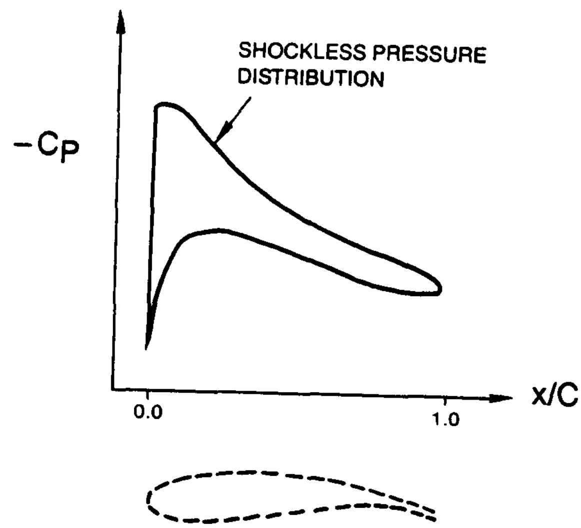
DIRECT



ADVANTAGES :
- FIRM CONTROL OF GEOMETRY
- RAPID CONVERGENCE RATES
- APPLICABLE FOR SHOCKED & SHOCKLESS DESIGNS

LIMITATIONS :
- ABILITY TO CONTROL AERODYNAMIC CHARACTERISTICS IS ABSENT (TRIAL AND ERROR)

INVERSE

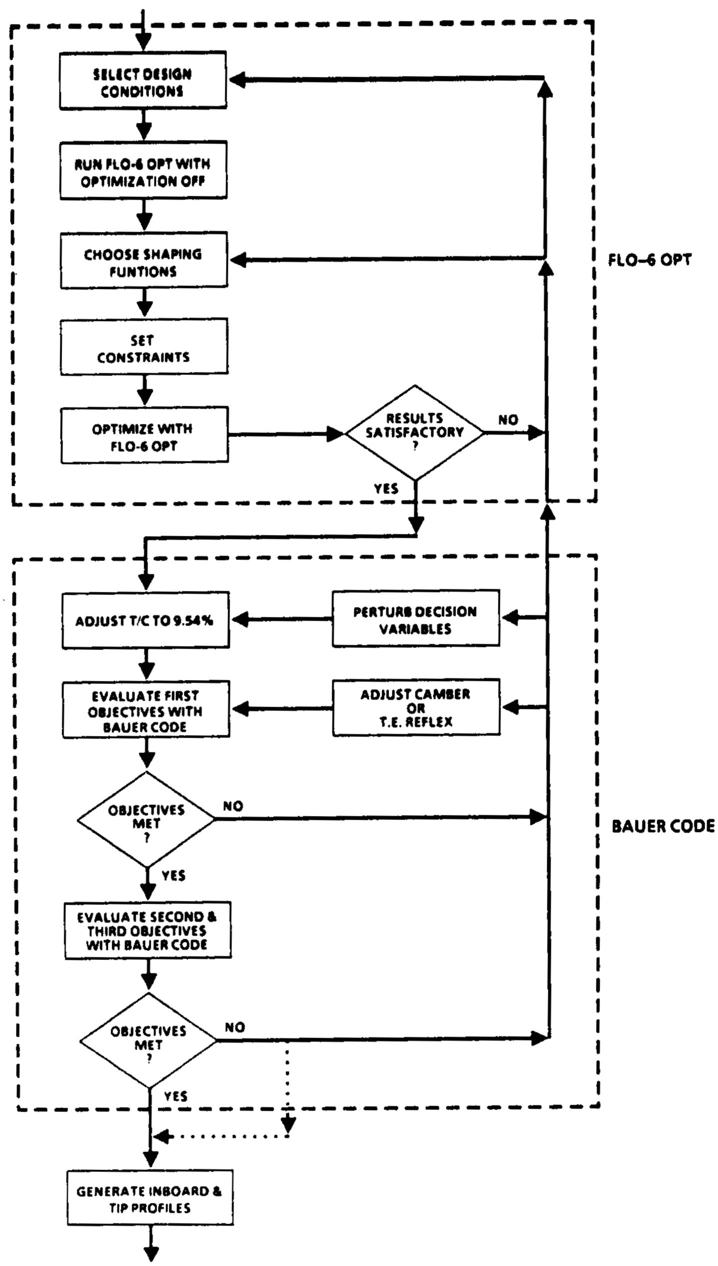


ADVANTAGES:
- BETTER CONTROL OF AERODYNAMICS

LIMITATIONS :
- LACKS CONTROL OF GEOMETRIC REGULARITY
- SLOWER CONVERGENCE RATES
- LIMITED TO SHOCK-FREE DESIGNS

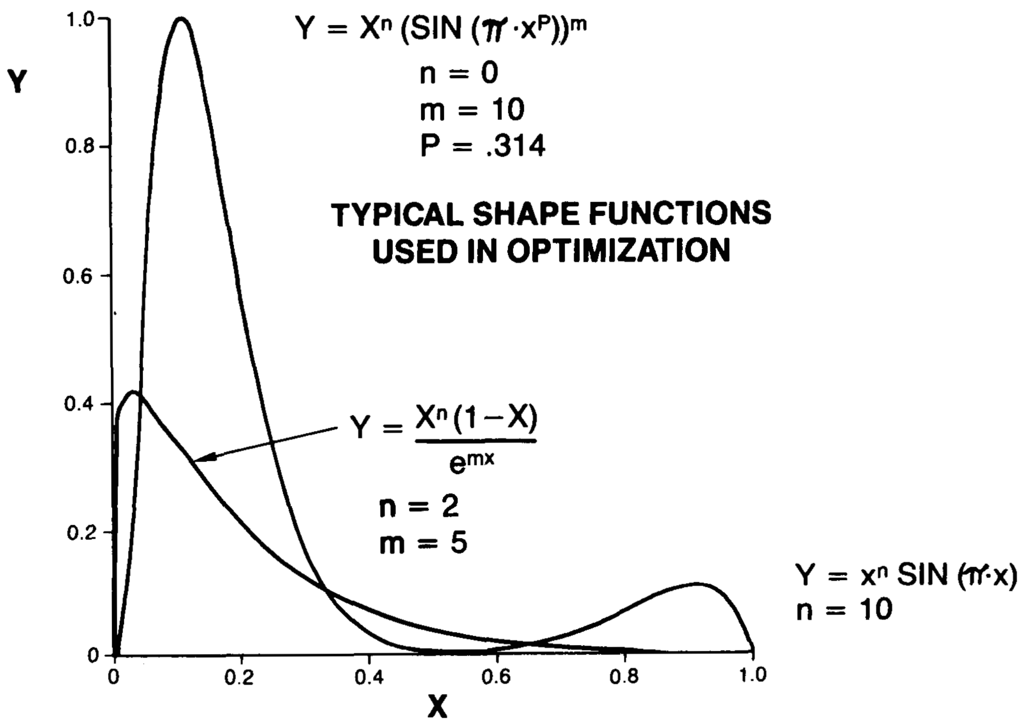
ITERATIVE DIRECT PROCEDURE

Two primary design tools were utilized at McDonnell Douglas Helicopter Company in generating an airfoil designated HH-06 [8-11]. FLO-6 OPT [12-14]; a two-dimensional transonic full potential direct solver with a constrained function minimization routine and, the BAUER code [15]; a two-dimensional transonic full potential direct solver with boundary-layer corrections. In the design process, the airfoil geometry was optimized using FLO-6 OPT to meet the prescribed design objectives. The resultant profile was then evaluated (at design and off-design conditions) and further refined using the BAUER code.



DESIGN PROCEDURE

In the design of the HH-06 airfoil, the initial profile was modified through the application of different shape functions to its upper and lower surfaces. A specific aerodynamic parameter (or object function) such as the drag coefficient is minimized through adjusting the decision variables (e.g., n, m, p, ...etc) which control the magnitude and location of the shape functions. Constraints, either geometric or aerodynamic, may be added to the minimization process. The effect of each shape function is then assessed by perturbing its decision variable and computing the change in the object function. The resulting gradient is then traced until a local minimum is found or a constraint is reached.



Object function	:	CD @ M=0.81, Alfa=-0.5°
Geometric Constraint	:	$0.10 \geq t/c \geq 0.095$
Aerodynamic constraints	:	$\lvert CM \rvert \geq 0.010$ @ M=0.30, Alfa=-0.5°
		$\lvert CM \rvert \geq 0.015$ @ M=0.80, Alfa=-0.5°
		$ML \leq 1.400$ @ M=0.80, Alfa=-0.5°
		$ML \leq 1.400$ @ M=0.40, Alfa=12.5°

RESULTS OF THE ITERATIVE DIRECT PROCEDURE

In the late seventies, the National Aeronautics and Space Administration awarded two contracts (Boeing VERTOL, Lockheed Georgia) for the design of an advanced airfoil for rotorcraft applications [16,17]. A set of design objectives was defined which, when met, would ensure acceptable performance during hover and through high-speed flight. The VERTOL design later evolved to the successful VR-12 family of airfoils. In 1983 engineers at the McDonnell Douglas Helicopter Company embarked on the further refinement of the Lockheed design using the NASA set objectives as design goals.

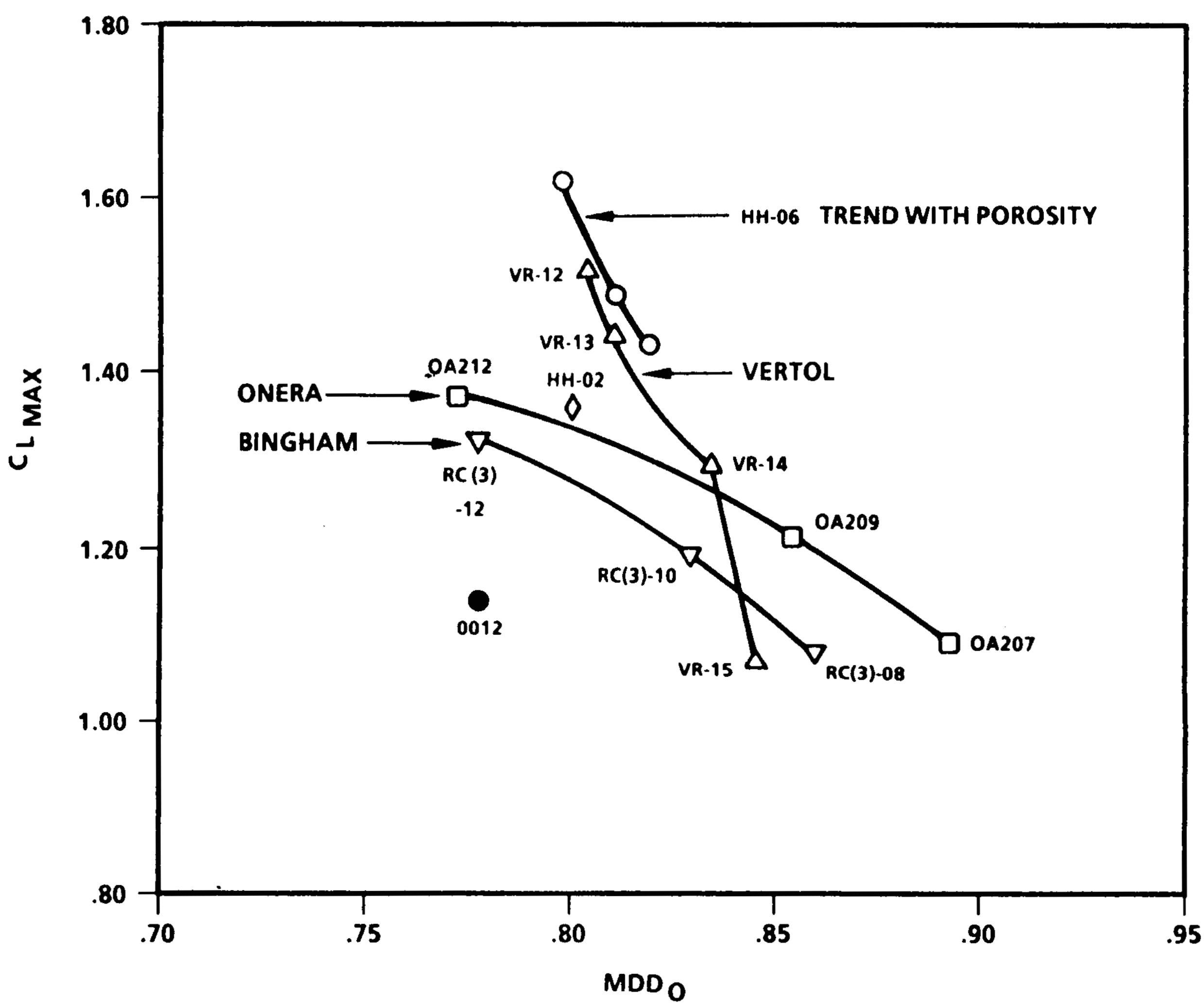
COMPARISON OF HH-06 TEST RESULTS WITH DESIGN OBJECTIVES

	OBJECTIVE	HH–06
	$t/c = .0954$	$t/c = .09542$
First Priority:		
	1) $\lvert C_{M_0}\rvert \leq .01$ $M = .3$	$C_{M_0} = .0014$
	2) $C_{L_{max}} \geq 1.5$ $M = .4$	$C_{L_{max}} = 1.49$
	3) $M_{DD_0} \geq .81$	$M_{DD_0} = .808$
	4) $\lvert C_{M_0}\rvert \leq .015$ $M \leq .80$	$C_{M_0} = -.0055$
Second Priority:		
	5) $C_D \leq .008$ $C_L = .6,\ M = .6$	$C_D = .0094$
	6) $C_{L_{max}} \geq 1.5$ $M = .5$	$C_{L_{max}} = 1.21$
	7) $\lvert C_M\rvert \leq .02$ $C_L = 1.0,\ M = .3$	$C_M = -.0174$
	8) $C_{D_0} \leq .01$ $M = M_{DD_0} + .02$	$C_{D_0} = .0137$ $M = .828$
Third Priority:		
	9) $M_{T_0} \geq M_{DD_0}$	$M_{T_0} = .800$
	10) Gradual Stall $M = .3$ $M = .4$	 MIXED MIXED
	11) $C_{D_0} \leq .007$ $M_{DD} = M_{DD} - .1$	$C_{D_0} = .0070$ $M = .708$

M_{DD} @ $dC_D/dM = .1$ $\qquad$ M_T @ $dC_M/dM = -.25$

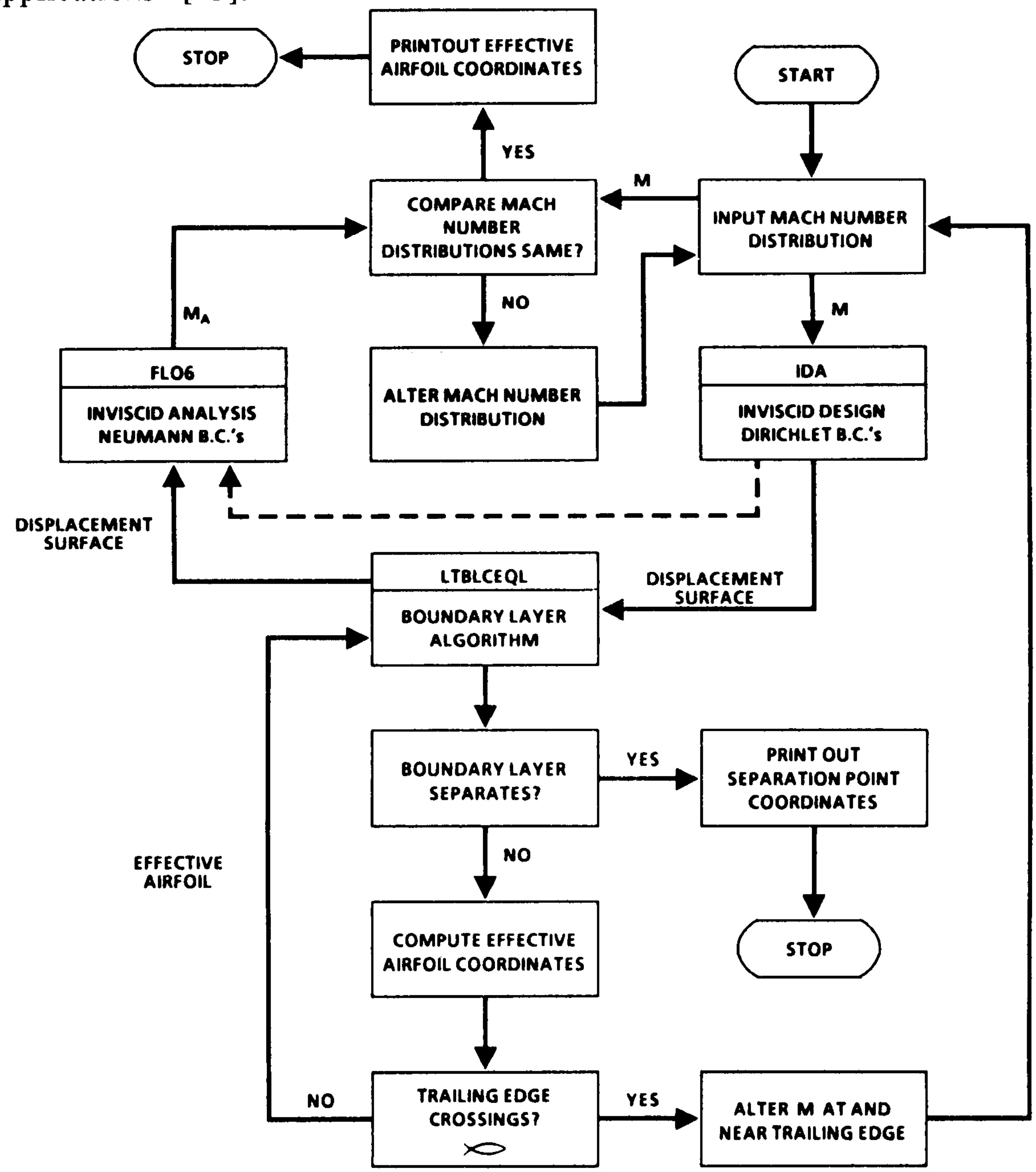
AERODYNAMIC CHARACTERISTICS OF THE HH-06 AIRFOIL

A comparison is made between the aerodynamic characteristics of the designed HH-06 airfoil and those of other airfoils which represent state-of-the-art designs. The comparisons represent the variation in the maximum sectional lift (Clmax) at a free-stream Mach number of 0.40 versus zero-lift drag divergence Mach number. As seen, the HH-06 characteristics compare quite well with the other recently developed families of airfoils [18-21].



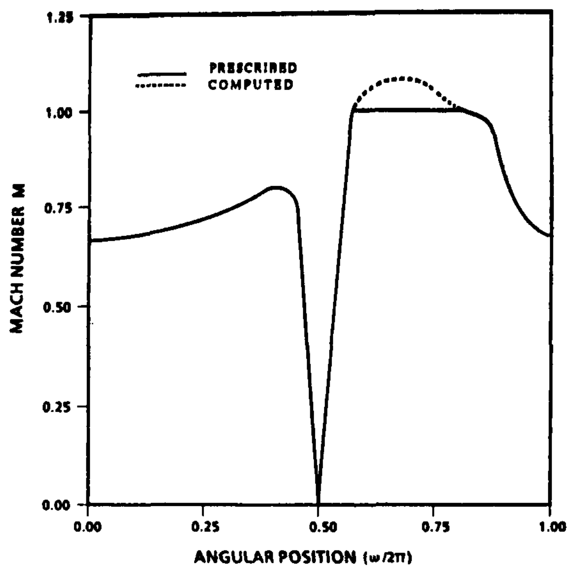
HYBRID DESIGN PROCEDURE

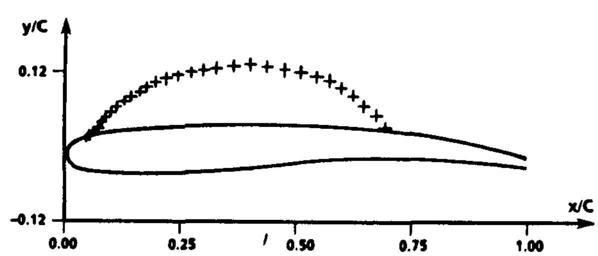
It is obvious that for many practical applications, structural or aerodynamic, that the most desirable design procedure is one which combines the advantages from a direct computational method with those of an inverse method. In this respect, the shortcomings of each are overcome by the strengths of the other. Such methods, commonly referred to as "***Hybrid Methods***" have been successfully applied in the design of subcritical airfoil sections for fixed wing applications [22], and in the design of supercritical cascades for turbomachinery applications [23].



RESULTS OF HYBRID PROCEDURE

The inverse design procedure is based on a conformal transformation of the semi-infinite, two-sheeted Riemann hodograph free-surface representation of the airfoil into the unit circle. The input to the procedure includes a prescription of a target subsonic-sonic pressure distribution (or Mach number) and the free-stream conditions. The analysis of the airfoil configuration which results from the inviscid inverse procedure at design and off-design conditions is carried out using Jameson's [24] full potential solver FLO6. To account for viscous effects, the basic approach is to calculate a boundary - layer displacement thickness and use it to correct the location of the displacement surface. That is, vector subtraction of the displacement thickness from the inviscid displacement surface yields the effective airfoil configuration.



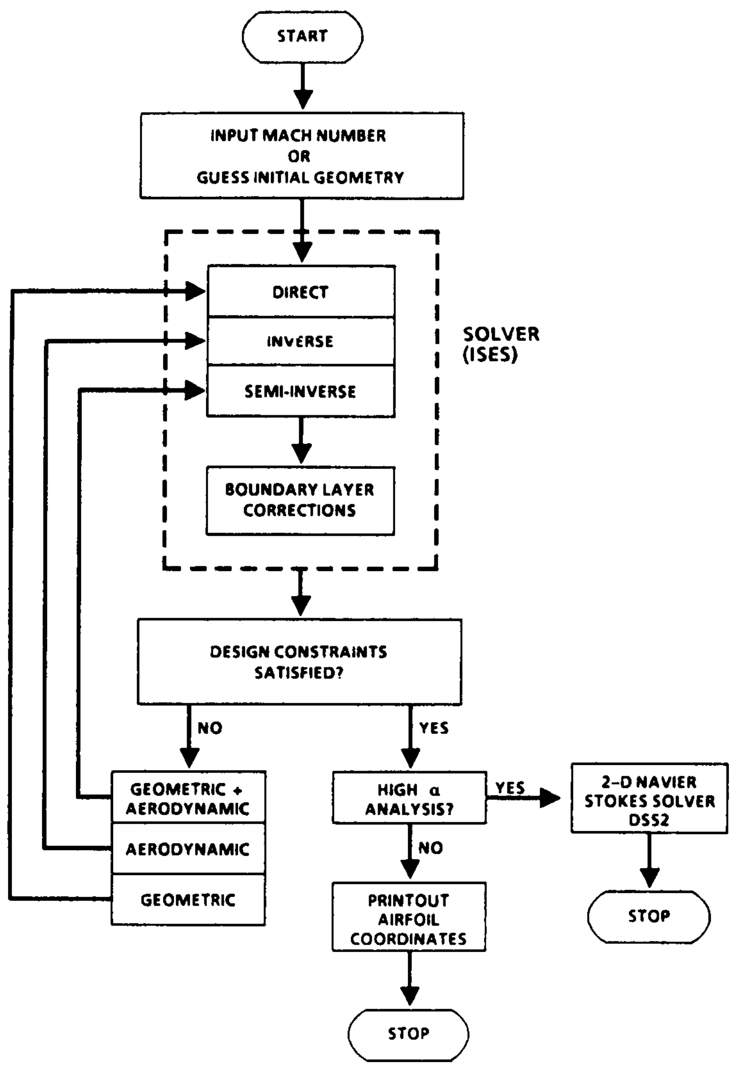


INPUT MACH NUMBER AND RESULTING AIRFOIL

	M	CL	CD	CM	ALFA
DESIGN :	0.75	0.055	0.0093	-0.065	1.30
OFF-DESIGN :	0.40	1.175	0.0124	-0.083	8.24

A PROPOSED EFFICIENT HYBRID DESIGN PROCEDURE

It is apparent that the existing structure of the hybrid design procedure could be further enhanced if a more "*GENERAL*" flow solver assumes the roles of both the existing direct (FLO6) and inverse (IDA) solvers. This in turn, eliminates the required interpolation of the computational results between the two different grid systems.



CONCLUSIONS

- OPTIMIZATION ROUTINES ARE A POWERFUL TOOL FOR FINDING SOLUTIONS TO MULTIPLE DESIGN POINT PROBLEMS

- THE OPTIMIZATION PROCESS MUST BE GUIDED BY THE JUDICIOUS CHOICE OF GEOMETRIC AND AERODYNAMIC CONSTRAINTS

- OPTIMIZATION ROUTINES SHOULD BE APPROPRIATELY COUPLED TO VISCOUS, NOT INVISCID, TRANSONIC FLOW SOLVERS

- HYBRID DESIGN PROCEDURES IN CONJUNCTION WITH OPTIMIZATION ROUTINES REPRESENT THE MOST EFFICIENT APPROACH FOR ROTOR AIRFOIL DESIGN

- UNSTEADY EFFECTS RESULTING IN THE DELAY OF LIFT AND MOMENT STALL SHOULD BE MODELED USING SIMPLE EMPIRICAL RELATIONS

- INFLIGHT OPTIMIZATION OF AERODYNAMIC LOADS (e.g., use of variable rate blowing, flaps, etc........) CAN SATISFY ANY NUMBER OF REQUIREMENTS AT DESIGN AND OFF-DESIGN CONDITIONS

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