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OPTIMIZATION OF A TRANSONIC TURBINE AIRFOIL USING ARTIFICIAL INTELLIGENCE, CFD AND CASCADE TESTING

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ABSTRACT

A transonic turbine airfoil design is optimized using an artificial intelligence engineering design shell coupled with an inviscid, adaptive grid, CFD solver. The objective of the optimization is to minimize the downstream static pressure variation resulting from the trailing edge shock structure. Cascade test results verify the analytical predictions. Techniques are described which were used to couple the optimization shell to the 2-D turbine airfoil shape to allow the search for optimal designs and indicate the quality of those designs. The emphasis of the discussion is upon the application of these techniques rather than the physical details of the resulting blade design.

NOMENCLATURE

L	Total Pressure Loss
c	Axial Chord
x	Axial Distance (Leading Edge = 0.0)
y	Tangential Distance
h	Blade Pitch
P	Pressure
ρ	Density
u	Velocity
M	Mach Number

Subscripts

0	Total Conditions
is	Isentropic Conditions
exit	Cascade exit plane
c	Corrected for Bow Shock
max	Maximum
min	Minimum

Abbreviations

CFD	Computational Fluid Dynamics
CAE	Computer Aided Engineering
GEAE	General Electric Aircraft Engines
GE CR&D	General Electric Corporate Research and Development

Definitions

PSDEVTN	$[(P_{max} / P_{min}) - 1]$, defined for one blade pitch at an axial location downstream of the trailing edge.
M_{2is}	Pitch averaged isentropic Mach number at Station 1
rCu	(radius) x (tangential velocity)
Station 1	x/c = 1.17
Station 2	x/c = 1.67

INTRODUCTION

There have been significant improvements in turbomachinery aerodynamic analysis methods and computer aided design tools over the past decade. The designer has the ability to interactively manipulate geometry to describe any arbitrary shape leading to "custom-tailored" airfoil shapes. Today's CFD methods give the designer the capability of satisfactorily analyzing most aerodynamic shapes for engineering purposes. With the advances in CFD, the capability to analyze any arbitrary shape may be possible in the near future.

Despite these advancements, aerodynamic shape optimization remains a tedious, iterative process. The designer iterates between geometric definition and complex 2-D and 3-D analyses. Interpretation of the analysis results and subsequent geometric manipulation is time consuming. Once a satisfactory aerodynamic design has been completed, there remain many more

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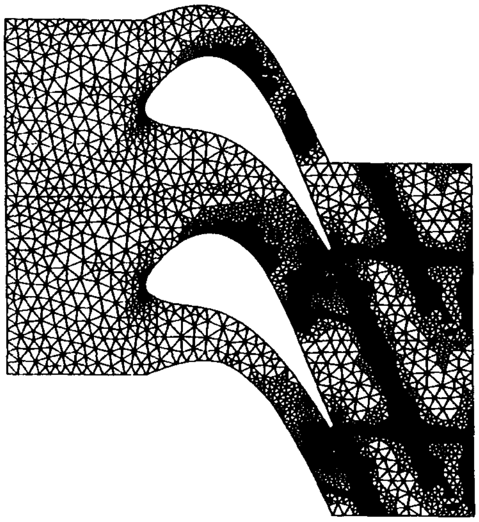


Typical NOVAK2D Solution - Final Unstructured Grid

FIGURE 1

iterations to address mechanical, aero-mechanical, cooling (for cooled turbines), cost, manufacturing, and cycle issues. Turbomachinery designers are always searching for ways to accelerate the process and reduce the product development cycle while improving the design.

In recent years, application of "artificial intelligence" (AI) techniques has become increasingly popular. Application of AI techniques has included preliminary turbine design (Tong and Gregory, 1990), preliminary axial compressor design, and preliminary centrifugal compressor design. Now, AI is becoming a useful tool for detailed aerodynamic design.

The design problem described in this paper is the 2-D aerodynamic optimization of a transonic turbine airfoil. The AI tool used in this optimization is ENGINEOUS, a combined knowledge based, numerical optimization, object oriented code, developed at GE Corporate Research and Development (Ashley, 1992). The aerodynamic analysis tool used is NOVAK2D, an unstructured, adaptive grid, 2-D CFD code also developed at GE CR&D (Holmes and Connell, 1988 and 1990). A typical NOVAK2D final grid for a transonic turbine a foil is shown in Figure (1).

The objective of the optimization is to minimize the downstream shock strength to give a more homogeneous flow field into the downstream blade row. It is expected that homogeneous flow will result in a performance improvement in the downstream blade row. Traditional parameters that are known to strongly influence the downstream shock strength include wedge angle, unguided turning, overturning, and trailing edge thickness. The airfoil suction side contour downstream of the throat is also critical for a transonic turbine airfoil. As the trailing edge suction side shock strength is reduced, the trailing edge pressure side shock typically becomes stronger. This shock will reflect off the adjacent suction side, affecting the downstream flow field. Thus the optimization process becomes a delicate balance between minimizing the suction side trailing edge shock strength and minimizing the strength of the shock reflected from the suction side.

The AI problem becomes one of how to parameterize the airfoil geometry in a manner that will permit numerical optimization while maintaining enough generality to not

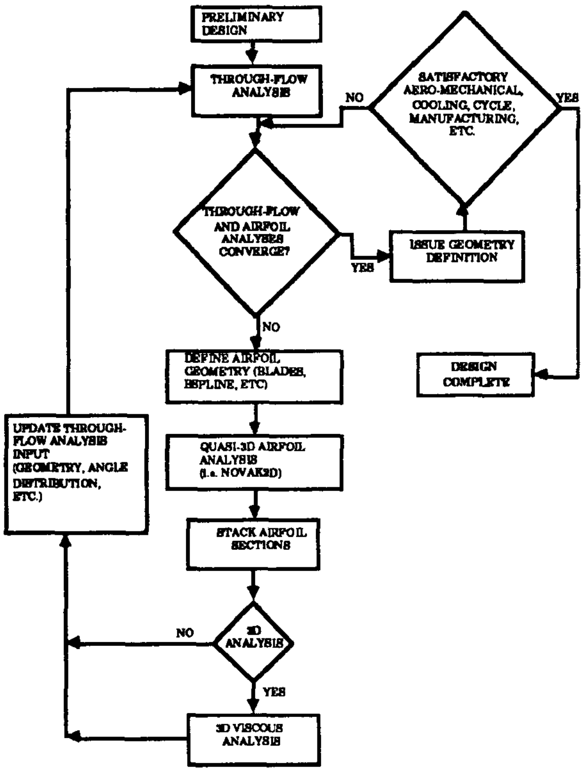


FIGURE 2

arbitrarily limit the design space. Another issue is whether the solution represents a true optimum or a local minimum. This is particularly relevant for a finite thickness trailing edge, which will always produce trailing edge shocks. The objective is to find the best possible solution for a given trailing edge thickness.

TURBOMACHINERY AERODYNAMIC DESIGN PROCESS

Before addressing the application of AI to detailed design, the typical design process must be understood. Initially, in the preliminary design phase, the design is optimized based on vector diagram analysis combined with empirical data to determine the number of stages, maximum tip diameter, minimum hub diameter, a "stick" flow path, stage loading values, pitch line vector triangles, estimates of number of blades and vanes, etc. Then the design enters the detailed design phase.

A brief description of GE Aircraft Engine's turbomachinery detailed design system is given in Figure (2). The basis of the system is a streamline curvature through flow analysis that solves the full circumferentially averaged radial equilibrium equation. The flow path is defined, edge stations are defined, radial angle and efficiency profiles are input and meridional streamlines are calculated from the through flow analysis. Two-dimensional airfoil sections are then defined along the meridional streamlines. A variety of interactive geometry programs are available to define the airfoil depending on the type of design, i.e. turbine or compressor, and the designer's preference. For turbines, the airfoil geometry program typically used is BLADES. BLADES utilizes traditional design parameters such as stagger angle, throat dimension, trailing edge wedge angle, unguided turning, overturning, trailing edge thickness, leading edge thickness, leading edge suction surface angle, leading edge pressure surface angle, suction surface peak point location, pressure surface peak point location, etc. The airfoil contour is defined by splines of third, fourth or fifth order polynomial curves that are constrained by the traditional engineering parameters previously described. The designer must manually manipulate the input parameters to obtain a smooth and continuous curvature distribution in the blade-to-blade plane.

Another geometry program available to the designer is BSPLINE, which describes the airfoil contour using, as the name suggests, B-splines. The designer can add or delete as many B-spline control points as desired to define the airfoil. The designer manipulates the geometry by interactively moving the B-spline control points. Once again, the designer must iterate manually to define a geometry with smooth and continuous curvature. Typically, BLADES is used for most of the design and BSPLINE is used to "fine tune" local regions of the airfoil surface (the nature of BSPLINE makes it cumbersome to make large changes such as stagger angle, trailing edge wedge angle, leading edge suction surface angle, etc.).

After the geometry is described, the airfoil is analyzed in the blade to blade plane with a quasi-3D analysis. The streamline lamina thickness comes from the through flow analysis. Based on the analytical results, the designer changes the airfoil contour. This process is repeated for several meridional streamlines to define airfoils at several spans. The airfoils are then "stacked" to create a 3-D geometry which may include sweep and lean. The designer also checks for a smooth and continuous surface along the span and may have to adjust the airfoil geometry again before proceeding with the analysis. The 3-D geometry is then input to the through flow analysis in the form of its meanline parameters such as lean, sweep and blockage. The quasi-3D analysis results are also input to the through flow analysis in the form of circumferentially averaged angle distributions or rCu distributions. When the through flow analysis is updated, streamlines will shift, and the flow field will change which will subsequently change the airfoil design.

The iteration between the through flow analysis, the geometry definition, and the blade-to-blade quasi-3D analysis continues until the static pressures calculated from the through flow analysis match the circumferentially averaged static pressures from the quasi-3D analysis. This process must be repeated for every blade row, stator and rotor, of the machine. Also, full 3-D viscous analysis of each blade row may be performed at some stage of the process, either before or after the other blade rows have been defined. Then, of course, a larger iteration loop encompasses this process where mechanical, aero-mechanical, cooling, manufacturing, cost, schedule, cycle, and other project issues must be addressed.

As with the geometry programs, there are several blade-to-blade, quasi-3D analysis tools available to the GEAE designer. These quasi-3D analysis tools include inviscid analysis, viscous analysis, coupled inviscid and boundary layer analyses, structured grid, unstructured grid, streamline curvature methods, and inverse design codes. However, for transonic airfoil analysis, NOVAK2D is the preferred code. NOVAK2D utilizes an unstructured, adaptive triangular grid algorithm that increases grid density in regions of high velocity and pressure gradients (Holmes and Connell, 1988 and 1990). This makes NOVAK2D ideal for locating shocks. It also makes NOVAK2D ideal for the ENGINEOUS shell since the NOVAK2D grid will automatically adjust to geometric and aerodynamic changes during the optimization. If a structured grid were used in this particular AI application, there would exist the possibility the shock could be smeared by the grid. The resulting "optimum" design might really represent a clever distortion of the grid rather than a real reduction in shock strength. NOVAK2D also has the option of viscous analysis using a laminar solution, a Baldwin and Lomax turbulence model, or a k-epsilon turbulence model. For the viscous cases, a quadrilateral "o" or "c" grid is used around the airfoil surface and in the wake region.

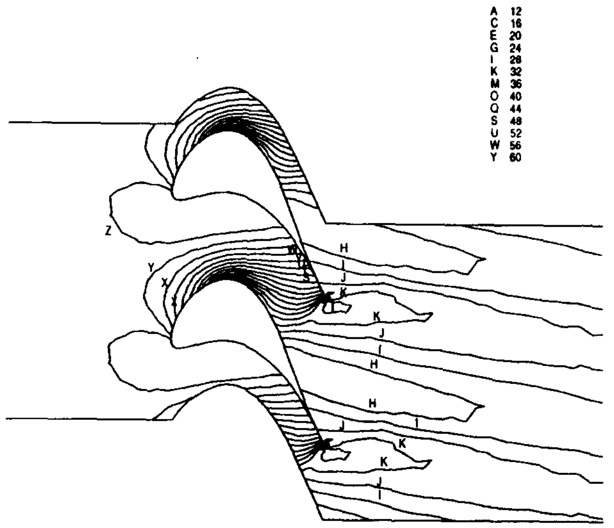
DESIGN APPROACH

For the purposes of this optimization, the inviscid option was used for the NOVAK2D analyses. The inviscid NOVAK2D analysis was previously shown to provide reasonable predictions for transonic turbine airfoil shock location and strength. The viscous option adds considerable computational time to an already CPU-intensive calculation, the coupling of AI with CFD. In addition, the viscous option is not as robust as the inviscid option. Intermediate damping and relaxation are sometimes required during a viscous analysis, which would further complicate the coupling of ENGINEOUS to NOVAK2D.

The chosen approach to the design process was to couple a generic design support tool to the NOVAK2D adaptive unstructured grid Euler solver. ENGINEOUS (Ashley, 1992 and Tong, 1992) is the design tool developed at GE/CRD to provide Artificial Intelligent, numeric, and stochastic based optimization strategies to design tasks for which CAE analysis computer codes exist. In this work, the CAE analysis was provided by NOVAK2D. Given the property that NOVAK2D can be relied upon to automatically obtain good flow solutions, it could be inserted into the ENGINEOUS driven optimization process.

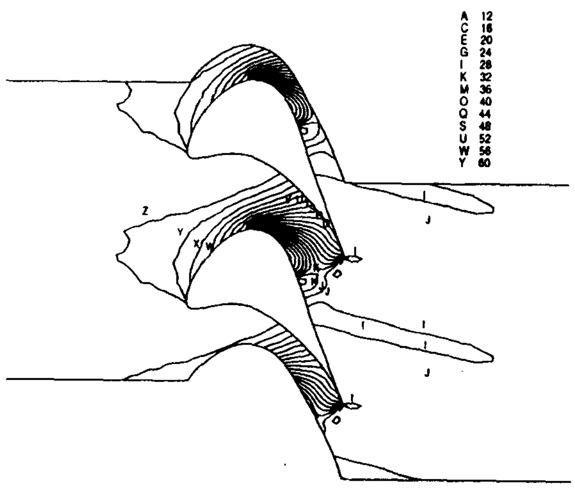
ENGINEOUS is a generic design support system. It is accessed through an X windows based interface, providing support for selecting design variables, multiple optimization search strategies, satisfying constraints, and maximizing or minimizing an objective function. The design is defined for ENGINEOUS in terms of a set of parameters which are considered input parameters. Any result of executing the CAE analysis codes for a particular design is part of the set of output variables. ENGINEOUS starts with some initial design. From the set of input parameters, the design variables are those the user selects to be varied while trying to improve the design. Other input variables are held constant. The search strategies represent various methods for systematically altering the design variables to find some set of design values which optimize the objective function while satisfying any defined constraints (constraints may be defined for input or output variables).

In order to evaluate prospective designs, ENGINEOUS invokes external CAE analysis codes. The CAE input files are created based on current values of the design input parameters, one or more CAE analysis codes are invoked, and the output variables are extracted from the CAE output files to determine the quality of the design according to user selected criteria. Where possible, design knowledge is entered in the rule knowledge base to guide or accelerate the design search. ENGINEOUS uses one or more search strategies to find improvements in the design and to satisfy constraints specified. Being a generic system, ENGINEOUS has



Initial ENGINEOUS Solution
Pressure Contours
M_{exit} = 1.2

FIGURE 3



Final ENGINEOUS Solution
Pressure Contours
M_{exit} = 1.2

FIGURE 4

no built in knowledge specific to aerodynamic design or the type of physics involved. All of this is either entered in the rule knowledge base or is embedded in the CAE application.

The inviscid NOVAK2D output is the Euler equation flow solution over some domain. In order to evaluate each prospective design, the field solution must be reduced to a discrete set of parameters that can be scanned by ENGINEOUS. For this purpose, NOVAK2D computes quantities such as accumulated adverse pressure gradient along the blade surface, flow homogeneity (volume average of the standard deviation of the downstream tangential velocity), and static pressure range just aft of the trailing edge (PSDEVTN). The parameter PSDEVTN, which is defined as $[(P_{max} / P_{min}) - 1]$ for a given blade pitch and downstream axial location, gives an indication of the downstream shock strength. This definition is convenient since PSDEVTN=0 for uniform flow. Basically, any quantity the CAE analysis can compute can be selected as an objective to be minimized.

The objective function chosen for the current design task was to minimize the range of static pressure for a circumferential traverse 17% of an axial chord length downstream of the trailing edge. This location was chosen to correspond to the Station 1 measurement location for the Virginia Tech cascade tests. Large values of static pressure range (PSDEVTN) are generated by the strong trailing edge shock in the Baseline design.

For this work, the simplest ENGINEOUS search strategy was employed, a simple 1D search. In this method, ENGINEOUS selects each design variable in turn to increase and/or decrease its value. Changes which show improvement are pursued until further changes in that direction cease to be favorable. The step size for parameter changes is doubled for successful changes and halved for unsuccessful changes. This simple method is a greedy hill climbing technique which should find the local optimum taking as few steps as possible. This is important due to the execution time requirements of detailed Euler solutions for transonic turbomachinery.

More elaborate search strategies offered in ENGINEOUS may be used in the future. As experience with the system is combined with existing design practice guidelines and engineering know-how, AI rules may be entered into an ENGINEOUS turbine design knowledge base in the form of if-then rules to suggest design changes likely to correct specific design problems. Genetic Algorithms (GA) provide a powerful technique for difficult optimization problems (Goldberg, 1989). GA can be used to find optimal solutions not found by hill climbing and gradient based methods which find the nearest local optimum to the initial design. GA is based on an analogy to evolution of the genetic pools for a species, with parameter "mutation", cross-over, and favored survival of the fittest. GA, however, may be too computationally expensive to be applied to CFD analysis for the foreseeable future. Much success has been demonstrated with other ENGINEOUS applications using dynamic intermingling of several search strategies, referred to as interdigitation (Powell et. al., 1991).

AIRFOIL GEOMETRY

More significant than the choice of optimization algorithms is the specific parameterization by which the turbine blade geometry is manipulated. Engineous uses a discrete set of design parameters to define each design point. The continuous geometry of a turbine blade must be described in terms of discrete parameters in order to be coupled to the design system. We find a large improvement in the gains achieved by Engineous when the design variables may be manipulated one at a time to find improvements in performance. When the change in one design variable does not show any improved performance until several other parameters are also adjusted, it becomes much more difficult for an optimizer to detect the best direction to proceed in design space. This result does not apply only to AI based optimization, but also to numerical optimization methods. The BSPLINE blade design system described earlier provides the coupling of geometry to discrete parameters (design variables) with cubic bspline control points.

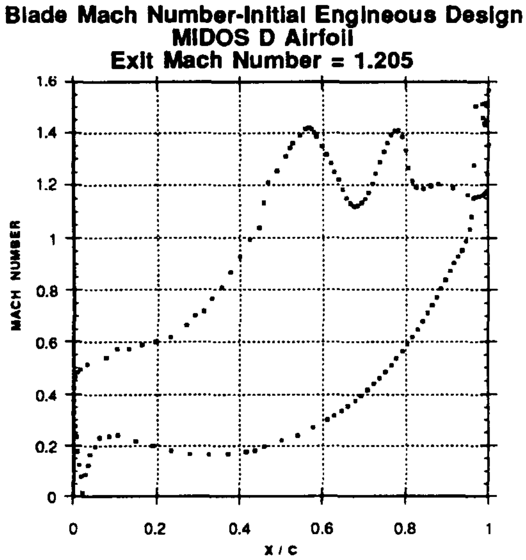


FIGURE 5

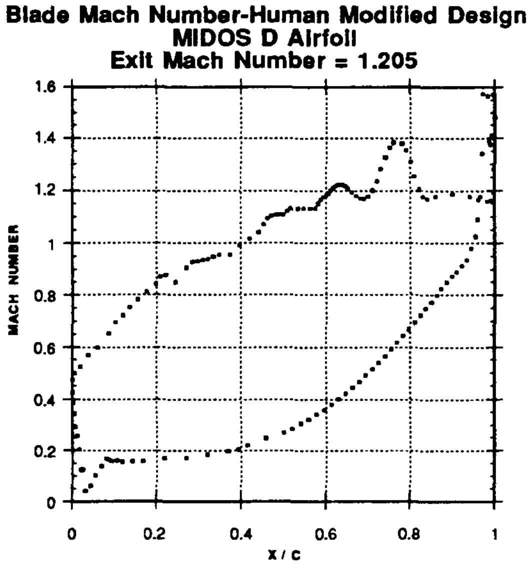


FIGURE 6

In addition, BSPLINE was modified for this study to allow Bezier control points. Both geometric representations provide a well defined mathematical definition of a curve such as a turbine blade, but provide no connection with the engineer's design concepts. To provide this bridge, parameters were chosen to simulate the traditional design concepts (see the BLADES parameters mentioned previously), but expressed in terms of linear combinations of displacements of geometry control points. These parameters are referred to as ESP's, Engineering Significant Parameters. For example, we can displace each control point from its initial position in the circumferential direction an amount linearly decreasing from the leading edge to zero at the trailing edge. Varying this parameter by ten per cent will alter the blade shape in the sense of increasing the blade stagger angle. In making this change, the blade surface curvatures will remain well balanced, particularly with the Bezier geometry.

By combining the geometric curve definition with intuitive design concepts via ESP's, we have the advantages of a rigorous and flexible geometry with familiar design concepts. Now that the design variables are expressed in terms familiar to engineers, it is easier to select a smaller set of design parameters, as well as to express accumulated expertise for blade design in AI rules, both of which will accelerate the design search process. The parametric representation chosen for the optimization process is crucial in a highly non-linear design space like transonic turbine design. To use the stagger angle example again, imagine a designer manually designing a turbine blade for some system. If the designer decides to increase the stagger angle for some reason, several other BLADES parameters will also need to be adjusted to maintain a uniform blade surface curvature distribution. It might be possible to train an expert system to fine

TABLE I

Calculated Downstream Static Pressure Variation

Airfoil	T. E. Thickness % Axial Chord	PSDEVTN x/c = 1.167
MIDOS A	0.5%	0.044
MIDOS B	1.2%	0.143
MIDOS C	2.7%	0.176
MIDOS D	3.7%	0.202
Final Engine MIDOS	3.6%	0.172
Va. Tech MIDOS	3.6%	0.159
Engine Baseline	2.5%	0.472
Va. Tech Baseline	2.5%	0.557

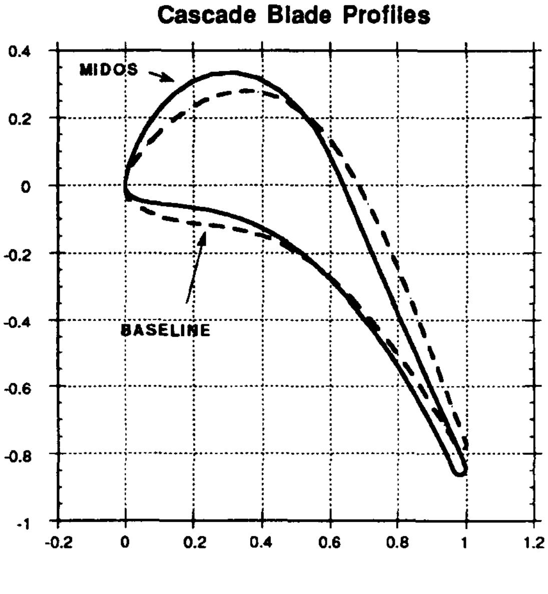


FIGURE 7

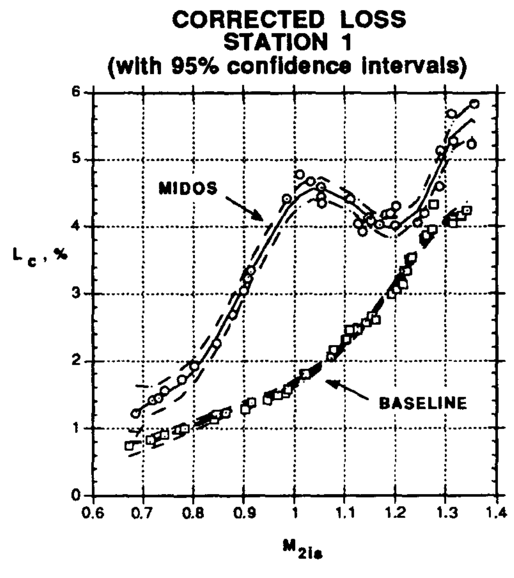


FIGURE 8

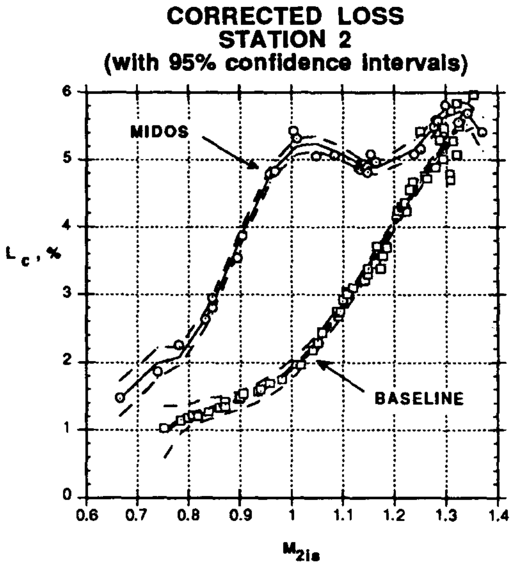


FIGURE 9

tune these other parameters each time the stagger angle is altered. However, this can be avoided by using the ESP stagger angle parameter, which combines the BLADES stagger angle parameter plus the manual fine tuning done by the designer into a single ESP parameter. Now the designer can vary a single parameter and move from one design to another potentially feasible design.

ENGINEOUS RESULTS

In order to validate the ENGINEOUS/NOVAK2D model, a suitable test case was needed. Ideally, for any supersonic exit Mach number, a shock free design should be possible with an infinitesimally thin trailing edge. Therefore, for a sufficiently small trailing edge, ENGINEOUS/NOVAK2D should converge to a nearly homogeneous exit flow field. For this test case, the trailing edge thickness was 0.5% axial chord. In the initial effort, the ENGINEOUS/NOVAK2D model failed to gain any significant improvement (See Figure 3). This was attributed to the simplistic search strategy used in this effort and the fact that no design knowledge base was provided to ENGINEOUS.

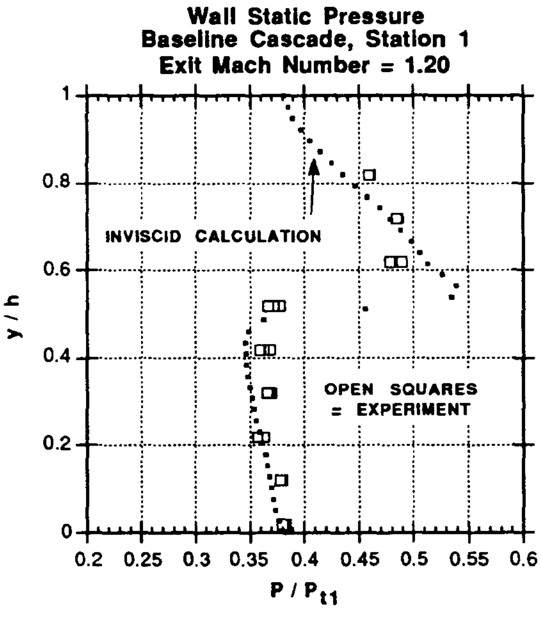


FIGURE 10

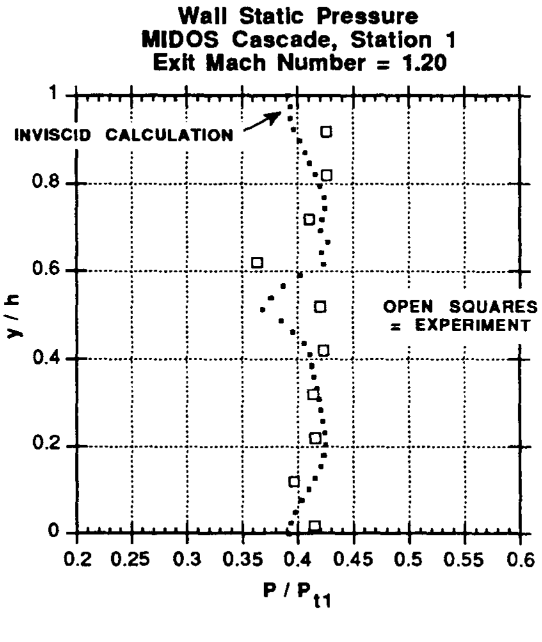


FIGURE 11

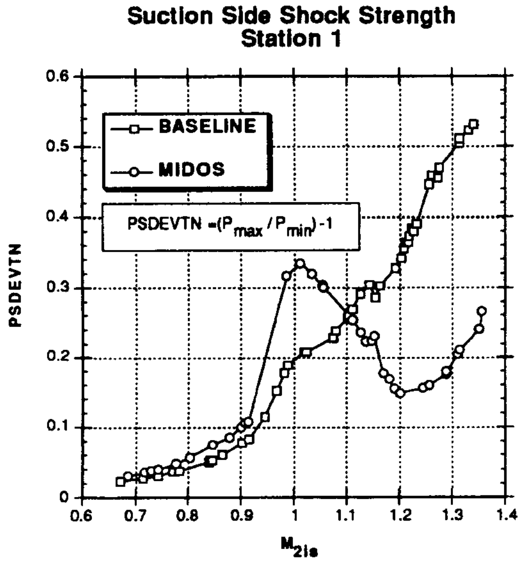


FIGURE 12

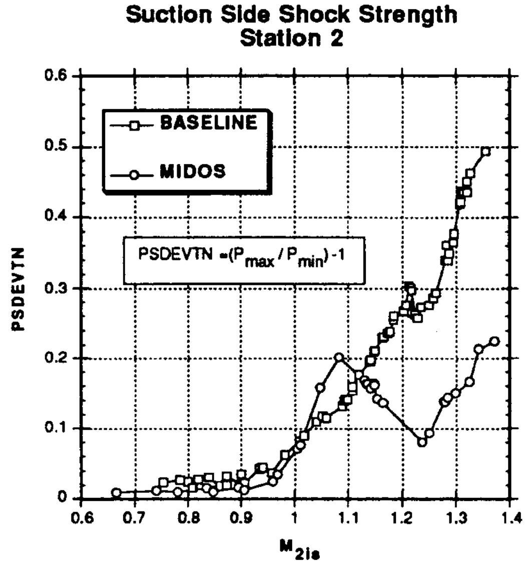


FIGURE 13

Recognizing that the final solution would require a converging-diverging (C-D) passage, the initial airfoil was modified to locate the throat upstream of the trailing edge. This time ENGINEOUS/NOVAK2D iterated to the airfoil shape shown in Figure (4). The resulting downstream flow field was nearly homogeneous. The objective function for this case, PSDEVTN, was 0.04, a significant improvement from the Baseline value of 0.47. This test case verified that the ENGINEOUS/NOVAK2D model would indeed converge to a homogeneous flow field given a sufficiently small trailing edge thickness.

The fact that ENGINEOUS/NOVAK2D failed to gain a significant improvement until an airfoil with a C-D passage was input for the starting solution illustrates that AI systems cannot be used as a "black box". Perhaps with sufficient development, all possible scenarios could be accounted for with rules in a knowledge base, but at present, human intervention and engineering insight are still required to utilize AI effectively.

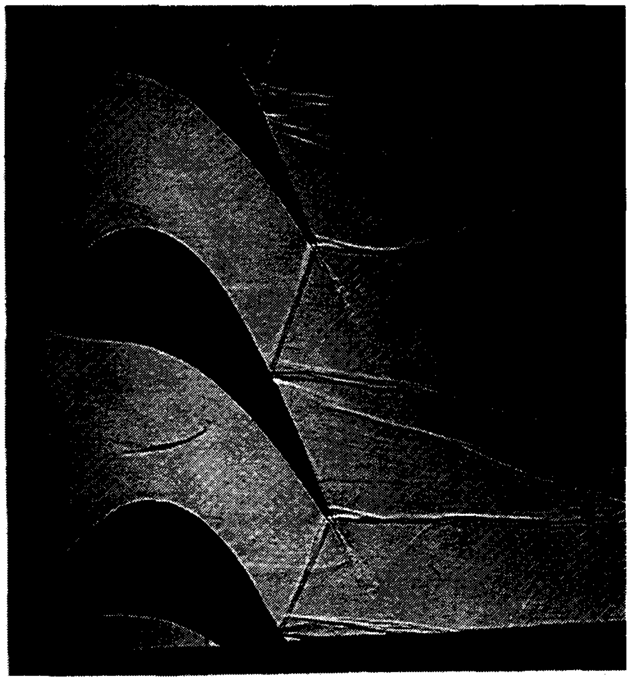
In order to assess the impact of the trailing edge thickness, optimizations were performed for 1.2%, 2.7%, and 3.7% axial chord trailing edge thicknesses. The resulting designs are tabulated in Table 1. The average run required about 80 NOVAK2D solutions with each solution taking about 1 hour on an HP750 work station. The ENGINEOUS portion of the analysis was performed on a Sun work station. All of the resulting airfoil shapes were similar and tended to confirm one's intuition. All of the airfoil shapes have very small wedge angles, very low unguided turning, and a slightly concave suction surface downstream of the throat. The trailing edge thickness has a noticeable effect as indicated in Table 1. However, comparison of the Baseline airfoil with the optimized airfoil indicates that the airfoil shape, including wedge angle, unguided turning, and suction surface contour, dominates the shock strength. Even though the Baseline airfoil has a trailing edge thickness of 2.5% axial chord, the ENGINEOUS designed airfoil with the 3.7% axial chord trailing edge thickness has a reduced shock strength. The airfoil with the 3.7% axial chord trailing edge thickness was chosen from among the various ENGINEOUS designs for further investigation because of cooling considerations. With the small wedge angle, the larger trailing edge thickness was needed for cooling passages.

ENGINEOUS/NOVAK2D was given no constraints for Mach number distribution, which is obvious from the distribution shown in Figure (5). The two peaks in the suction side Mach number are atypical of design practice. Once again, the human engineer intervened and modified the design to obtain a more suitable Mach number distribution, as shown in Figure (6). The manual design effort made one appreciate ENGINEOUS/NOVAK2D as it was very difficult to modify the airfoil shape (12 manual iterations were required) without impacting the suction surface contour that produced the desired results.

The optimized airfoil design became known as the MIDOS airfoil based on the phrase MInimized DOwnstream Shock. For the purposes of testing the airfoils in the Virginia Tech transonic cascade, the airfoils, both the Baseline and the MIDOS, had to be redesigned to accept a zero degree inlet angle. These designs are shown in Figure (7). The airfoils for the Virginia Tech cascade had a 1.5 inch axial chord and a span of 6.0 inches. The Baseline airfoil had a trailing edge thickness of 2.53% axial chord while the MIDOS airfoil trailing edge thickness was 3.60% of axial chord. The manufacturing tolerances were about +-0.002" on the airfoil surface contour. The airfoils were eyelashed to verify that they met the specified tolerance. This was important since there was some concern that the MIDOS airfoil shock characteristics may not be achievable due to manufacturing tolerances.

CASCADE TESTS

The MIDOS blade was tested in the Virginia Tech Transonic Cascade Tunnel to verify the design. The experimental data was also compared to data for the Baseline blade obtained in the cascade tunnel. The blade profiles were compared on the basis of



Baseline Cascade
$M_{2is} = 1.21$

FIGURE 14

MIDOS Cascade
$M_{2is} = 1.21$

FIGURE 15

mass averaged total pressure loss and an estimate of the suction side shock strength.

The Virginia Tech cascade tunnel is a blow-down tunnel with a duration of approximately twenty seconds. Air is supplied to the test section from a four-stage reciprocating compressor and dryer system. The inlet flow angle is restricted to axial. Cascades of eleven blades with a six inch span and 1.5 inch axial chord are placed in the test section. See Shelton et. al. (1992) for a more detailed discussion of the test facility. For the purposes of this experiment, the measurements of interest are the mass-averaged total pressure loss and the suction side shock strength downstream of the cascade trailing edge. The total pressure loss is defined as

$$L = \int_0^h \left[\frac{\rho u(\Delta P_0 / P_{01})}{\rho u} \right] dy.$$

The total pressure deficit ΔP_0 is measured with a traversing differential probe at one of two downstream measuring stations: Station 1 (x/c = 1.167) or Station 2 (x/c = 1.667). The probe measurement is corrected for the bow shock at supersonic Mach numbers. The loss measurements for the Baseline and MIDOS blades at both measurement stations are presented in Figures (8) and (9). Note that the isentropic Mach number is used on these figures, rather than the actual Mach number. At the design Mach number (M_{2is}=1.205) the total pressure loss for the MIDOS airfoil is about 25% greater than the loss for the Baseline airfoil, and the MIDOS airfoil clearly has higher losses below the design Mach number. The likely reasons for the higher off-design losses, while an important factor in the blade design, are not discussed here for brevity. The loss curves have 95% confidence intervals on them (dashed lines), which indicate the range for the true mean value of the loss at a given Mach number. See Shelton et. al. (1992) for further discussion on confidence intervals.

The blade suction side shock strength downstream of the cascade is estimated using a ratio of endwall static pressures (PSDEVTN). Ten endwall taps covering one blade pitch are mounted in the cascade endwalls at each measuring station. Example measurements at Station 1 are shown for each cascade in Figures (10) and (11) and are compared with the inviscid calculated values from NOVAK2D.

The suction side shock strength is estimated by a ratio of the maximum and minimum measured values of wall static pressure (PSEDVTN). Because of the discontinuous nature of shocks, this is not a good method for measuring the actual strength of the shock wave but is a simple and useful experimental comparison. From Figures (12) and (13) it is clear that the MIDOS design reduced the suction side shock strength as compared to the Baseline case. Defining PSDEVTN=0.0 to be a 100% reduction in shock strength, the MIDOS reduction is about 50% at Station 1 and 67% at Station 2. Shadowgraph pictures of the two blades at the design Mach number are shown in Figures (14) and (15).

DISCUSSION OF RESULTS

The airfoil shock characteristics can be understood by analogy to simple 1-D oblique shock and Prandtl-Meyer expansion theory. The Baseline and MIDOS designs differ in two major features, which are unguided turning and wedge angle. Both the Baseline and MIDOS airfoils accelerate the suction side Mach number to nearly 1.4 in order to generate the necessary lift to turn the flow. In both cases, the suction side Mach number is then sharply

Blade Mach Number - Baseline Cascade
Exit Mach Number = 1.205

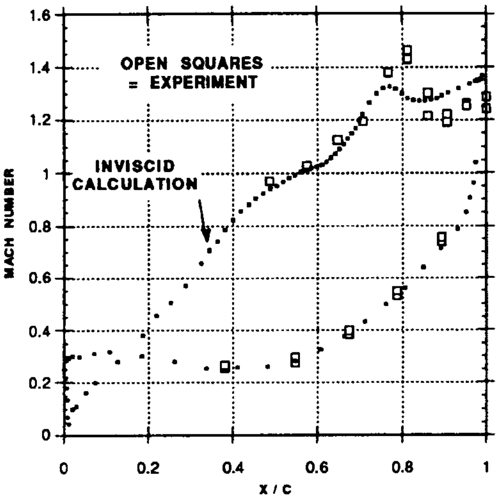


FIGURE 16

Blade Mach Number - MIDOS Cascade
Exit Mach Number = 1.205

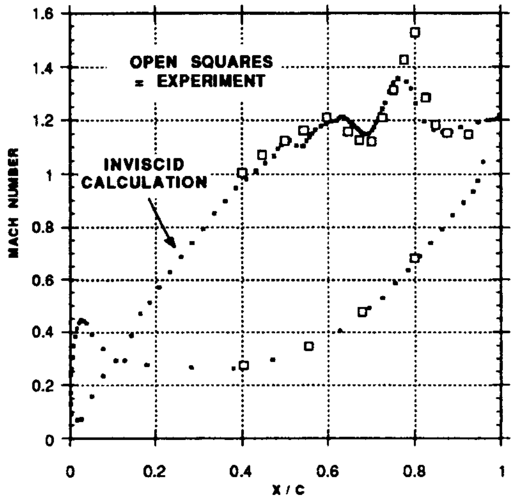


FIGURE 17

reduced, in part due to the cross passage shock emanating from the pressure side of the trailing edge.

On the Baseline airfoil, the suction side Mach number continues to increase to a value of almost 1.3 at the trailing edge due to about 10 degrees of unguided turning (see Figure 16). The cascade exit Mach number is 1.2. Therefore, a strong oblique shock is formed at the trailing edge which turns and compresses the flow to match the downstream boundary conditions. On the pressure side, the Mach number does not become sonic until the tangency point of the trailing edge semicircle. Now the flow must accelerate to match the downstream boundary condition but it can only do this through turning in a Prandtl-Meyer type expansion. Therefore, it must accelerate past Mach 1.2 and then be turned and recompressed in an oblique shock to match the downstream boundary condition.

The MIDOS airfoil Mach number distribution is different (see Figure 17). Because of the low unguided turning and the suction surface contour, the suction side Mach number only reaches 1.22 at the trailing edge. This flow only has to be turned and compressed slightly to match the downstream boundary conditions. On the pressure side, the C-D passage causes the pressure side Mach number to go supersonic before the trailing edge semicircle tangency point. Because of the small wedge angle and the supersonic Mach number, much less acceleration and recompression is required than with the Baseline airfoil. Of course in both cases, there is the finite thickness trailing edge which will cause an over expansion and re-compression shock structure. This shock structure due to trailing edge thickness interacts with the shock structure created by the airfoil aerodynamics. Neither the inviscid analysis nor the small scale of the cascade test permits a reasonable discussion of this aspect of the flow field.

The analytical predictions also suggested that the shock strength attenuates as it passes through the wakes of the airfoils positioned above it in the cascade. Since the analysis was inviscid, it was not known if this was a real or numerical phenomenon. However, as shown in Figures (12) and (13) the measured shock strength for both the Baseline and MIDOS airfoils diminishes somewhat between measurement Stations 1 ($x/c = 1.167$) and 2 ($x/c = 1.667$).

At the design point, M=1.21, the loss for the MIDOS airfoil is about 25% greater than the Baseline. This is to be expected since the trailing edge thickness is 42% larger on the MIDOS airfoil. Also, Denton and Xu (1990) pointed out that reduced unguided turning is likely to increase the shock loss. While the suction side shock strength is reduced, the cross passage shock emanating from the pressure side of the trailing edge is strengthened. These trends were also observed by Shelton et. al. (1992). Off-design, the MIDOS airfoil performs significantly worse than the Baseline with more than double the loss in the M=1.0 to 1.05 region. This fact plus increased losses at the design point must be weighed against the benefit of increased downstream blade row performance.

FUTURE OF AI IN DETAILED DESIGN

The authors of this paper are optimistic about the future potential for using AI in the detailed aerodynamic design process. The 2-D transonic airfoil optimization is simple compared to the scope of the entire design process. Yet, it is a difficult manual design due to the sensitive nature of the suction surface contour and the balancing of the suction side trailing edge shock and the reflected cross-passage shock. Optimizing a 3-D design is an order of magnitude more difficult with features such as lean and sweep in the design. Then of course, the stage must be optimized and finally, the entire machine.

With the ever increasing economic pressures for reduced product development time, AI may be the only feasible way to take advantage of the advances in CFD analysis methods. AI permits the designer to focus his time and energy on understanding the physics and optimizing the design as opposed to exercising analysis and geometry codes.

ENGINEOUS/NOVAK2D is a form of the so-called inverse design tools, but it has several advantages over traditional methods. Typical inverse design tools satisfy some specified Mach number distribution or rCu distribution that the user inputs. This presupposes the user knows what Mach number distribution or rCu distribution he wants. As in this case, the user may know what end result he wants and the design parameters that will influence the design, but what Mach number or rCu distribution that will give the desired result is unknown.

ENGINEOUS permits the designer to optimize any output parameter or combination of output parameters. ENGINEOUS can run parametric studies to give the designer insight into the design. Also, by coupling the ENGINEOUS shell to programs the designer is already familiar with, the designer has the capability of intervening in the process to gain the desired result. However, in order for Engineous or other optimization systems to incorporate design requirements and objectives, the requirements must be reduced to numerical values. Consider the manual redesign described which modified the blade surface Mach number distribution from that in Figure (5) to that in Figure (6). In order to include this redesign objective in the automated design process, we must devise a variable that has a lower value for the Figure (6) distribution than for the Figure (5) distribution, or other undesirable designs. An example of such a variable would be the magnitude of the largest range between a consecutive suction surface local Mach number maximum and local minimum. Designs with large values of this measure would be prone to boundary layer separation with subsequent losses not modeled in an inviscid flow solution.

The next logical step in the development of ENGINEOUS/NOVAK2D is to employ the viscous option to optimize loss. Also, multiple NOVAK2D analyses could be added to each ENGINEOUS iteration so that optimizing the airfoil characteristic for a range of Mach numbers may be possible. Another potential use would be to optimize several spans of a blade or vane to create a "pseudo-3D" optimization. In the long term, full 3-D optimization and stage optimization may be possible.

Despite the great potential for incorporating AI into detailed design, the engineer cannot be eliminated from the design process. Attempts to design "black box" systems will fail because the authors of the system cannot anticipate every possible use or need of the systems. The interaction of the engineer and an AI system is what holds the most promise. AI becomes a tool which permits the engineer to become more creative, far more productive, and gain more insight into the design than otherwise possible in the time frame allotted for the design.

CONCLUSIONS

1) Artificial intelligence tools can be combined with CFD analyses to optimize 2-D aerodynamic shapes.

2) The trailing edge shock structure for a transonic turbine airfoil is a strong function of design parameters such as wedge angle, unguided turning, and suction surface contour as well as trailing edge thickness.

3) Therefore, the designer has the capability to strongly influence the transonic turbine airfoil shock structure regardless of trailing edge thickness.

4) Artificial intelligence tools become most effective with intervention and interaction by the engineer.

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