NASA/TM–1998-208754

Neural Net-Based Redesign of Transonic Turbines for Improved Unsteady Aerodynamic Performance

Nateri K. Madavan and Man Mohan Rai
Ames Research Center, Moffett Field, California

Frank W. Huber
Riverbend Design Services, Palm Beach Gardens, Florida

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035-1000

November 1998

Available from:

NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at (301) 621-0134

- Telephone the NASA Access Help Desk at (301) 621-0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076-1320

Neural Net-Based Redesign of Transonic Turbines for Improved Unsteady Aerodynamic Performance

NATERI K. MADAVAN, MAN MOHAN RAI, and FRANK W. HUBER*
Ames Research Center

Summary

A recently developed neural net-based aerodynamic design procedure is used in the redesign of a transonic turbine stage to improve its unsteady aerodynamic performance. The redesign procedure used incorporates the advantages of both traditional response surface methodology (RSM) and neural networks by employing a strategy called parameter-based partitioning of the design space. Starting from the reference design, a sequence of response surfaces based on both neural networks and polynomial fits are constructed to traverse the design space in search of an optimal solution that exhibits improved unsteady performance. The procedure combines the power of neural networks and the economy of low-order polynomials (in terms of number of simulations required and network training requirements). A time-accurate, two-dimensional, Navier-Stokes solver is used to evaluate the various intermediate designs and provide inputs to the optimization procedure. The optimization procedure yields a modified design that improves the aerodynamic performance through small changes to the reference design geometry. The computed results demonstrate the capabilities of the neural net-based design procedure, and also show the tremendous advantages that can be gained by including high-fidelity unsteady simulations that capture the relevant flow physics in the design optimization process.

A patent application that covers some of the original ideas in this report has been filed by NASA. This report has been submitted for review toward presentation at the 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, June 20-24, 1999, Los Angeles, CA.

*Riverbend Design Services, Palm Beach Gardens, Florida.

Introduction

The aerodynamic design of transonic high pressure (HP) aircraft engine turbines is complicated by the presence of shocks, wakes, tip leakage, and other secondary flow effects in the flow field. These shocks, wakes, and vortical flows are ingested by downstream stages, resulting in complex interactions with one another and with the flow in these stages. All of these effects are complicated further by the inherent unsteadiness of the flow field that results from the relative motion of the rotor and stator rows and gives rise to unsteady interactions both within the HP turbine stages and between the HP turbine and the adjacent low pressure (LP) turbine stages. These unsteady interactions may be large enough to affect the time-averaged features of the flow. Cooling and heat transfer are also important considerations in the design process, since most HP turbine blades are typically cooled to withstand high operating temperatures. The heat transfer is closely coupled to the unsteady aerodynamics and is often affected greatly by it. However, heat transfer will not be addressed in this article since the emphasis here is on aerodynamic design.

Several experimental investigations of transonic turbines aimed at characterizing shock formation (ref. 1), unsteady stage interactions (ref. 2), heat transfer effects (ref. 3), and other physical flow phenomena involved have been carried out over the years. Various numerical investigations of these flow fields ranging from single blade row computations to time-accurate Navier-Stokes computations in two dimensions (ref. 4, 5, 6) and more recently in three dimensions (ref. 7, 8) have also added to our understanding of these flows.

Modern HP turbines are usually composed of either one or two stages. Two-stage turbines are longer and heavier but are subsonic and usually more efficient (ref. 8). Single-stage turbines are lighter and compact but operate in the transonic regime and suffer efficiency penalties due to shock losses and high aerodynamic blade loadings (ref. 8). Typically, weak oblique shocks occur at the stator and rotor airfoil trailing edges. The stator vane shock interacts with adjacent stator vanes and downstream rotor blades to set up a complex pattern of direct and reflected shock waves (see Giles (ref. 4) and Abhari et al. (ref. 5) for instructive illustrated descriptions) within the stage. The rotor blade trailing edge shock on the other hand interacts with the downstream LP stage. The efficiency penalties resulting from these shocks can be quite large. For example, Giles (ref. 4) notes that the unsteady shocks are responsible for a 40% variation in the lift on the rotor, resulting in structural vibrations, increased losses, and temporary leading edge boundary layer separation on the rotor suction surface; Jennions and Adamczyk (ref. 8) report a turbine design where it was speculated that a 5.6% loss in efficiency was due largely to the HP rotor shock interactions with the LP turbine stator vanes. Even in two-stage designs that are designed to operate in the subsonic regime, there is the potential for unsteady shocks in the flow field with high blade loadings. Because of the detrimental effects of these shocks, such as degraded aerodynamic performance, unsteady stresses, fatigue, vibration, and reduced blade life, designers have to pay special attention to them. A design optimization method that would help the designers in their efforts to mitigate the effects of these shocks would serve as a very useful tool.

A variety of formal optimization methods have been developed in the past and applied to turbine design. These include inverse design methods (see, e.g., Demeulenaere and Van den Braembussche (ref. 9)), blade shape optimization procedures (see, e.g., Chattopadhyay et al. (ref. 10)), and multidisciplinary optimization procedures that integrate the heat transfer and aerodynamic effects (ref. 11). The gas turbine industry has also been incorporating design optimization techniques in the turbine design process for some time now. There are several references in the literature (see, e.g., Tong and Gregory (ref. 12), and Shelton et al. (ref. 13)) dealing with the use of a commercially available optimization environment (iSight) in preliminary design as well as design optimization. However, most of this work has its basis in traditional numerical optimization procedures.

More recently, the authors have developed a different approach to turbomachinery blade design optimization that is based on neural networks (ref. 14, 15). This method offers several advantages over traditional optimization procedures. First, neural networks are particularly suitable for multidimensional interpolation of data that lack structure. They can provide a greater level of flexibility than other methods in dealing with design in the context of unsteady flows, partial and complete datasets, combined experimental and numerical data, the need to include various constraints and rules of thumb, and other features that characterize the aerodynamic design process. Second, neural networks provide a natural framework within which a succession of numerical solutions of increasing fidelity incorporating more and more of the relevant flow physics can be represented and utilized subsequently for optimization. Third, and perhaps most important, neural networks offer an excellent framework for multidisciplinary design optimization. Simulation tools from various disciplines can be integrated within this framework. Efficient use can also be made of parallel computing resources. Rapid trade-off studies across one or many disciplines can also be performed.

While neural networks have been used in other applications, including aeronautics, for some time now, their application to turbine design optimization is relatively new. The only other reference in this area is the work of Sanz (ref. 16), who uses a neural network to determine, from a database of input pressure distributions, a pressure distribution that would produce the required flow conditions. An inverse design method is then used to compute the airfoil shape that corresponds to this desired pressure distribution. In other work (ref. 17), although not directly related to neural networks, a turbine aerodynamic design method is developed that is based on an evolutionary optimization technique and uses "reinforcement learning" to learn adaptively from the design environment.

This paper reports on continuing work by the authors in developing a neural network-based turbomachinery blade design method. It deals with the application of this method (ref. 15) to the redesign of a transonic HP turbine with the goal of improving its unsteady aerodynamic performance. The turbine chosen here is a two-stage configuration with an aggressive design characterized by high turning angles and high specific-work per stage (ref. 18). Our interest is in the first stage of this configuration. Although the turbine is designed to operate in the high-subsonic regime, an unsteady analysis shows very strong interaction effects due to the presence of an unsteady moving shock in the axial gap region between the stator and rotor rows. It is hypothesized that the strength of this shock can be reduced by optimizing the airfoil geometries, and the overall unsteady aerodynamic performance of the turbine can thereby be improved. Since the shock can only be discerned by an unsteady aerodynamic analysis, a time-accurate Navier-Stokes solver (ref. 19) is coupled to the neural net-based optimizer and provides simulation inputs to it. The results presented here demonstrate that the neural-net based optimization method yields a modified design that is very close to the reference design and achieves the same work output, yet has better unsteady aerodynamic performance since the flow through it is shock-free.

The rest of this report deals with the application of the design optimization method of Rai and Madavan (ref. 15) to the redesign of a transonic HP turbine. The design goal is to improve its unsteady aerodynamic performance. Details regarding the redesign procedure and the results obtained are discussed in the following sections.

The Reference Design

The transonic turbine that is considered for redesign in this report is a preliminary design developed by Pratt and Whitney for a new generic gas generator (G^3) turbine (ref. 18). This turbine is designed to operate in the high-subsonic regime. Table 1 lists all the relevant flow and geometry parameters for the turbine, a two-stage configuration that is characterized by very high turning angles (160 deg. in the rotor passage) and high specific work per stage. Further, low-convergence airfoil shapes are used for the rotor blades. All these features made the design process for this turbine very critical. In particular, the 160 deg. turning angle was well above most existing designs. Because this design was so far beyond the range of their existing data base, the designers were unsure of the effects of unsteady interactions on turbine performance. A post-design unsteady time-accurate analysis of the flow was performed (ref. 6) as a final evaluation of the design. This analysis revealed significant unsteady effects and an unsteady shock on the suction surface of the stator that spanned the gap region and impinged on the rotor blades as they passed by the stator airfoils. The position of this unsteady moving shock on the stator suction surface and its strength oscillated periodically in time at blade-passing frequency. The shock is entirely due to the stator-rotor interaction and any analysis that does not account for this interaction will fail to indicate the presence of the shock (ref. 6). On the basis of these findings, a design modification that increased the axial gap between the stator and rotor rows (from 30% of mean chord to 75% of mean chord) was recommended. Unsteady analysis of this modified design showed that the flow through the stage was shock-free. The uncooled stage efficiency of the modified design was also higher, and the overall performance level was closer to that expected by the designers. The reference design in this report is the original design without the axial gap modification.

Table 1. Geometry and flow parameters for the reference and modified designs. All angles are measured from the axial direction.

Parameter	Reference Design	Modified Design
Number of stator vanes	38	38
Number of rotor blades	52	52
Pressure ratio across stage	0.455	0.455
Unit Reynolds Number at stator inlet (per inch)	490,000	490,000
RPM	24,000	24,000
Ratio of specific heats	1.3699	1.3699
Stator inflow angle	0.0°	0.0°
Stator outflow angle	83.2°	83.2°
Rotor-relative inflow angle	79.4°	79.4°
Rotor-relative outflow angle	-82.0°	82.0°
Stator inflow Mach number	0.0585	0.0587

The Redesign Procedure

General Objective

In this report we use our recently developed neural net-based turbomachinery airfoil design procedure to improve the reference design by successfully mitigating the effects of the unsteady shock. We accomplish our redesign objective by optimizing the shape of the airfoils while maintaining the original axial gap (30% of mean chord). Our purpose is to demonstrate the capabilities of our method in unsteady design and also to show the tremendous advantages that can be gained by including high-fidelity unsteady simulations that capture the relevant flow physics in the design optimization process.

Airfoil Geometry Parameterization

Geometry parameterization and prudent selection of design variables are among the most critical aspects of any shape optimization procedure. Since this study focuses on airfoil redesign, the ability to represent various airfoil geometries with a common set of geometrical parameters is essential. Variations of the airfoil geometry can be obtained then by smoothly varying these parameters. Geometrical constraints imposed for various reasons, structural, aerodynamic (e.g., to eliminate flow separation), etc., should be included in this parametric representation as much as possible. Additionally, the smallest number of parameters should be used to represent the family of airfoils.

The method used for parameterization of the airfoil geometries is described in Rai and Madavan (ref. 15) and is reviewed here for completeness. Figure 1 illustrates the method for a generic airfoil. Some salient features of the method are noted:

1. The leading edge is constructed using two different ellipses, one for the upper surface and one for the lower surface. The eccentricity of the upper ellipse and the semi-minor axes of both ellipses are specified as geometric parameters (e_u, t_u, and t_l), respectively. All other related parameters can be determined analytically. The major axes of both ellipses are aligned with the tangent to the camber line at the leading edge. This tangent is initially aligned with the inlet flow but is allowed to rotate as the design proceeds. The angles α_u and α_l determine the extent of the region in which the leading edge is determined by these ellipses. The two ellipses meet in a slope-continuous manner.

2. The trailing edge can also be constructed in a similar manner with the major axes of the ellipses aligned with the tangent to the camber line at the trailing edge. However, in this study the trailing edge was defined using a single circle. The angles β_u and β_l determine the extent of the region in which the trailing edge is determined by this circle.

3. The region of the upper surface between the upper leading edge ellipse and the trailing edge circle is defined using a tension spline. This tension spline meets the leading edge ellipse and the trailing edge circle in a slope-continuous manner. Additional control points for the tension spline that are equispaced in the axial direction are introduced as necessary. These points provide additional control over the shape of the upper surface. The lower surface of the airfoil between the lower leading edge ellipse and the trailing edge circle is obtained in a similar manner.

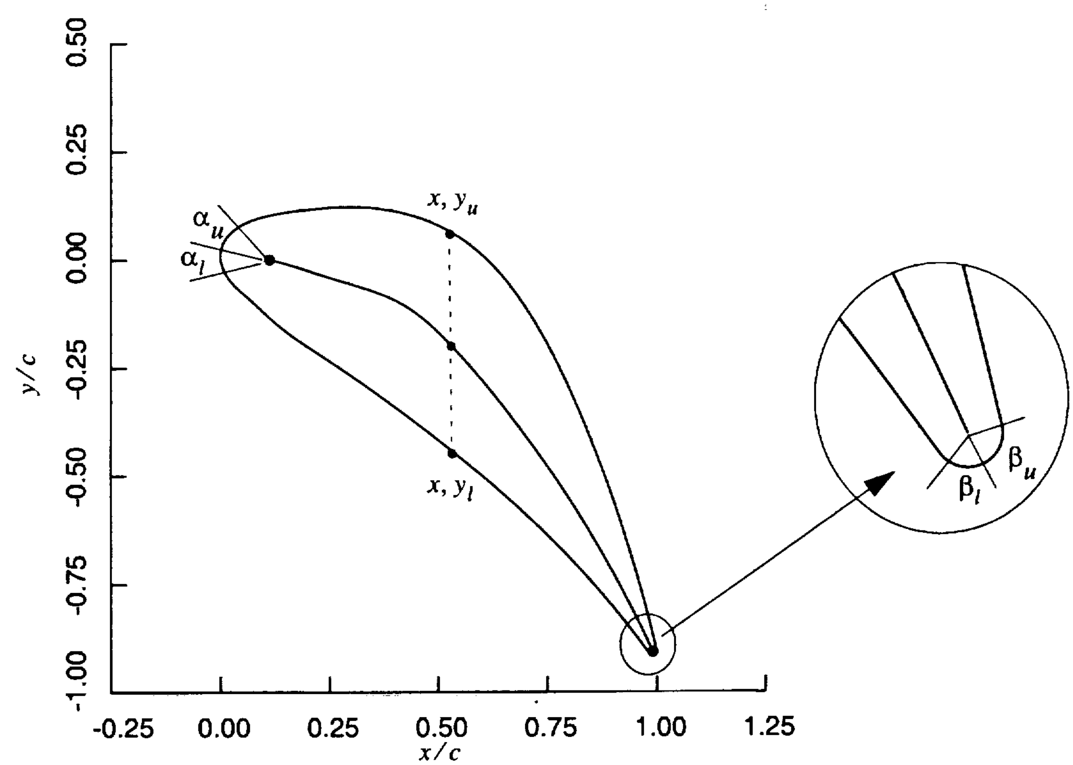

Figure 1. Schematic of a generic airfoil showing location of nodal points on the airfoil surface and the defining angles used in the parameterization of the airfoil geometry.

A total of 13 geometric parameters were used to define the airfoil geometries in the current study. These parameters are listed below:

(1) Leading edge and trailing edge airfoil metal angles (2 parameters).

(2) Eccentricity of upper leading edge ellipse (1 parameter).

(3) Angles defining the extent of the leading edge ellipse (2 parameters).

(4) Angles defining the extent of the trailing edge circle (2 parameters).

(5) Airfoil thickness values at the leading edge (2 parameters).

(6) Airfoil y-coordinate values (see fig. 1) at mid-chord on the upper surface and lower surfaces (2 parameters).

(7) Airfoil y-coordinate values (see fig. 1) at intermediate points on the upper surface (2 parameters).

These parameters were adequate to obtain an accurate representation of the reference airfoils, and acceptable modified shapes required by the optimization procedure could be obtained by varying these parameters.

Unsteady Aerodynamic Analysis

Unsteady aerodynamic analyses of the turbine stage configurations required during the redesign process were obtained using the ROTOR-2 computer code (ref. 19). This code solves the unsteady, two-dimensional, thin-layer Navier-Stokes equations for rotor-stator configurations in a time-accurate manner. Three-dimensional effects of streamtube contraction are also modeled. The computational method used is a third-order-accurate, iterative-implicit, upwind-biased scheme that solves the time-dependent, Reynolds-averaged Navier-Stokes equations. Details regarding the solution methodology can be found elsewhere (ref. 19).

The flow domain is discretized using a system of patched and overlaid grids; the grids attached to the rotor airfoils can move relative to the grids attached to the stator airfoil to simulate the rotor motion. Figure 2 shows the stator and rotor airfoil cross sections at midspan for the reference turbine design. The reference design has 38 airfoils in the stator row and 52 in the rotor row. To simulate this flow at least 19 stator airfoils and 26 rotor airfoils would have to be modeled as a system. The computational expense of such a simulation can be reduced considerably by modifying the number of stator airfoils to 39, since this would permit a simulation with three stator and four rotor airfoils as a system with periodicity conditions to account for the rest of the airfoils. The modification of the stator airfoil count is accomplished by rescaling the stator geometry by a factor of 38/39 and keeping the pitch-to-chord ratio the same as the actual design. This rescaling is relatively minor and is not expected to significantly alter most of the relevant features of the flow.

Figure 2 also shows the grid system used to discretize the flow domain. Each airfoil has two grids associated with it: an inner "O" grid that contains the airfoil and an outer "H" grid that conforms to the external boundaries. For the analyses performed here, each inner O-grid has 151 points in the circumferential direction and 41 points in the wall-normal direction. Each outer H-grid has 100 points in the axial direction and 71 points in the transverse direction. For the sake of clarity, only some of the grid points are shown in figure 2.

The dependent variables are initialized to freestream values and the equations of motion are then integrated to convergence, subject to the boundary conditions. The flow parameters that are specified are the pressure ratio across the turbine airfoil (ratio of exit static pressure to inlet total pressure), the inlet Mach number, and the inlet flow angle.

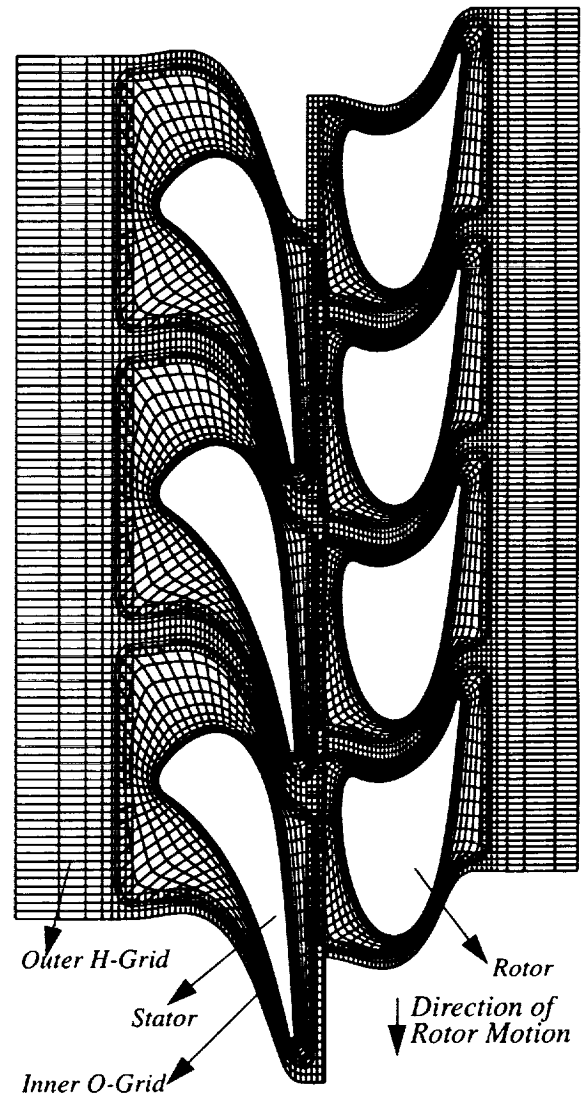

Figure 2. Turbine geometry (at midspan of reference design) and computional grid used.

Optimization Problem Formulation

The goal of the redesign is to improve the unsteady aerodynamic performance of the turbine by optimizing the shape of the stator vane (the rotor blade geometry is kept the same). This is accomplished by formulating an objective function that minimizes the unsteady amplitudes $\tilde{p}_i$ on the stator vane subject to the constraint that the tangential force on the airfoil does not change from the reference design by more than 1%. The pressure amplitude $\tilde{p}_i$ is used as a measure of the unsteadiness in the flow field and is defined as the difference between the maximum and minimum pressures occurring over a complete cycle at each point on the airfoil surface. (For the stator vane, a cycle is a rotor pitch; for the rotor blade, a cycle is a stator pitch.) Thus, the pressure amplitude $\tilde{p}_i$ is defined as:

$$\tilde{p}_i = (p_{i,max} - p_{i,min})_{cycle} \tag{1}$$

In the current redesign the goal is to improve unsteady aerodynamic performance by eliminating the shock. The presence of the unsteady shock in the reference design results in large unsteady pressure amplitudes. Thus the pressure amplitudes are directly related to the shock strength. Hence it is assumed that a reduction in the unsteady amplitudes on the stator vane will result in a weakened shock. The results obtained demonstrate the validity of this assumption.

Neural Net-Based Redesign Procedure

The redesign procedure used here is based on Rai and Madavan (ref. 15). The procedure uses a sequence of response surfaces based on both neural networks and polynomial fits to traverse the design space in search of the optimal solution. A technique called *parameter-based partitioning* of the design space is used, where the functional dependence of the variables of interest (e.g., pressure) with respect to some of the design parameters is represented using neural networks, and the functional dependence with respect to the remaining parameters is represented using polynomials. The power of neural networks and the economy of low-order polynomials (in terms of number of simulations required and network training requirements) are thus effectively combined. The method (ref. 15) can be viewed as a variant of Response Surface Methodology (ref. 20, 21), or RSM, where the response surfaces are constructed using both neural networks and polynomials. Traditional RSM uses only low-order polynomials in constructing the response surfaces.

The method of Rai and Madavan (ref. 15) uses polynomial approximations on multidimensional simplexes. An s-dimensional simplex is a spatial configuration of s dimensions determined by $s+1$ equispaced vertices, on a hypersphere of unit radius, in a space of dimension equal to s. (By this definition, a two-dimensional simplex is an equilateral triangle that is circumscribed by a unit circle.) This approach assumes that the *local* variation of the design objective function can be accurately represented using low-order polynomials, which is very often the case. The polynomial fit on this simplex together with the trained neural network represents a composite response surface. The optimization procedure then uses a sequence of such composite response surfaces to traverse through the design space in search of the optimal solution.

Following Rai and Madavan (ref. 15), parameter-based partitioning of the design space is accomplished in the following manner. Since the variation of the unsteady pressure amplitudes along the airfoil surfaces is typically far more complicated than the variation with small changes in geometric parameter values, a neural network is used only to represent unsteady pressure amplitude variation in physical space. The three-layer neural network (with two hidden layers) shown in figure 3 is used for this purpose. The first node in the input layer is a bias node (input of 1.0). The second set of nodes is used to specify the physical location. Since we are dealing with two-dimensional geometries only, physical location is specified by a single parameter: the axial location on the airfoil surface. Figure 3 shows a third set of input nodes that are not activated in this study, but may be used in cases where the functional behavior of the pressure amplitudes with some of the geometric parameters is "complex" and one wishes to use the neural network to represent this behavior.

The variation of the unsteady pressure amplitudes with the geometry parameters is approximated using simple polynomials. Since a linear variation is assumed, the points at which the pressure amplitude data are determined are located at the vertices of a simplex of dimension equal to the number of geometry parameters.

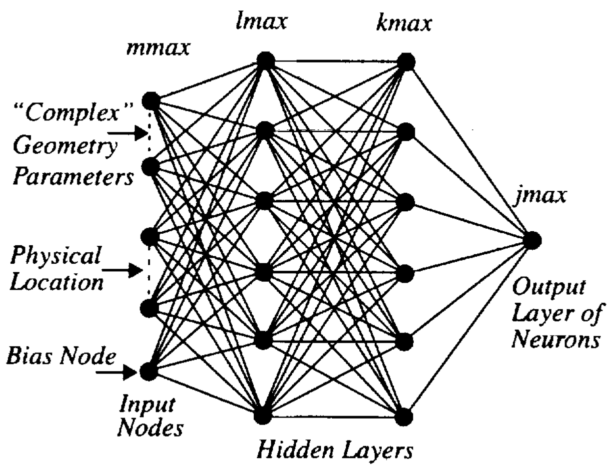

Figure 3. Schematic of the three-layer feed-forward neural network used in this study.

The optimization strategy used here to redesign the turbine airfoil geometry starting from the reference design can be summarized as follows:

1. *Populate the design space in the vicinity of the reference geometry.* The reference design geometry serves as the centroid of the first simplex in the optimization process. A simplex in design space is constructed around this centroid and unsteady aerodynamic analyses (computational fluid dynamics (CFD) simulations) at each of the vertices (a linear variation is assumed) are obtained.

2. *Train the neural networks and compute the polynomial coefficients to define the composite response surface.* The input nodes of the neural nets will typically contain parameters that correspond to the physical location on the airfoil and those geometric parameters that give rise to "complex" surface pressure variations. The neural nets are trained and the polynomial coefficients that define the pressure variation within the simplex are computed. The trained neural networks in combination with the polynomial fit then constitutes the composite response surface (ref. 15).

3. *Search the region of the design space represented by the composite response surface.* A conjugate gradient method was used in this study to perform this constrained search. Geometrical and other constraints can be incorporated within this search procedure easily. In addition, constraints that limit the search procedure to the volume of the simplex are also incorporated in the search.

4. *Relocate the simplex.* If the local optimum obtained in the previous step lies on the boundaries of the simplex then this point is chosen as the new centroid and steps 1-4 are repeated until the search culminates inside the simplex. However, the process can be stopped at any time when the design is deemed adequate.

5. *Validate the design.* As a final step in the process the unsteady aerodynamic analysis is carried out for the geometry corresponding to the optimal design to determine the adequacy and quality of the design.

Implementation Details

The optimization procedure was initiated from the reference design. The process focused on the suction surface of the stator vane. Although 13 geometric parameters were used to represent the stator vane, only 5 of these parameters that were related to defining the suction surface were considered. A linear variation in the parameters was assumed, resulting in a five-dimensional simplex (with six vertices) at each design optimization step. The process of constructing new simplexes and searching for the local optimum was repeated 3 times.

Each of the six 3-layer nets (representing the six vertices of the simplex) had two input nodes, one for the bias and one for the axial location, and one output neuron. The first and second hidden layers had 15 and 7 neurons, respectively, for a total of 136 connection weights. Thus, the total number of connection weights for all six nets was 816. During the training process the training error was reduced by about four orders of magnitude from the initial value. Further details regarding the training process can be found in Rai and Madavan (ref. 14, 15).

Results

The neural net-based redesign method was used to optimize the unsteady performance of the reference turbine. This optimization yielded a modified design. Detailed comparisons with the reference design are presented in this section.

Comparison of Stator Vane Geometry for Reference and Modified Designs

Figure 4 compares the stator vane geometry for the reference and modified designs. It is worth noting that the geometry of the modified design obtained at the end of the optimization process is very close to that of the reference design. The suction surface has been thinned out in the aft region, and the location of the point where the maximum thickness occurs (the airfoil "crown") has moved slightly downstream. Since the geometry modifications are slight, the effect on flow angles and other mean flow parameters is small. However, the impact on the unsteady flow features through the turbine stage is quite substantial, as the following results will show.

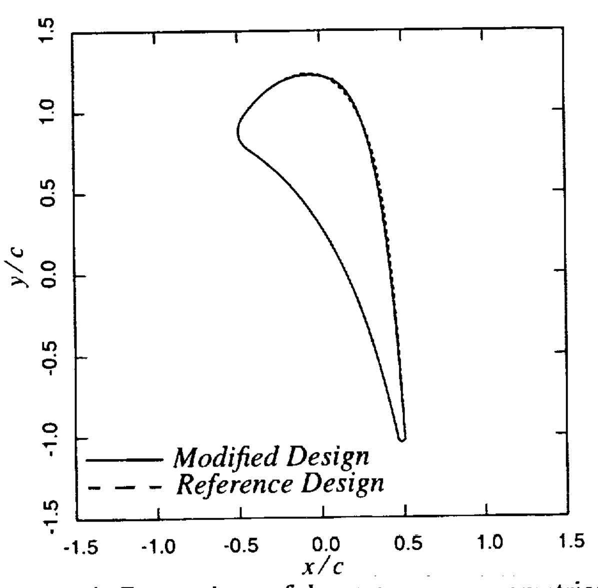

Figure 4. Comparison of the stator vane geometries for the reference and modified designs.

Comparison of Flow Parameters for Reference and Modified Designs

Table 1 compared the flow parameters for the reference and modified designs. The differences between the overall flow parameters in the two cases are very small. This is to be expected, since the geometry has been modified very slightly from the reference design.

Static Pressure Variation on Airfoils

Figure 5 shows the time-averaged static pressure variation on the stator vane. The reference pressure, $p_{t,ref}$, in this case is the total pressure at the stator inlet. The static pressure is time-averaged over a stator cycle which corresponds to the rotor blades moving by a distance equal to that between adjacent rotor blades (i.e., rotor pitch). The major difference between the time-averaged pressures on the reference and modified designs is along the suction surface where the loadings are quite different. Also, the sharp pressure minimum toward the trailing edge of the stator vane in the reference design has been smoothed out in the modified design.

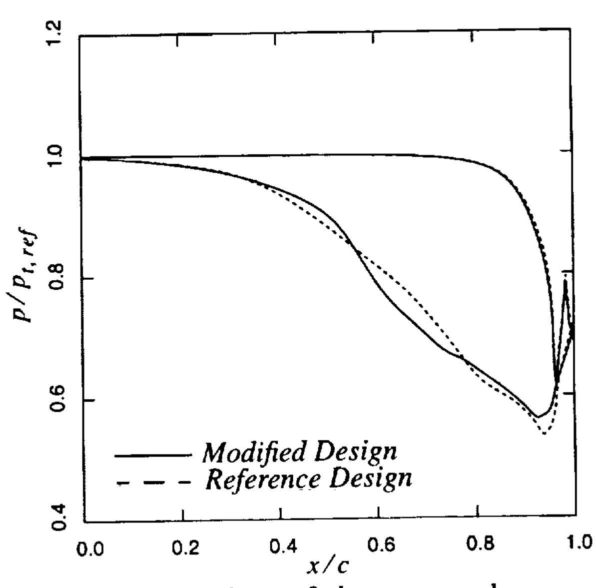

Figure 5. Comparison of time-averaged pressure distributions on the stator vanes for the reference and modified designs.

The variation of time-averaged pressures on the rotor blades is compared for the reference and modified designs in figure 6. The reference pressure, $p_{t,ref}$, in this case is the relative total pressure at the inlet to the rotor row, and the time-averaging is performed over one rotor cycle which corresponds to the rotor blades moving by a distance equal to that between the stator blades (i.e., stator pitch). Since the rotor blade geometry was not modified, the difference in time-averaged pressures between the reference and modified designs is quite small and is limited to the vicinity of the leading edge of the blade. This small change is a result of the flow field being altered by the modified stator vane.

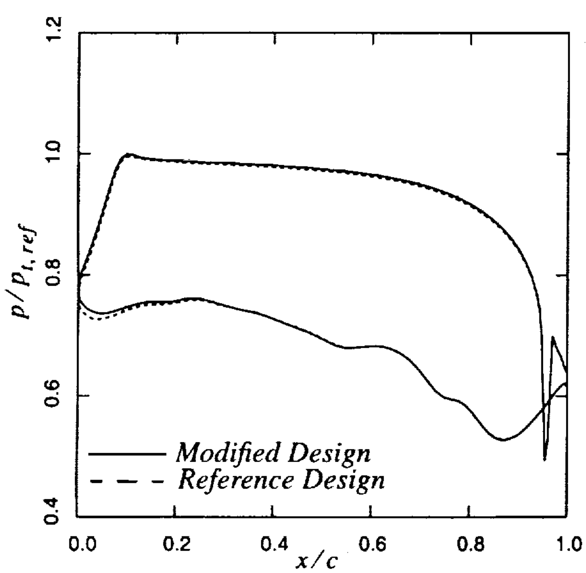

Figure 6. Comparison of the time-averaged pressure distributions on the rotor blades for the reference and modified designs.

Unsteady Pressure Amplitudes on Airfoils

A quantitative measure of the unsteadiness in the flow can be obtained from the unsteady pressure amplitudes on the surfaces of the stator and rotor airfoils. The pressure amplitudes $\tilde{p}$ are defined as the difference between the maximum and minimum pressures occurring over a complete cycle at each point on the airfoil surface (see eqn. 1.)

The pressure amplitudes on the stator vanes for the reference and modified designs are shown in figure 7. The abscissa on figure 7 is the axial distance x (normalized by the stator axial chord, c) along the stator vane measured from the leading edge ($x/c = -1.0$) along the suction surface to the trailing edge ($x/c = 0.0$) and then back to the leading edge along the pressure surface ($x/c = 1.0$). It is evident from the figure that the high unsteady interaction effects in the reference design have been reduced substantially in the modified design. In particular, the maximum pressure amplitude that is located at the trailing edge of the vane has been reduced by about 30%. As noted earlier (ref. 6), the large pressure amplitudes are caused by the presence of an unsteady moving shock in the gap region. The reduced pressure amplitudes in the modified design indicate that the strength of this shock has been reduced drastically and its detrimental effects have been mitigated.

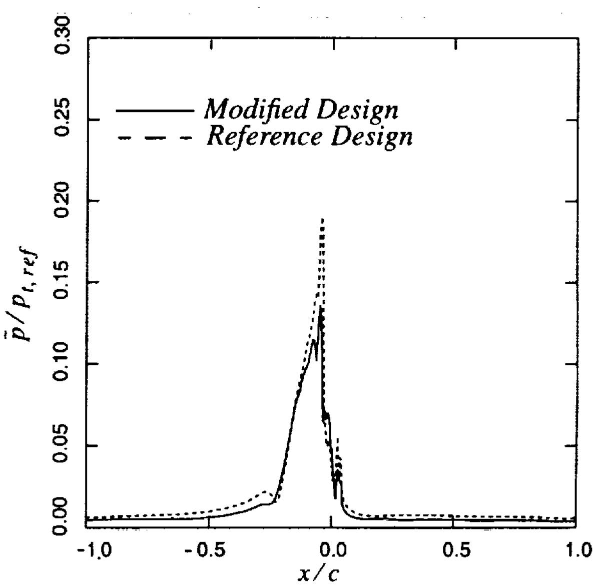

Figure 7. Comparison of the pressure amplitude distributions on the stator vanes for the reference and modified designs.

The pressure amplitudes on the rotor blades for the reference and modified designs are shown in figure 8. Unlike in figure 7, the abscissa on figure 8 is the axial distance x (normalized by the rotor axial chord, c) along the rotor blade measured from the trailing edge ($x/c = -1.0$) along the suction surface to the leading edge ($x/c = 0.0$) and then back to the trailing edge along the pressure surface ($x/c = 1.0$). Although the time-averaged pressure on the rotor blade is hardly affected by the stator vane modification, the unsteady pressures on the rotor blades are considerably reduced in the modified design. At the leading edge, the reduction is again about 30%.

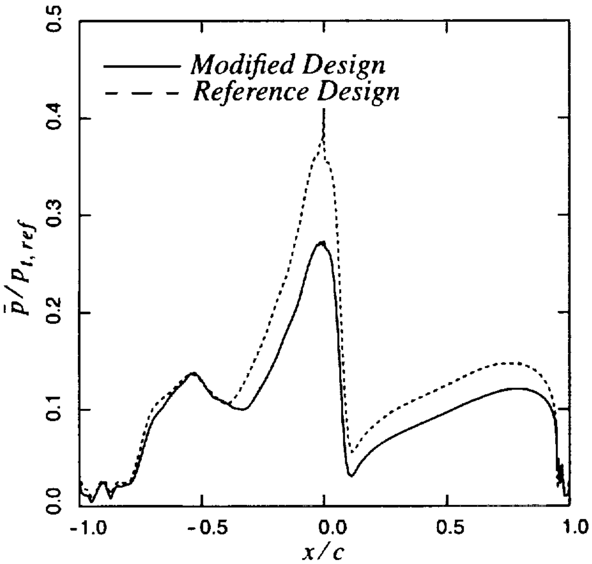

Figure 8. Comparison of the pressure amplitude distributions on the rotor blades for the reference and modified designs.

It is important to note that the reduction of unsteady effects in the modified design is due primarily to the weakening of the shock. The unsteadiness due to potential flow interactions and wake/blade interactions between the stator vanes and rotor blades continues to be present since the axial gap between the vanes and blades was not changed in the optimization process.

Instantaneous Contours in the Flow

Figures 9 and 10 compare the instantaneous pressure contours in the flow for the reference and modified designs, respectively. These contours show the overall features of the time-averaged pressure distributions on the vane and blade surfaces shown earlier. For example, there is very little pressure variation on the forward half of the stator vane in both designs, and most of the flow expansion occurs on the latter half of the vanes. The major difference between the reference and modified designs is the unsteady shock in the gap region. This shock can be seen clearly in the reference design, while the flow in the modified design appears shock-free. In the reference design, the shock lies on the vane surface and impinges upon the rotor blades as they pass by the vanes. This unsteady shock and its motion is one of the causes of the large time variations in the vane and blade surface pressures seen in figure 7 and figure 8, respectively. This shock is entirely due to the interaction between the stator and rotor airfoils. The slight change in the stator vane geometry on the suction side of the modified design effectively weakens the shock strength. It is important to note that figure 9 and figure 10 represent different instances in the rotor blade passing cycle. The time instances correspond to the rotor position when the instantaneous Mach number in the flow field is maximum and was chosen to represent the worst-case scenario.

Instantaneous Mach number contours are shown in figure 11 and figure 12 for the reference and modified designs, respectively. The maximum instantaneous Mach number is noted to be 1.33 in the reference design and 1.13 in the modified design. While pressure contours, in general, highlight only the inviscid aspects of the flow, Mach number contours also highlight the viscous aspects, such as boundary layers and wakes. The shock-wake interaction in the reference design can be clearly seen in figure 11. Despite the unusually high turning angles, the contours show no indication of boundary-layer separation.

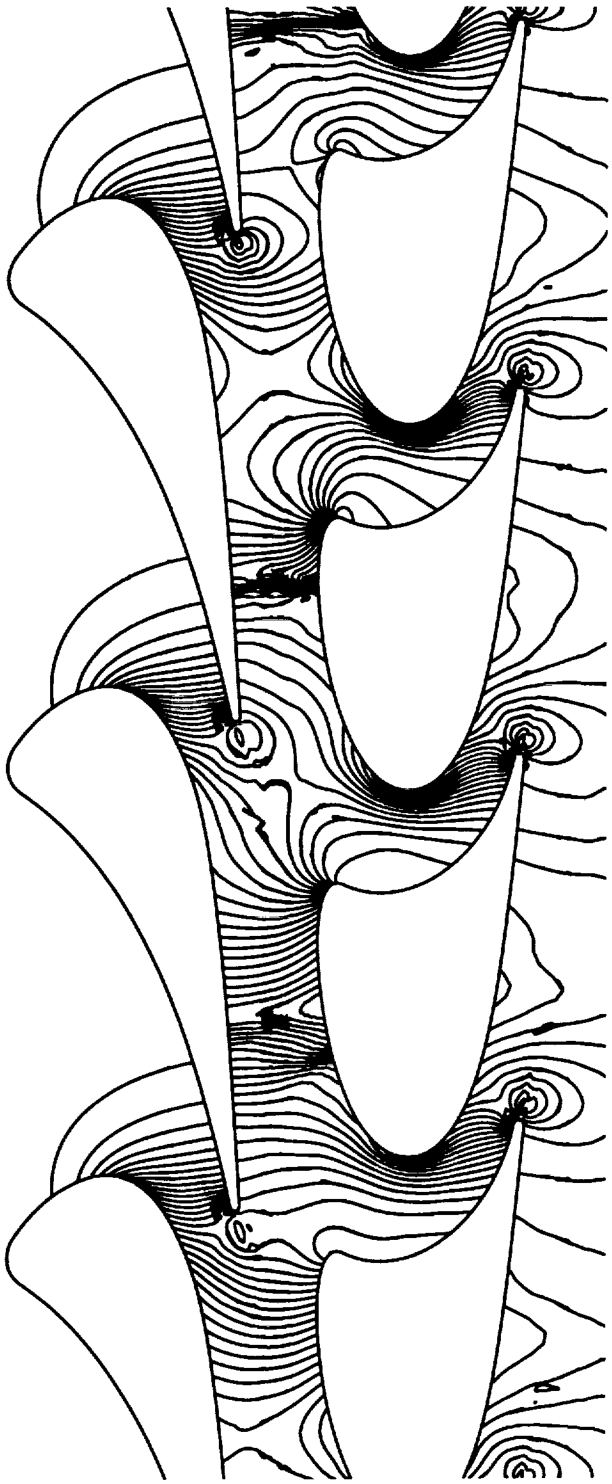

Figure 9. Instantaneous pressure contours in the flow for the reference design.

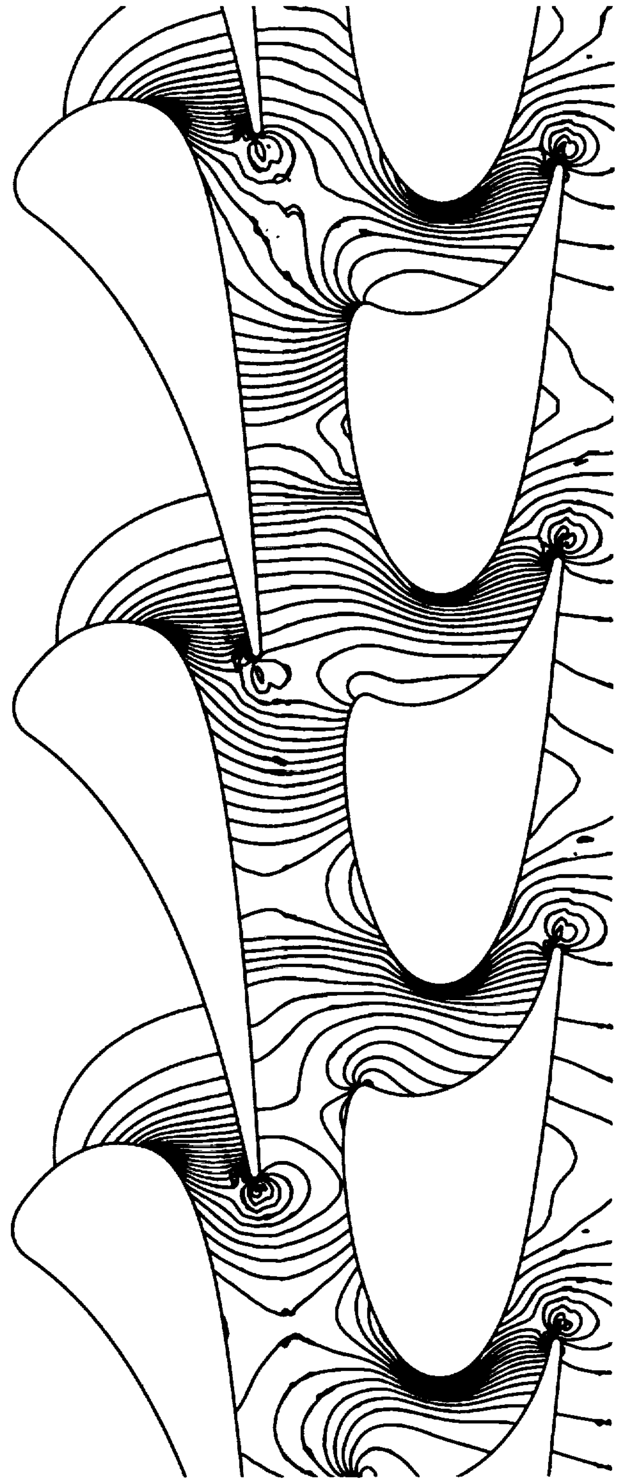

Figure 10. Instantaneous pressure contours in the flow for the modified design.

Figure 11. Instantaneous Mach number contours in the flow for the reference design.

Figure 12. Instantaneous Mach number contours in the flow for the modified design.

Computing Time Requirements

The time required to compute the unsteady CFD simulations represents almost all of the computing time required. The time required to train the neural nets and search the design space is negligible in comparison. The redesign was accomplished in three optimization steps, with seven (six vertices plus the centroid) CFD simulations being required at each step. Each CFD simulation required about 5 hours of single-processor CPU time on a Cray C-90. The total computing time required for the redesign was thus about 100 hours.

Concluding Remarks

A recently developed method for aerodynamic design that incorporates the advantages of both traditional RSM and neural networks has been applied to the redesign of a transonic turbine to improve its unsteady aerodynamic performance. The redesign procedure employs a strategy called parameter-based partitioning of the design space and uses a sequence of response surfaces based on both neural networks and polynomials to traverse the design space in search of the optimal solution. This approach results in response surfaces that have both the power of neural networks and the economy of low-order polynomials (in terms of number of simulations needed and network training requirements). By using high-fidelity, time-accurate Navier-Stokes simulations to steer the optimization process, the relevant physics of the flow field is included at every stage of the redesign process. The use of such unsteady simulations is mandatory in the current study, since the moving shock in the reference design could not be simulated accurately by any other means.

The application of this design method to a reference transonic turbine yielded a new design with a slightly different geometry. Results shown in this report indicate that the unsteady shock in the reference design has been eliminated in the modified design. This leads to much lower unsteady pressure amplitudes on the airfoil surfaces and hence improved aerodynamic performance. These results demonstrate the capabilities of the neural net-based design method.

References

1. Sieverding, C. H.: Experimental Data on Two Transonic Turbine Blade Sections and Comparison with Various Theoretical Methods. In *Transonic Flows in Turbomachinery, VKI Lecture Series 59,* Von Karman Institute, Rhode-St.-Genese, Belgium, 1973.
2. Ashworth, D. A.; LaGraff, J. E.; Schultz, D. L.; and Grindod, K. J.: Unsteady Aerodynamic and Heat Transfer Processes in a Transonic Turbine Stage. *Journal of Engineering for Gas Turbines and Power,* vol. 107, 1985, pp. 1022-1030.
3. Guennette, G. R.; Epstein, A. H.; Giles, M. B.; Haimer, R.; and Norton, R. J. G.: Fully Scaled Transonic Turbine Rotor Heat Transfer Measurements. *ASME Journal of Turbomachinery,* vol. 111, 1989, pp. 1-7.
4. Giles, M. B.: Stator/Rotor Interaction in a Transonic Turbine. *AIAA Journal of Propulsion and Power,* vol. 6, 1990, pp. 621-633.
5. Abhari, R. S.; Guenette, G. R.; Epstein, A. H.; and Giles, M. B.: Comparison of Time-Resolved Turbine Rotor Blade Heat Transfer Measurements and Numerical Calculations. *ASME Journal of Turbomachinery,* vol. 114, 1992, pp. 818-827.
6. Rangwalla, A. A.; Madavan, N. K.; and Johnson, P. D.: Application of an Unsteady Navier-Stokes Solver to Transonic Turbine Design. *AIAA Journal of Propulsion and Power,* vol. 8, no. 5, 1992, pp. 1079-1086.
7. Rangwalla, A. A.: Unsteady Navier-Stokes Computations for Advanced Transonic Turbine Design. AIAA Paper No. 94-2835, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Indianapolis, IN, June 1994.
8. Jennions, I. K.; and Adamczyk, J. J.: Evaluation of the Interaction Losses in a Transonic Turbine HP Rotor/LP Vane Configuration. *ASME Journal of Turbomachinery,* vol. 119, 1997, pp. 68-76.
9. Demeulenaere, A.; and Van den Braembussche, R.: Three-Dimensional Inverse Method for Turbomachinery Blade Design. *ASME Journal of Turbomachinery,* vol. 120, 1998, pp. 247-255.

10. Chattopadhyay, A; Pagaldipti, N.; and Chang, K. T.: A Design Optimization Procedure for Efficient Turbine Airfoil Design. *Journal of Computers and Mathematics with Applications*, vol. 26, no. 4, 1993, pp. 21-31.

11. Talya, S. S.; Rajadas, J. N.; and Chattopadhyay, A.: Multidisciplinary Optimization of Gas Turbine Blade Design. AIAA Paper No. 98-4864, 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, September 1998.

12. Tong, S. S.; and Gregory, B. A.: Turbine Preliminary Design Using Artificial Intelligence and Numerical Optimization Techniques. ASME Paper No. 90-GT-148, 1990.

13. Shelton, M. L.; Gregory, B. A.; Lamson, S. H.; Moses, H. L.; Doughty, R. L.; and Kiss, T.: Optimization of a Transonic Turbine Airfoil Using Artificial Intelligence, CFD, and Cascade Testing. ASME Paper No. 93-GT-161, 1993.

14. Rai, M. M.; and Madavan, N. K.: Application of Artificial Neural Networks to the Design of Turbomachinery Airfoils. AIAA Paper No. 98-1003, AIAA 36th Aerospace Sciences Meeting, Reno, NV, January 1998.

15. Rai, M. M.; and Madavan, N. K.: Aerodynamic Design Using Neural Networks. AIAA Paper No. 98-4928, 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, September 1998.

16. Sanz, J. M.: Development of a Neural Network Design System for Advanced Turbo-Engines. Fourth U.S. National Congress on Computational Mechanics, San Francisco, CA, August 1997.

17. Goel, S.; and Hajela, P.: Turbine Aerodynamic Design Using Reinforcement Learning Based Optimization. AIAA Paper No. 98-4774, 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, September 1998.

18. Johnson, P. D.; and Huber, F. W.: GGGT Preliminary Design. United Technologies Pratt and Whitney Memo Pass 57, West Palm Beach, FL, 1990.

19. Rai, M. M.; and Madavan, N. K.: Multi-Airfoil Navier-Stokes Simulations of Turbine Rotor-Stator Interaction. *ASME Journal of Turbomachinery*, vol. 112, 1990, pp. 167-190.

20. Montgomery, D. C.: *Design and Analysis of Experiments*. John Wiley and Sons, New York, 1997.

21. Myers, R. H.; and Montgomery, D. C.: *Response Surface Methodology--Process and Product Optimization Using Designed Experiments*. John Wiley and Sons, New York, 1995.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 1998	Technical Memorandum

4. TITLE AND SUBTITLE
Neural Net-Based Redesign of Transonic Turbines for Improved Unsteady Aerodynamic Performance

5. FUNDING NUMBERS
519-40-12

6. AUTHOR(S)
Nateri K. Madavan, Man Mohan Rai, and Frank W. Huber*

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Ames Research Center
Moffett Field, CA 94035-1000

8. PERFORMING ORGANIZATION REPORT NUMBER
A-9900398

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TM–1998-208754

11. SUPPLEMENTARY NOTES
Point of Contact: Author, Ames Research Center, MS T27A-1, Moffett Field, CA 94035-1000
(650) 604-4427
*Riverbend Design Services, Palm Beach Gardens, Florida.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified — Unlimited
Subject Category 07 Distribution: Standard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A recently developed neural net-based aerodynamic design procedure is used in the redesign of a transonic turbine stage to improve its unsteady aerodynamic performance. The redesign procedure used incorporates the advantages of both traditional response surface methodology (RSM) and neural networks by employing a strategy called parameter-based partitioning of the design space. Starting from the reference design, a sequence of response surfaces based on both neural networks and polynomial fits are constructed to traverse the design space in search of an optimal solution that exhibits improved unsteady performance. The procedure combines the power of neural networks and the economy of low-order polynomials (in terms of number of simulations required and network training requirements). A time-accurate, two-dimensional, Navier-Stokes solver is used to evaluate the various intermediate designs and provide inputs to the optimization procedure. The optimization procedure yields a modified design that improves the aerodynamic performance through small changes to the reference design geometry. The computed results demonstrate the capabilities of the neural net-based design procedure, and also show the tremendous advantages that can be gained by including high-fidelity unsteady simulations that capture the relevant flow physics in the design optimization process.

14. SUBJECT TERMS
Turbine, Design optimization, Unsteady aerodynamics

15. NUMBER OF PAGES
20

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified		

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102