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Thermal/Structural Tailoring of Engine Blades (T/STAEBL)

User's Manual

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1. SUMMARY

The objective in the development of the Thermal/Structural Tailoring of Engine Blades (T/STAEBL) program was to produce a computer code capable of performing engine cooled turbine blade and vane thermal/structural numerical optimizations. These optimizations seek a practical blade or vane design of minimum operating cost that satisfies realistic blade design constraints, by tuning from just a few to up to 100 aerodynamic, internal cooling, and structural design variables.

The design constraints of the T/STAEBL program can be classed in two categories: geometric limits and performance characteristics. Under geometric limits, such parameters as minimum wall thickness, maximum cooling hole diameter, etc., are provided to ensure the manufacturability of the optimized design. Performance characteristics include the airfoil stress, life, and vibratory frequencies. These are the calculated parameters that must have adequate margin if the blade is to have acceptable endurance in the harsh turbine environment.

To perform a cooled blade optimization, an initial configuration is required. Due to the intelligence provided by the T/STAEBL system, however, this initial configuration may be quite roughly defined. A good starting point would be to scale the T/STAEBL verification case to fit the new size requirements.

To perform a cooled blade optimization analysis, three categories of analysis are required: an optimizer to select a candidate design; a design update algorithm to generate the candidate geometry for analysis; and a full, robust set of analysis tools to evaluate the performance characteristics of the candidate design. These analyses must be robust, for the optimizer may request evaluation of some configurations that the human designer might dismiss outright as unworthy of evaluation. Hence, numerical difficulties with these improbable designs is a decided possibility.

The optimization algorithm of T/STAEBL is the ADS (Automated Design Synthesis) optimization package (Reference 1). ADS has the flexibility of providing many different optimization algorithms, selected on the data input level. ADS is a well accepted and proven tool for optimizations employing a small to medium (1 to 30) number of design variables. In the T/STAEBL program, the design variable capability has been stretched to the 100 design variable milestone.

The T/STAEBL design update algorithm processes the design variable set selected by the optimizer, and generates in effect a new blade geometry, with every relevant blade descriptor updated. This updated blade is saved in a data base for analytical evaluation. Since these hollow blades are quite complex, this geometry update module has proven to be a critical and robust segment of the T/STAEBL package.

Upon geometry generation for the candidate design, T/STAEBL then performs a complete thermal, life and vibratory blade analysis. At each stage of the blade optimization, then, all characteristics of the candidate designs are well known. This provides a significant advantage over present cooled blade design procedures, where the vibratory characteristics of a design are evaluated only when the design is nearly complete, and is very difficult to alter, even if a problem is encountered. In T/STAEBL, all performance characteristics are well categorized for each candidate design at each step of the design process.

Verifications of the T/STAEBL code were conducted using the first turbine stage of the Energy Efficient Engine which was designed under NASA contract NAS3-20646. In the verification case, the referenced airfoil design served as the starting point for the thermal/structural optimization. In this demonstration, significant savings potential was demonstrated by the application of the T/STAEBL procedure. The biggest potential savings, however, is not in refining what is already a good

design, but in applying the system to new designs. In this mode, T/STAEBL holds the promise of less expensive, more efficient engines developed in a shorter design cycle.

Cooled blade thermal/structural design tailoring, as performed by T/STAEBL, has been demonstrated to be a very powerful automated design process through applications of the system to cooled airfoils from the Energy Efficient Engine. T/STAEBL provides the computational capability to simultaneously evaluate many design variables to optimize a comprehensive objective function while satisfying numerous design requirements.

2. INTRODUCTION

High bypass jet engine turbine blades and vanes are complex structures with thermal coatings, internal cooling passages, and strategically placed cooling holes. The airfoil exterior shapes are configured to provide aerodynamic performance. From this given shape, it is the job of the designer to develop internal cooling and retention configurations such that the airfoil has adequate structural durability. These design iterations require that specific design criteria, determined through empirical correlations, must be satisfied. The aerodynamics engineer, in establishing the exterior contours of the airfoil, seeks maximum performance, regardless of durability considerations. The structural designer, on the other hand, must design a blade which is structurally durable with little or no penalty in performance. To design a structurally durable blade, the structural designer interactively conducts cooling air flow, heat transfer, steady–state stress, and durability analyses for proposed designs, comparing the results with design criteria. Often, the blade designer must use personal experience and intuition to establish which path to follow to improve a design, and to decide when a design is adequate. When this arduous task has been completed, the candidate design is passed to another group for retention design and vibrations verification. Due to the complexities involved in cooled airfoil design, this vibratory evaluation occurs quite late in the design cycle, so that little can be done to update the airfoil design even if a vibratory problem is anticipated.

Thus, the current turbine engine cooled airfoil design procedures are partly engineering and partly art. The quality of a design is often dependent on the judgment and experience of the engineering team that performed the design task. Often, compromises are required, such as excess cooling air to provide sufficient durability for a given aerodynamic shape, or an overly stiff attachment to provide vibratory margin for an overly flexible cooled airfoil. The penalties for these less than optimum designs are increased engine weight and cost, including decreased efficiency, and needlessly long development cycles, due to the need to fix failures and improve engine performance. Correcting a problem is always more expensive than designing the part correctly initially, when design constraints are less rigidly defined. Once a design fault has been corrected, it is usually at the expense of engine cost or weight. Thus, degradation of the overall engine performance is generally the result.

It is apparent that the current cooled blade design procedures require a team of experienced design engineers to decide what are appropriate trade–offs during the blade design process. The purpose of the Thermal/Structural Tailoring of Engine Blades (T/STAEBL) program is to formalize the cooled airfoil structural design procedure, such that automated design optimization procedures may be applied to it. Such formalized optimum design procedures have been developed and used with considerable success for optimum structural design of linear static structures, and are now being used with success for the aeroelastic tailoring of fixed aircraft wings. The T/STAEBL procedure can reduce human error and increase productivity in the blade design process by automating what is currently a cumbersome, judgmental design process.

The capabilities of the cooled airfoil automated design procedure have been demonstrated through its application to a cooled, hollow turbine blade and a cooled turbine vane. The design optimization of these complex, hollow airfoils was a rigorous test of the T/STAEBL program.

To meet the objectives of the T/STAEBL program, 26 technical tasks were established as part of NASA Contract NAS3–22525. The results of the first 17 tasks were reported in Reference 2. The remaining tasks consisted of:

- *Task XVIII – Cooled Turbine Blade (Vane) Controlling Variables* – Design variables, fixed variables, constraints, analyses, cooling concepts and design requirements were identified for the aero–thermo–structural tailoring of cooled turbine blades and vanes.

- *Task XIX – Turbine Blade (Vane) Configuration* – Computer codes were developed to automatically generate turbine blade and vane outer surfaces, interior configurations, material descriptions, and coating models.
- *Task XX – Approximate Analyses for Cooled Turbine Blades (Vanes)* – Approximate analysis modules were developed for the aerodynamic, heat transfer, interior/film cooling, blade coating, structural and durability analyses of the turbine optimizer.
- *Task XXI – Resident Data Bank and Manager* – A resident data bank was developed to provide materials data, including fluid and mechanical properties, life descriptors, and cumulative effect parameters. A data bank manager was developed to control data bank information and perform composite mechanics.
- *Task XXII – T/STAEBL Code Modifications for Cooled Turbine Blade (Vane) Structural Tailoring* – The STAEBL computer code was modified to provide the capability for aero–thermo–structural tailoring of cooled turbine blades (vanes). An executive module uses command language and provides communication links with all STAEBL modules.
- *Task XXIII – Validation of the Modified T/STAEBL Code* – The modified T/STAEBL code was validated by tailoring turbine blades and vanes of a variety of constructions, including directionally solidified material and single crystal material. Calibrations with refined analyses were performed to determine the validity of the tailoring result.
- *Task XXIV – Modified STAEBL Code Documentation* – Theoretical and User's Manuals for the modified STAEBL code were provided.
- *Task XXV – Modified STAEBL Computer Code Delivery* – The modified STAEBL code was delivered to and made operational at the NASA–Lewis facility. A seminar was conducted showing usage of the program.
- *Task XXVI – Reporting* – Reporting requirements were met in accordance with the contract Statement of Work and the Reports of Work attachment. These requirements included the completion of the technical and financial progress reports.

3. OVERVIEW

The cooled turbine blade and vane design process is a critical part of the aircraft turbine engine development process. The limitations imposed by the durability requirements for the airfoils have a direct bearing on the aerodynamic performance that can be achieved. Cooling air, required to ensure adequate airfoil life, reduces bypass ratio, reduces cycle efficiency, and adds to component geometric complexity. In addition, a significant portion of engine weight and engine cost is a simple multiple of airfoil weight.

The cooled airfoil design problem is very complex. While the exterior configuration is basically set by aerodynamic considerations, the interior geometry of these hollow airfoils is highly detailed. Parameters available to the designer include coating thickness, cavity wall thickness, cooling passage geometry, cooling air pressure, trip strip size and location, and film hole location, spacing and diameter. Design requirements include adequate life, minimum degradation of performance, as well as flutter and vibration resistance.

Recent advances in application of numerical optimization procedures (Reference 2) have shown promise for automating this type of complex design problem, which includes many design variables and many performance requirements. The cooled airfoil application is particularly appropriate because the complex shapes defined by the optimization procedures do not add to manufacturing cost. These complex, single crystal and directionally solidified structures are cast, and the molds are easily modified to accept the results of structural tailoring.

Not surprisingly, there are problems associated with application of structural tailoring to engine blades:

1. Analysts and/or designers are hesitant to develop optimization procedures for cooled airfoils due to their ingrained reliance on past design experience

2. The analysis packages required to perform the airfoil optimization were developed with an individual's interaction in mind – to assemble them into a single package is a significant programming challenge

3. The computer expense for a cooled airfoil optimization is quite high

4. To ensure that all analyses in an optimization system are current requires a high degree of modularity, and a continued investment in code maintenance

5. A reliable geometry modifier is required, to take the design variable data passed down by the optimizer, and update all relevant design definitions

6. The optimization system must be flexible, modular, and highly robust, to handle analyses of designs that would otherwise be rejected outright by the analyst.

The T/STAEBL system has been established with the above reservations in mind. We have assembled a highly modular package, complete with a design data base, that easily and flexibly allows generality of design definition, and analysis updates, and provides as robust a design update and analysis system as is currently possible for the complex, cooled airfoil geometries being optimized. Figure 1 summarizes the procedure employed for the Thermal–Structural Tailoring of Engine Blades. Design variables are initiated by input to the procedure and are varied during the optimization, as desired by the optimizer. The effects of changes in these design variables are passed to all relevant geometry descriptions in the data base, and analyses for flow, temperature distribution, stress, life, and vibrations are performed, to evaluate the performance of the candidate design relative to design objective and constraints.

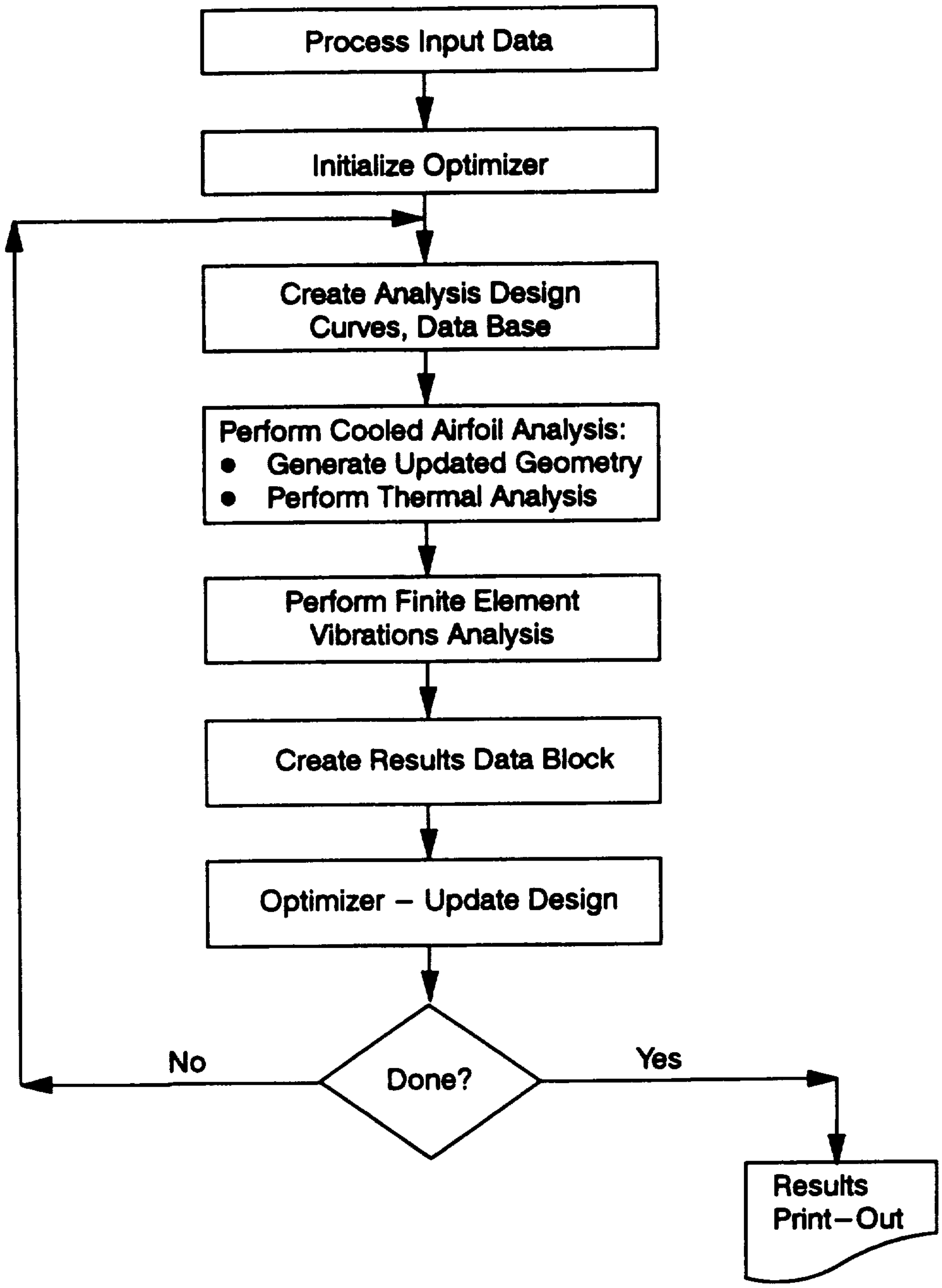

Figure 1 *T/STAEBL Overall Program Flow*

The objective function to be minimized in the T/STAEBL procedure is derived from the relationships illustrated in Figure 2. The complexity encountered in finding the design which minimizes this function can be illustrated by examining its relationship with cavity wall thickness (Figure 3). While the design trade would appear simple on the surface, the minimization becomes complicated when structural constraints are introduced (Figure 4). The design that the tailoring procedure selects must minimize user costs without violating these imposed constraints, while satisfying the side limits on the designated design variables.

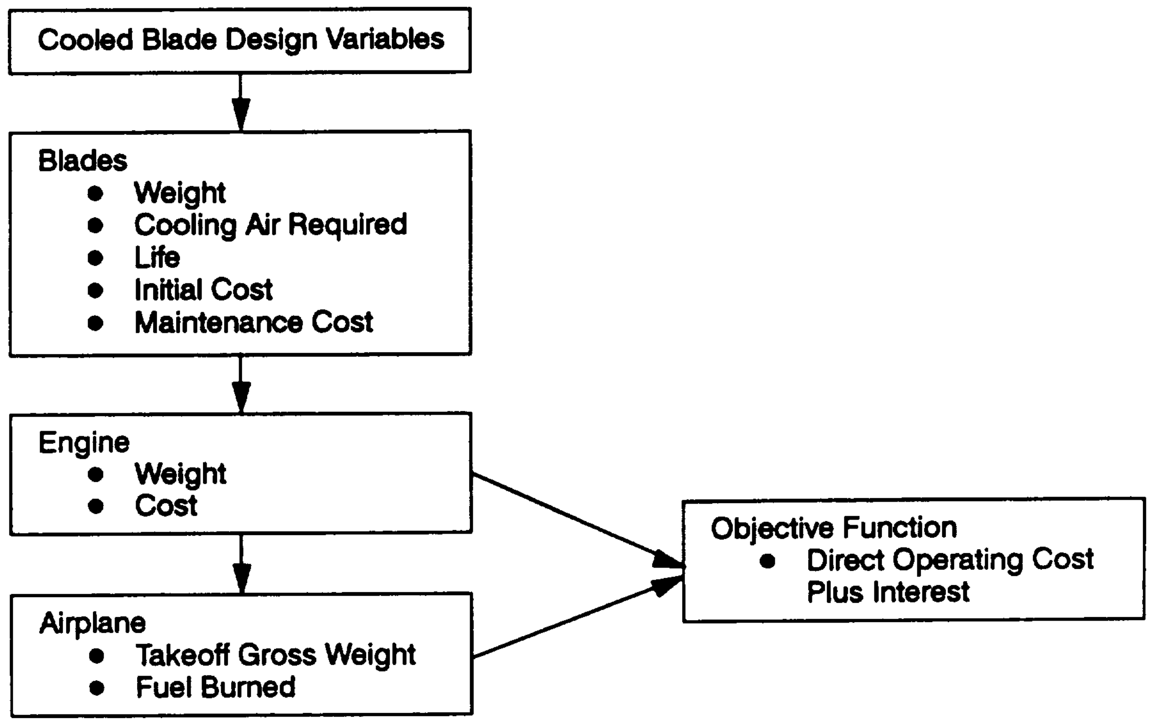

Figure 2 *The Objective Function Relates Airline Economics to Cooled Blade Design Variables*

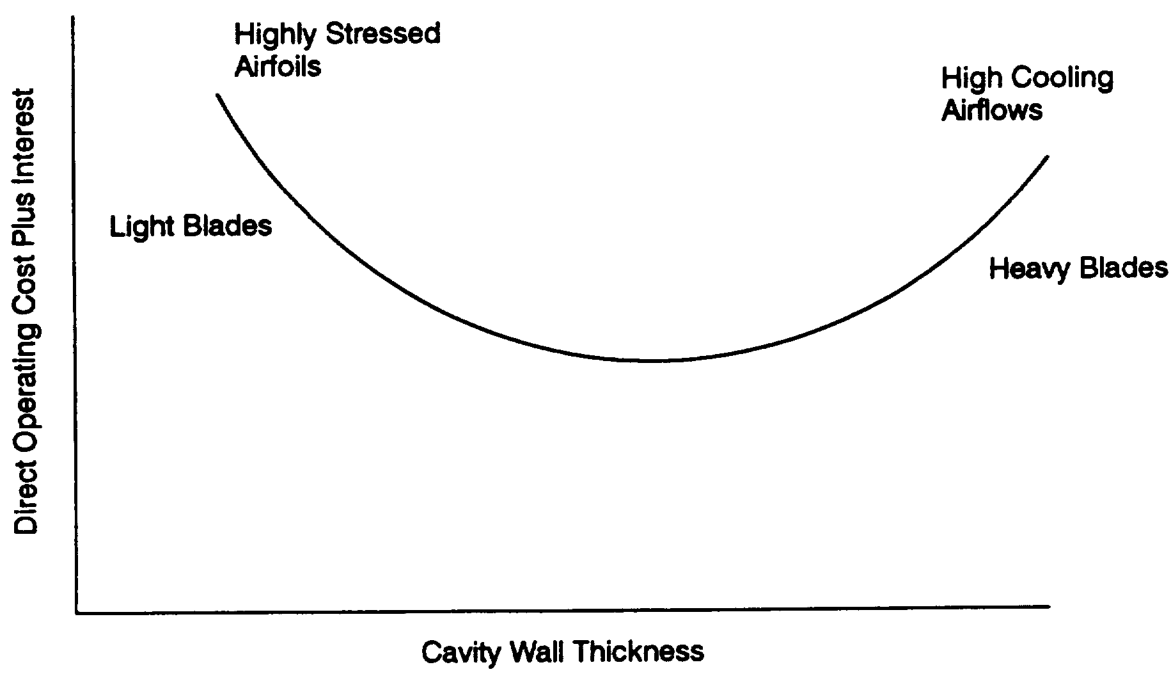

Figure 3 *Cavity Wall Thickness Optimization Appears to Be a Simple Design Problem*

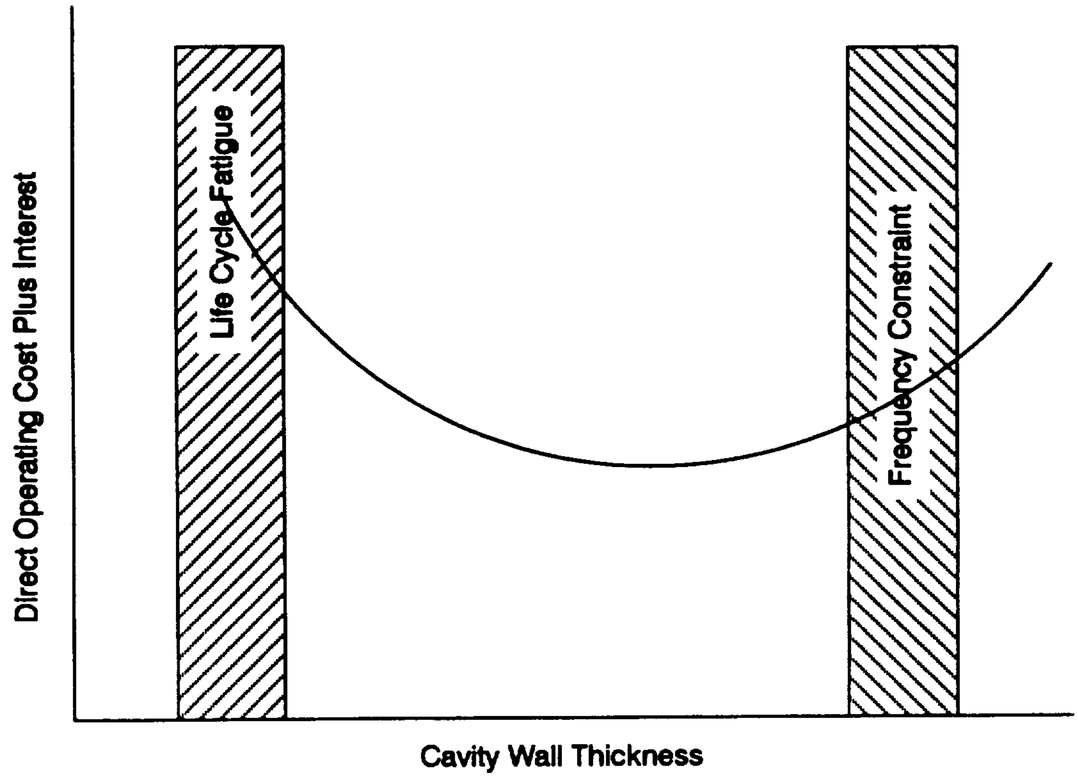

Figure 4 Optimization Design Problem Complexity Is Introduced Through Structural Constraints (Disjointed Design Space)

The ADS (Automated Design Synthesis) optimization program was selected as the most effective available technique for solving nonlinear optimization problems. The ADS program is a general purpose optimization algorithm that includes a wide variety of optimizers (Reference 1).

The thermal/structural tailoring methodologies embedded in the T/STAEBL procedure identify a finely tuned optimum design that is ready to be validated by more detailed, refined analysis. In assembling T/STAEBL, every effort was made to ensure that the approximate methods employed were identical or as similar as possible to those used in the everyday, interactive design iteration process. This ensures that the refined analysis will not be widely different from the approximate analysis made during the design process, and also gives the designer a higher confidence level in the capability of the tailoring algorithm to make intelligent design selections.

The T/STAEBL computer code has made significant strides in the quest for automated design of cooled turbine airfoils. Design time and human error are reduced by automating with computer precision what was formerly user judgment in a long, tedious, interdisciplinary interactive design process.

4. INPUT

To perform an optimization using the T/STAEBL system, a comprehensive initial geometry must be defined. Due to the complexity of cooled airfoils, this initial definition set must include an external profile, internal profiles, and rib, trip strip, pedestal, and film hole descriptions, as well as definitions of the materials involved. For a blade, extended neck and retention descriptions are also required. To perform an optimization, further definitions are needed, including the function to minimize (objective function), constraints which must be satisfied, and parameters (design variables) which are available to the optimization process. Table I summarizes the features available within the T/STAEBL system, including available design variables, behavior variables, constraints, side constraints, and gradient information.

Table I. T/STAEBL Optimization Features

Design Variables	*Behavior Variables*	*Constraints*
Supply Pressure	*Weight*	*Weight*
Tilt	*Stress*	*Stress*
Secondary Material Angle	*Cooling Flow Rate*	*Cooling Flow Rate*
Coating Thickness	*Profile Loss*	*Profile Loss*
Rib Thickness	*Film Mixing Loss*	*Film Mixing Loss*
Cavity Wall Thickness	*Maximum Temperature*	*Maximum Temperature*
Trip Strip Height, Pitch, and Angle	*Average Temperature*	*Average Temperature*
Pedestal Diameter and Spacing	*Life*	*Life*
Film Hole Diameter and Spacing	*Frequency*	*Frequency*

Side Constraints	*Gradients (for Sensitivity Analysis)*
Max, Min Limits, All Design Variables	$\frac{d(obj)}{d(var)}, \quad \frac{d(constraint)}{d(var)}$

As detailed in Section 5, the basis for definition of designs for T/STAEBL is the design data base. Sections of the data base, called data blocks, define all relevant T/STAEBL input. In discussing the required input, references to data blocks refer to these data base files. A detailed discussion of the data blocks required to initiate a T/STAEBL run is contained in the T/STAEBL User's Manual (Reference 3).

4.1 Cooled Airfoil Geometry

In defining the cooled airfoil geometry, both the external aerodynamic shape and the internal cooling cavities must be defined. Both of these are input as closed curves at several cross-sections (five is recommended), using data Block 1. Additional input is provided through Block 23, which defines the film hole geometries, Block 37, which describes the pedestal geometry, and Block 501, which gives the coating thickness.

For turbine blades, support structure input is also required, since the cooled airfoil descriptions end at the airfoil root. The input required includes attachment radius, and neck geometry, stiffness, and orientation.

4.2 Thermal Analysis Boundary Conditions

To properly describe the thermal and flow boundary conditions, a rather large amount of data is required for film coefficient, temperature, and film effectiveness. Blocks 24, 25, and 26 describe the film heat transfer coefficients. Blocks 27 and 28 describe the coolant thermal coefficients. Blocks 29 through 32 describe the pedestal and film hole thermal coefficients. Blocks 93, 95, 96, and 97 provide the external and internal pressure data required to perform the flow analysis. Blocks 101 and 102 provide the surface boundary layer data, and Block 104 provides the needed film effectiveness data.

4.3 Materials

The T/STAEBL materials data is input on data Block 12. Due to the high temperatures involved in cooled turbine materials, properties must be input as functions of temperature. Properties that are required include: specific heat, thermal conductivity, coefficient of expansion, elastic modulus, .2% yield strength, .02% yield strength, density, creep and stress rupture properties. Properties are required for each material utilized, including coatings.

A materials data base program has been provided with the STAEBL system to ease generation of Block 12 input data. This program allows generation of a data bank of materials which may be extracted interactively by the user. Additionally, new materials may easily be input or properties updated. Convenient splining algorithms allow for flexible material property input. Details are provided in the T/STAEBL User's Manual.

4.4 Objective Function

The T/STAEBL procedure seeks to minimize an engine cost function, using weighting parameters that are provided by the user. The cost function may be a simple as the airfoil weight, or it may consist of a sophisticated total value to the engine operator which considers trades between weight, initial cost, maintenance cost and even aerodynamic performance. The value function is defined on the OBJECTIV card of data Block 503 which provides weighting values for the appropriate calculated behavior variables.

4.5 Constraints

For cooled turbine airfoils, static durability requirements are usually included in the objective function, as a maintenance penalty when the airfoils must be prematurely replaced. T/STAEBL provides the user the capability to put side limits on all design variables, and to limit the values for any of the behavior variables. Thus, the user may impose stress limits beyond those included in the objective function. Additionally, stage vibratory frequencies may be constrained.

Design margins may be included relative to idealized limits to recognize the effects of geometric, material, and operational tolerances and to compensate for approximations in the analyses or underlying assumptions. The constraint input for the T/STAEBL procedure is included in data Block 503.

4.6 Design Variables

A cooled airfoil is a complex structure, with many inputs required just to describe the basic geometry. Within the T/STAEBL system, many possible design alterations have been provided – more, in fact, than the ADS optimizer can effectively utilize. Some of the available design parameters, including supply pressure, tilt, and coating thickness, are single valued. Most of the parameters, however, may include spanwise variations. These include rib and wall thicknesses, trip strip height, pitch and angle, and pedestal spacing and diameter. Provisions have been made for chordwise variations of the cavity, trip strip, and pedestal design variables.

5. T/STAEBL ARCHITECTURE

The Thermal/Structural Tailoring of Engine Blades system is a large, complicated system. Many different analyses are present. These analyses are diverse in background and large in size. To assemble a single computer program with all of the capabilities present in T/STAEBL would require excessive amounts of memory resources.

To assemble the T/STAEBL system, therefore, required careful system planning. The T/STAEBL system has evolved to become a collection of separate computer codes, or modules, each of which is actually a stand-alone program. These modules are driven by a control program, which accesses each module as needed, controlling iteration loops on both the analysis and optimization levels. The programs communicate with each other through a data block structure, with file communications controlled by the control program.

5.1 T/STAEBL Control Program

The T/STAEBL control program controls the execution flow for the entire system. This executive system decides which of the program modules to execute, which data block files to assign as module input/output (I/O) units, and controls program looping, both on the analysis and on the optimization level. This T/STAEBL structure makes the system very flexible, for modules are very easily replaced. Since each module is a stand-alone program, argument list and common block consistency are not required, greatly simplifying system debugging, enhancement, and alteration.

5.2 T/STAEBL Analysis Modules

The T/STAEBL analysis modules consist of a collection of stand-alone computer programs that perform all of the tasks required to perform the design and analysis of a cooled turbine airfoil. The analysis capabilities of T/STAEBL include: thermal breakup, coating, network, boundary layer, film, conduction, creep, and finite element stress and vibrations analysis capabilities. Many of these modules have dedicated pre- and post-processors, which serve as communication aids between the analyses and the data block structure.

In addition to the above analysis modules, the T/STAEBL system also includes an optimizer to control design perturbation, and the Tailor module, which updates the design geometries, enabling the thermal analysis process. The optimizer is discussed in Section 6.

5.3 The Tailor Module

The Tailor module is truly one of the keys to the success of the T/STAEBL system. The geometry of cooled airfoils is so complex that many data files are required to fully define it. To allow an optimizer to update a few or many design parameters, and then construct a meaningful updated cooled airfoil geometry is a difficult task indeed. The Tailor module successfully performs this difficult task.

The Tailor module actually consists of four separate packages: an initialization program, a geometry update program, a network update program, and a creep update program. The initialization program does not perform any design updates, but queries the initial design to determine initial values for design variables that are not explicitly detailed in the data input. These initial values are required for design scaling during the optimization, but can only be indirectly evaluated. Values required include the cavity wall thicknesses, which can only be obtained by processing the exterior surface coordinates, and comparing locations with the coordinates of the appropriate cavity. Similarly, the values for any other indirectly referenced design variables are obtained.

The geometry update program takes the list of design variables, and, using the initial airfoil configuration, performs an update of all the relevant geometry data files. A comparison of an initial airfoil cross-section and an updated cross-section is shown on Figure 5. The Tailor module is set up so that a null design change (all design variables equal zero) always replicates the base, or original, airfoil. Thus, the system is at all times capable of reproducing the original, input configuration.

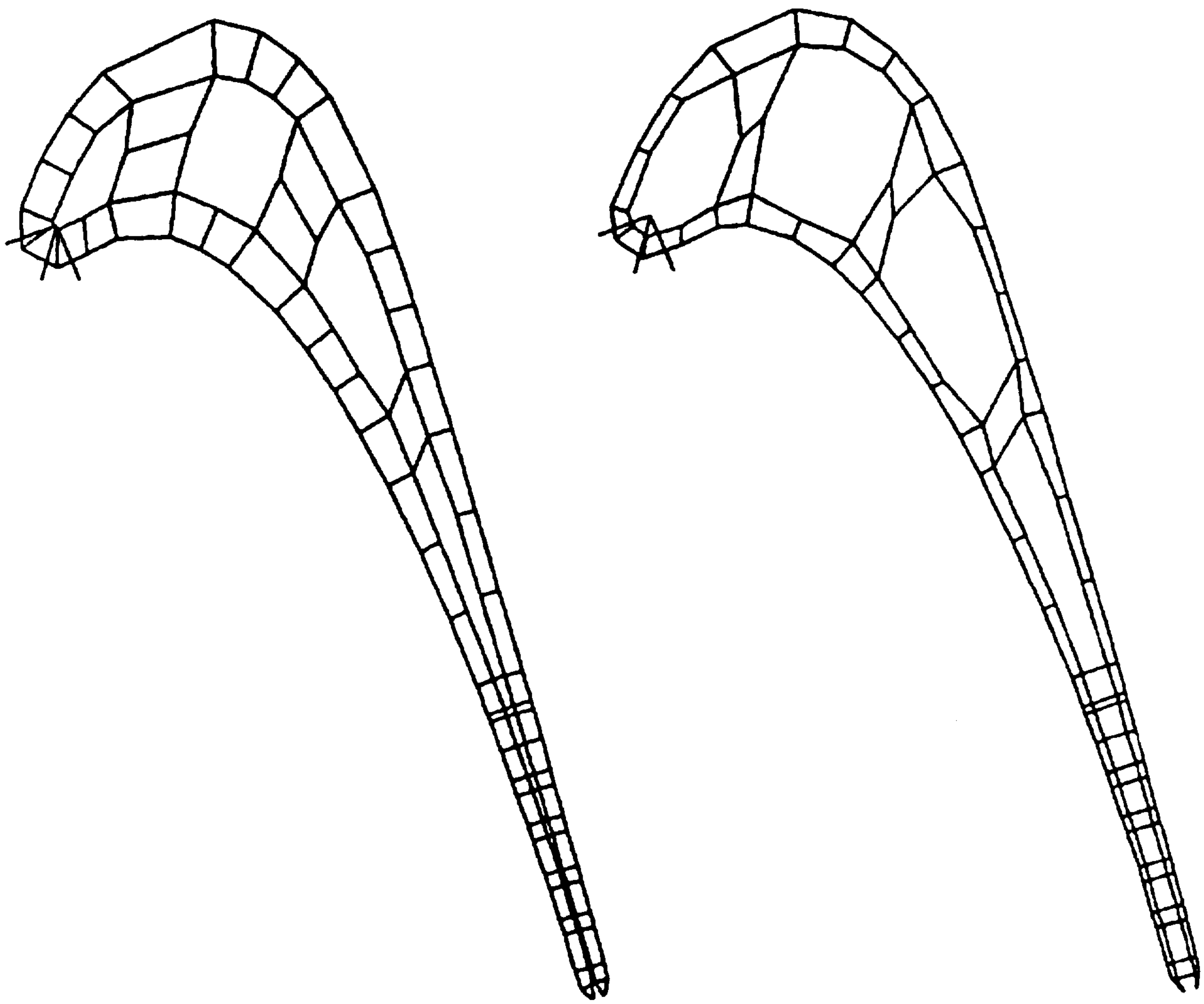

Figure 5   Initial Cross-Section Breakup, with Breakup Updated by the Tailor Module

The remaining Tailor programs update the airfoil network model and the centrifugal pulls required for the creep analysis. Each of these programs again reference the initial airfoil design, and update all relevant current design data blocks.

5.4 T/STAEBL Data Block System

Within the T/STAEBL system, the only means for the various modules to communicate amongst themselves and with the analyst is through an extensive data file system. All of the cooled airfoil thermal analysis data is stored in a system of data blocks, where each data block contains the data for a particular quantity for the entire blade – the convection coefficients, for example.

Each data block can consist of one or more data files. Those blocks which contain quantities that are not functions of span (e.g., supply pressure) consist of only a single data file. Those blocks that contain data which varies with the radial coordinate (airfoil coordinates, for example) consist of a separate file for each cross-section to be analyzed (five sections are recommended).

The data block system is further complicated by the presence of two complete sets of airfoil files: a set for the original, or base design, and another complete set for the design currently being analyzed. This potentially confusing situation is easily handled through a careful file naming convention. The filenames for the base blade all start with "b", while the filenames for the current blade start with "c". The remainder of the filename identifies the data block number. The file type indicates the airfoil section number, with a designator of "0" for those blocks which are independent of radial coordinate. Thus, file "b0001.3" indicates the block 1 file (airfoil coordinates) for the base blade, third cross section.

A full description of the T/STAEBL data blocks is included in the T/STAEBL Theoretical Manual (Reference 4). Detailed descriptions of those data blocks that must be assembled in order to perform a cooled airfoil optimization are included in the T/STAEBL User's Manual (Reference 3).

5.5 T/STAEBL/Optimizer Communications

The total number of potential design variables for the T/STAEBL system is well above 200 – more variables than have ever been optimized by the ADS optimizer, to our knowledge. Even if ADS can properly handle this large number of variables, the amount of computer time required to perform such an optimization would likely be prohibitive. Thus, for most if not all T/STAEBL applications, the design variables being used will be a subset of the total list available.

The ADS optimizer does not differentiate one design variable from another – it only knows that it has a list of quantities that it can change, and it seeks to find the best combination of potential changes. The Tailor module, on the other hand, was designed to work with the complete list of incremental values for potential variables. If a given parameter has not been designated as a design variable for an analysis, it simply has a value of zero. Thus, a variable list containing all zeroes will duplicate the base blade design.

To enable the optimizer to effectively communicate with the Tailor module, then, a list processing module was constructed. This processing module, called XPANDO, takes the current values of the design variables as selected by the optimizer, and then, using the current variable list, cross-references against the list of all potential design variables, finally constructing a full-sized file of all the design variable increments. This module also performs the curve splining required on design variables that are functions of radius. Thus, it is the XPANDO module that includes the effects of terms designated as Constant, or Dependent, in updating the relevant design curves.

Another module, the CONPROC module, reviews all of the analysis results and assembles a list of values of the objective function and the constraints for passage to the optimizer. It is this module, then, that processes the thermal and finite element analysis outputs, to pass the results to the rest of the system. CONPROC also assembles a summary file that is saved for review by the analyst.

6. OPTIMIZATION PROCEDURES

A common engineering design problem is the determination of values for design variables which minimize a design quantity such as weight, drag, or cost, while satisfying a set of auxiliary conditions. In the STAEBL program, the structural design of a composite or hollow fan blade is accomplished by varying airfoil section thicknesses, chord, titanium skin thickness, etc., to minimize a combination of weight and cost subject to constraints on resonance, flutter, stress, and foreign object damage.

6.1 General Optimization Theory and Background

The engineering design process can be modeled as a mathematical programming problem in optimization theory. In theoretical terms, this constrained minimization problem can be expressed as follows:

$$\text{minimize } f(\mathbf{x}) \tag{1}$$

subject to the auxiliary conditions,

$$g_i(\mathbf{x}) \leq 0, \; i=1, \ldots, m. \tag{2}$$

The quantity $\mathbf{x} = (x_1, \ldots, x_n)$ is the vector of n design variables. The scalar function to be minimized, $f(\mathbf{x})$, is the objective function; and $g_i(\mathbf{x}) \leq 0$, $i=1, \ldots, m$ are the m inequality constraints. Upper and lower bounds on the design variables, e.g.,

$$L_i \leq x_i \leq U_i, \; i=1, \ldots, n, \tag{3}$$

are referred to as side constraints. The n–dimensional space spanned by the design variables defines the design space. If $f(\mathbf{x})$ and $g_i(x)$, $i=1, \ldots, m$, are all linear functions of $\mathbf{x}$, the optimization problem is a linear problem (LP) which can be solved by well known techniques, such as Dantzig's simplex method. If $f(\mathbf{x})$ or any of the $g_i(\mathbf{x})$'s are nonlinear, then it is a nonlinear programming (NP) problem for which a number of solution techniques are also available. If the objective function, $f(\mathbf{x})$, is to be maximized, then the equivalent problem of minimizing $-f(\mathbf{x})$ is performed.

Any choice of variables, $\mathbf{x}$, in design space that satisfies all the constraints, (2) and (3), is a feasible point. As shown in Figure 6, the union of all feasible points comprises the feasible region. The locus of points which satisfy $g_i(\mathbf{x}) = 0$ for a particular i, forms a constraint surface. On one side of the surface, $g_i(\mathbf{x}) \leq 0$ and the constraint is satisfied; on the other side, $g_i(\mathbf{x}) \geq 0$ and the constraint is violated. Points on the interior of the feasible region are free points; points on the boundary are bound points. If it is composed of two or more distinct sets, the feasible region is disjoint. A design point in the feasible region that minimizes the objective function is an optimal feasible point and is a solution of the problem posed in (1) through (3). As in any nonlinear minimization problem, there can be multiple local minima. In this case, the global minimum is the optimal feasible point. If a design point is on a constraint surface (i.e., $g_i(\mathbf{x}) = 0$ for some i), then that particular constraint is active. A solution to a structural optimization problem is almost always on the boundary of the feasible region, and is usually at the intersection of two or more constraint surfaces (i.e., there are two or more active constraints).

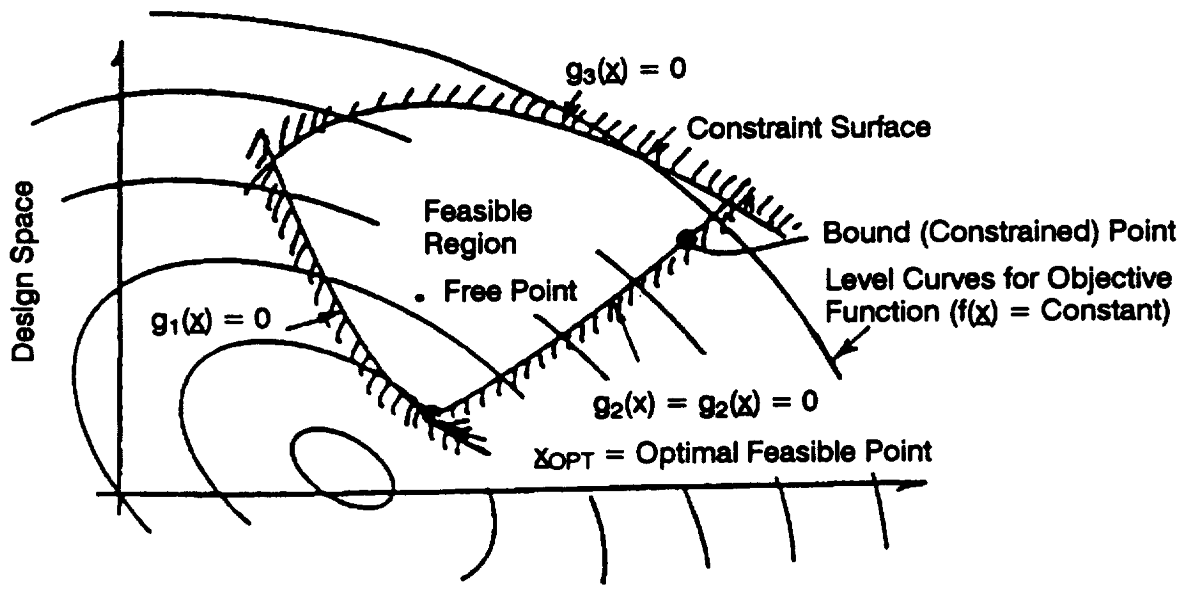

Figure 6 Feasible Region Is Union of All Points that Satisfy All Constraints

There are two basic approaches to solving the constrained optimization problem posed in (1) through (3): direct methods (e.g., methods of feasible directions), and indirect methods (e.g., penalty function methods).

In a direct method, the objective function and constraints are evaluated independently, and the constraints are treated as limiting surfaces. Zoutendijk's method of feasible directions is an example of a direct method.

In an indirect method, the problem is reformulated so that (1) through (3) are replaced by a single unconstrained optimization problem. For example, in an exterior penalty function method, violations of the constraints are added onto the objective function to form an augmented objective function. If a constraint is violated, a penalty term is added onto the objective function. By minimizing the objective function subject to increasing values of the penalty parameter, the optimum may be obtained. One advantage of this approach is that each of the successive minimization problems can be solved using a standard unconstrained function minimization technique, such as a conjugate gradient or quasi–Newton method. Computationally, however, the process is not usually competitive with direct procedures.

Many optimization software packages are available in software libraries (e.g., IMSL = International Mathematical and Statistic Libraries, Inc., and HARWELL) that can solve the constrained minimization problem using either direct or indirect techniques. Because of its proven success and versatility in solving structural optimization problems at Pratt & Whitney, NASA/Langley, General Motors, Ford, and other locations, the ADS (Automated Design Synthesis) computer program was selected for the T/STAEBL cooled blade optimization application. The ADS program (Reference 2) is a general optimization package developed by G. N. Vanderplaats of Engineering Design Optimization, Inc. for NASA/Langley.

6.2 T/STAEBL ADS Implementation

ADS is a general purpose numerical optimization program containing a wide variety of optimization algorithms. The solution of the optimization problem has been divided into three basic levels by ADS: (1) strategy, (2) optimizer, and (3) one–dimensional search. By allowing users to select their own strategy, optimizer, and one–dimensional search procedure, considerable flexibility is provided for finding an optimization algorithm which works well for the specific design problem being solved.

Strategy

The optimization strategies available in T/STAEBL are listed in Table II. The parameter ISTRAT is sent to the ADS program to identify the strategy selected by the user. Selecting the ISTRAT=0 option transfers control directly to the optimizer. This is selected when choosing the Method of Feasible Directions or the Modified Method of Feasible Directions for solving the constrained optimization problem.

Table II. ADS Strategy Options

ISTRAT	*Strategy to be Used*
0	*None. Go directly to the optimizer.*
1	*Sequential unconstrained minimization using the exterior penalty function method.*
2	*Sequential unconstrained minimization using the linear extended interior penalty function method.*
3	*Sequential unconstrained minimization using the quadratic extended interior penalty function method.*
4	*Sequential unconstrained minimization using the cubic extended interior penalty function method.*
5	*Augmented Lagrange multiplier method.*
6	*Sequential linear programming.*
7	*Method of centers.*
8	*Sequential quadratic programming.*
9	*Sequential convex programming.*

Optimizer

The IOPT parameter selects the optimizer to be used by ADS. Table III lists the optimizers available within T/STAEBL. Note that not all optimizers are available for all strategies. Allowable combinations are shown on Table V.

Table III. ADS Optimizer Options

IOPT	Optimizer to be Used
1	*Fletcher–Reeves algorithm for unconstrained minimization.*
2	*Davidon–Fletcher–Powell (DFP) variable metric method for unconstrained minimization.*
3	*Broydon–Fletcher–Goldfarb–Shanno (BFGS) variable metric method for unconstrained minimization.*
4	*Method of Feasible Directions for constrained minimization.*
5	*Modified Method of Feasible Directions for constrained minimization.*

One–Dimensional Search

Table IV lists the one–dimensional search options available for unconstrained and constrained optimization problems. The parameter ISERCH selects the search algorithm to be used.

Table IV. ADS One–Dimensional Search Options

ISERCH	One–Dimensional Search Option
1	*Find the minimum of an unconstrained function using the Golden Section method.*
2	*Find the minimum of an unconstrained function using the Golden Section method followed by polynomial interpolation.*
3	*Find the minimum of an unconstrained function by first finding bounds and then using polynomial interpolation.*
4	*Find the minimum of an unconstrained function by polynomial interpolation/extrapolation without first finding bounds on the solution.*
5	*Find the minimum of a constrained function using the Golden Section method.*
6	*Find the minimum of a constrained function using the Golden Section method followed by polynomial interpolation.*
7	*Find the minimum of a constrained function by first finding bounds and then using polynomial interpolation.*
8	*Find the minimum of a constrained function by polynomial interpolation/extrapolation without first finding bounds on the solution.*

Allowable Combinations of Algorithms

Not all combinations of strategy, optimizer, and one–dimensional search are meaningful. For example, it is not meaningful to use a constrained one–dimensional search when minimizing unconstrained functions. Table V identifies those combinations of algorithms which are meaningful in the T/STAEBL program. In this table, an X is used to denote an acceptable combination of strategy, optimizer, and one–dimensional search, while an O indicates an unacceptable choice of algorithm. To use the table, start by selecting a strategy. Read across to determine the admissible optimizers for that strategy. Then, read down to determine the acceptable one–dimensional search procedures. From the table, it is clear that a large number of possible combinations of algorithms is available.

Table V. ADS Program Options

			Optimizer		
Strategy	1	2	3	4	5
0	X	X	X	X	X
1	X	X	X	O	O
2	X	X	X	O	O
3	X	X	X	O	O
4	X	X	X	O	O
5	X	X	X	O	O
6	O	O	O	X	X
7	O	O	O	X	X
8	O	O	O	X	X
9	O	O	O	X	X
One–Dimensional Search					
1	X	X	X	O	O
2	X	X	X	O	O
3	X	X	X	O	O
4	X	X	X	O	O
5	O	O	O	X	X
6	O	O	O	X	X
7	O	O	O	X	X
8	O	O	O	X	X

Notes: X = Acceptable
O = Not Acceptable

6.3 Optimizer Comparison

A simplistic comparison of the optimization algorithms available to the ADS program was conducted by optimizing a simple beam. The problem is to minimize the weight of a rectangular cross–section cantilever beam under bending load, subject to bending stress, shear stress, aspect ratio, and deflection constraints. A sample of the options available in the ADS program was run, as detailed in Table VI. As can be seen from the table, the feasible directions and the modified feasible directions procedures are among the most efficient optimization algorithms yet developed. This trend has also applied to the T/STAEBL optimizations thus far conducted.

Table VI. ADS Optimization Algorithm Comparison

ISTRAT	IOPT	ISERCH	Function Calls	Min. Weight
0	4	7	21	6763
0	4	5	46	6525
0	5	5	43	6637
0	5	6	43	6637
0	5	7	29	6603
0	5	8	23	6574
1	1	8	62	8451
2	1	8	134	7440
3	1	8	137	7426
4	1	8	26	20000
5	1	8	55	10102
5	2	8	52	7445
5	3	8	56	7336
6	4	8	24	6613
6	5	8	24	6626
7	5	8	33	7548
8	5	8	34	6476
9	5	8	33	6757

6.4 Estimated Function Call Requirements

A reasonable estimate for the number of analysis function calls, and hence the amount of computer time that will be required, may be made based on experience with the ADS optimizer and T/STAEBL. As indicated in Figure 6, each optimizer design iteration consists of a gradient evaluation of the objective function and constraints to determine the search direction, followed by a one-dimensional line search in that direction. When the gradients are not known analytically (as is the case for the T/STAEBL application), a backward difference gradient approximation is used. For n design variables, n function calls are required for the finite difference gradient calculation.

Method of Feasible Directions

The one-dimensional line search usually requires 3 additional function evaluations to update the objective function and constraints and to determine where the search should terminate. Thus, for m iterations, with n+3 function calls per iteration, we have:

$$N = m\ (n + 3), \tag{4}$$

where N is the number of function evaluations required to determine the optimum design. Typically, convergence is attained in approximately 10 iterations, so that a good estimate for function call requirements is $N = 10\,n + 30$. Notably, N increases linearly with an increase in the number of design variables.

Modified Method of Feasible Directions

The modified method of feasible directions tends to follow the actual constraint surface more closely than does the method of feasible directions, and hence requires fewer design iterations, often converging in 4 or 5 iterations. This is done at the sacrifice of more moves along the one-dimensional line search, often taking 8 or 10 of these. In all, a reasonable estimate for function call requirements for this method is $N = 6\,n + 50$. Thus, for relatively large problems, this procedure promises to be more economical than the method of feasible directions. In practice, it is often useful to test each method, for at times one will achieve a superior design, regardless of function call requirements.

6.5 ADS Interface with T/STAEBL Approximate Analyses

As detailed in Sections 5.1 and 5.5, each of the T/STAEBL modules is a stand-alone program, with communications occurring through the T/STAEBL data base. To fit this architecture, a driver routine for the ADS program was assembled, to enable it to run in a "restart" mode. Notably, several updates to the ADS code itself (Version 2.1) were required to enable the work storage array to recover properly in restart operation.

The T/STAEBL modules that interface between ADS and T/STAEBL, as explained in Section 5.5, deal primarily in ensuring that the data forms are consistent between the optimizer and the Tailor program. The optimizer wants to deal with a compressed data set – only active design variables, and relevant constraints. The remainder of the T/STAEBL system, for simplicity, deals with a full list of available design variables and constraints. Modules are available that expand and contract the data lists to meet the requirements of the upcoming module(s).

7. T/STAEBL HOLLOW AIRFOIL ANALYSES

7.1 Cooled Airfoil Thermal Analyses

Within the T/STAEBL optimization system is a complete analysis system for the thermal and flow analyses of cooled airfoils, used to determine the performance characteristics of each candidate design proposed by the T/STAEBL optimization system.

Within the analysis process for each candidate design, many analysis modules are involved in the cooled blade evaluation process. These modules all execute separately, with the analysis flow controlled by the execution shell. Modules communicate with each other through the data block system. Figure 7 is a flow chart, detailing the cooled blade thermal analysis flow.

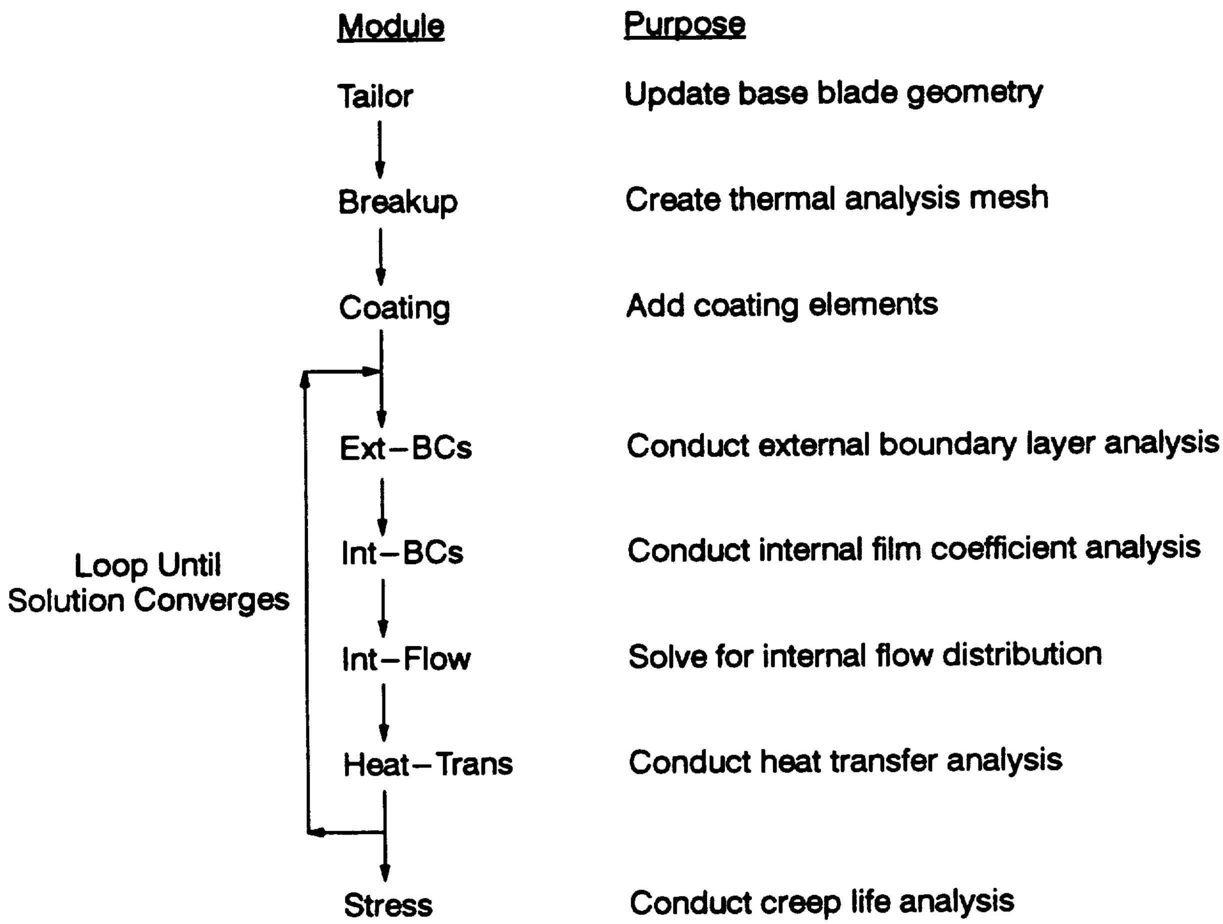

Figure 7 Cooled Airfoil Analysis Subsystem Flow

The Tailor module is an interpreter of the design change requests passed down for analysis by the optimizer. This module modifies the original blade geometry to create a modified geometry for design evaluation. Due to the rather specific nature of the geometry alterations available within T/STAEBL, Tailor code modification will be required for application of this optimization algorithm to geometries that are radically different from the triple pass cooled airfoil Energy Efficient Engine designs employed for this effort. This module creates updated geometry description blocks to reflect the altered blade design.

The Breakup program is a processor that uses coarse breakup blocks to create a refined mesh of elements for heat conduction analysis. In addition to application for heat conduction analysis, this element map is used to remap results from a boundary condition processor to the associated boundary condition block.

The Coating analysis is a module that adds a layer of coating to the airfoil by adding a face set of elements to the outer surface of the primary airfoil mesh. These elements are given a thickness equal to that of the coating, and are usually meshed to fit the existing refined elements of the primary airfoil.

The external boundary layer, internal film coefficient, internal flow distribution, and heat transfer analysis programs all fall within an iteration loop to generate geometries and breakups for each of the five airfoil cross–sections that will be analyzed. After all section geometries have been generated, an exit from the thermal analysis system is provided. This exit is utilized on the very first analysis pass, when the shell wants to generate an initial geometry, but is not yet ready to perform a design analysis. After this initialization, all passes through the thermal analysis system will include both the geometry and analysis modules.

The first analysis module, the external boundary layer analysis, updates the network model of the airfoil geometry, based on the current values of the design parameters, and the results of the airfoil remodelling and analysis that has been performed by the previous modules.

At this point, the T/STAEBL thermal analysis system is ready to begin a complete steady–state analysis of the updated hollow airfoil geometry. This analysis process is an iterative one, because the boundary conditions for one part of the analysis can change as the results of other modules of the analysis loop are received. To allow all boundary conditions to reach a converged state, a simple iteration procedure is employed. Starting with the converged boundary conditions of the previous analysis pass, this thermal analysis iteration loop is performed three times. Experience has shown that three passes through this analysis loop provide adequate boundary condition convergence for the T/STAEBL optimization procedure.

Within this iterative analysis loop, the first module employed is the Network analysis. This processor determines the flow distribution through an airfoil, using network geometry and one–dimensional correlations for internal geometry features. Outputs include temperatures and heat transfer coefficients from the airfoil interior, and also the mass flow of the coolant. Results apply to all sections of the airfoil.

At this point, a loop is entered, and three analysis modules, along with three boundary condition update processors, are executed for the interior three cross–sections of the airfoil. The Boundary Layer analysis performs a numerical solution of the boundary layer equations to determine external heat transfer coefficients.

The Film analysis uses correlations associated with film cooling to identify the differences between uncooled external heat transfer coefficients and those that exist downstream of film holes.

With both the external and internal heat transfer boundary conditions determined, the Conduction Analysis module is executed, to solve for the heat transfer that occurs inside the metal portions of the airfoil. This program is a finite difference solution to the heat conduction equations.

After the heat transfer analyses have been performed, three modules are executed to update the boundary conditions associated with these analyses. Two more passes are made through this iterative solution to ensure convergence of the thermal analyses.

After the airfoil thermal condition has been determined, a life prediction analysis is conducted. This analysis calculates the stresses in each of the airfoil elements, assuming that the elements are free to slip between each other. As some of the elements move into a yielded condition, the life prediction module accumulates the yield deflection as a portion of the component life.

For vanes, the life prediction uses an empirically based calculation to calculate the oxidation life of the part.

Technical details of each of the cooled airfoil thermal analyses, including the correlations employed, are listed in Section 2.3 of the Thermal/Structural Tailoring of Engine Blades (T/STAEBL) Theoretical Manual (Reference 4).

7.2 Finite Element Structural Analysis

To perform a finite element vibrations analysis of a cooled airfoil, an efficient yet accurate model of the geometry is required. To remain computationally feasible in STAEBL's optimization application, a plate element, rather than a brick element, model was selected. To accurately model the geometry, each wall is modelled as a separate array of plates. Ribs, which tie the walls together, are also modelled using plate elements. The same procedure was applied to the trailing edge, where pedestals provide a wall to wall shear tie.

To accurately model the airfoil vibratory characteristics, the neck flexibility must be included. In T/STAEBL, the airfoil neck is modelled using beam elements that are tied to the root of the airfoil using rigid elements, which automatically write the correct kinematic links between the neck and the airfoil, even though the airfoil grid locations may be varying from design step to design step. The beam elements are oriented so that their minimum bending inertia aligns with the disk broach angle.

7.2.1 Airfoil Finite Element Mesh Generation

Within the T/STAEBL system is the capability to change the thicknesses of walls and ribs. These changes must be reflected in any finite element model of the blade to assure a proper coupling with the changes being made to the design.

This interaction of structural and thermal analyses has been effectively included in T/STAEBL by interfacing the finite element mesh generator with the TAILOR cooled blade design update module. The TAILOR module outputs the airfoil updated geometry to several "current" data blocks. The data block used by the finite element mesh generator is Block 91, which contains information relevant to the thermal breakup as well as the structural breakup.

7.2.2 Airfoil Neck Model

To model the airfoil attachment and extended neck regions, a beam representation has been found sufficiently accurate for frequency determinations. In T/STAEBL, two options are available. If no NECKGEOM card is included in Block 503 of the input data, the airfoil will be fully restrained at its root. Attachment and neck flexibility may be included by using the NECKGEOM option.

When a NECKGEOM card is included, T/STAEBL will model the attachment to airfoil root section using a beam finite element model. The user inputs the cross-sectional (assumed constant with radius) area, bending moments of area, and torsional stiffness constant. Also included is an orientation, or broach, angle.

7.2.3 The T/STAEBL Finite Element Analysis

The airfoil natural frequencies are calculated in T/STAEBL by using an in-core, limited size finite element analysis. The finite element code is fashioned after NASTRAN, so that a mesh run in T/STAEBL or in NASTRAN will give nearly identical results. While several elements are available, the elements employed by T/STAEBL include a spring element, a beam element, and a four-noded quadrilateral thin shell element.

Specifically designed for the analysis of rotating airfoils, the finite element module first performs a static analysis, then calculates a differential stiffness matrix. Third, the finite element analysis calculates the natural frequencies of the rotating blade. In the static case (vane), the first two steps are skipped.

7.2.4 Model Performance

The finite element mesh of Figure 8 was used for analysis of the Energy Efficient Engine first-stage turbine blade. In total, it contains 68 grid points and 83 quadrilateral plate elements. The stiffness matrix has a semi-bandwidth of 102. To run the analysis, the finite element code must have work storage of 1 megabyte available. Execution of all the T/STAEBL modules took 58 seconds per full function call on an IBM-3090.

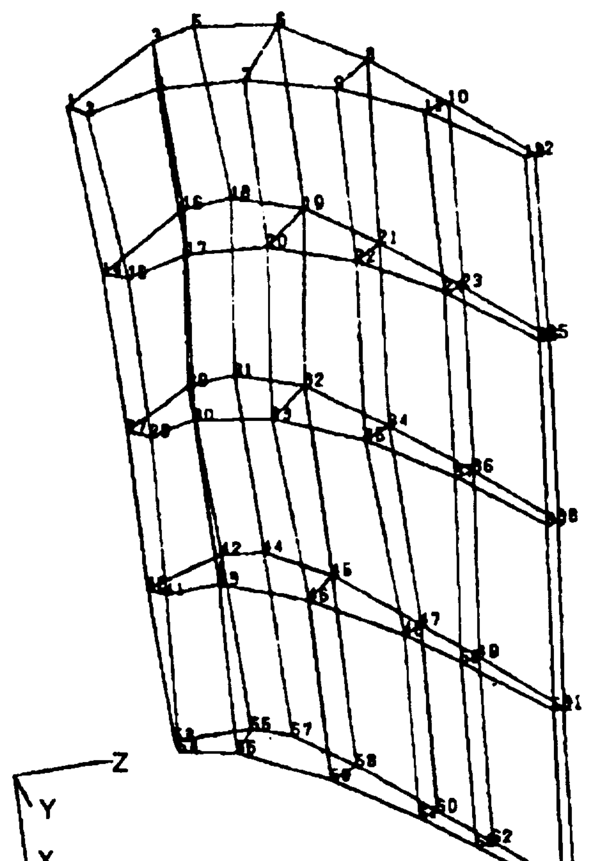

Figure 8 Cooled Turbine Blade Vibration Analysis Mesh

The T/STAEBL finite element turbine blade model compares quite well with much more detailed NASTRAN analysis. Table VII shows the frequency comparisons between the detailed NASTRAN model and the approximate T/STAEBL model. The detailed results were generated in the design phase for the Energy Efficient Engine (Reference 5).

Table VII. Energy Efficient Engine High Pressure Turbine Frequency Analysis Comparisons

Mode	Detailed NASTRAN Model (cps)	T/STAEBL (cps)
1	1788	1800
2	2616	2617
3	3178	3287

8. PROGRAM USAGE

8.1 Input Data Blocks

T/STAEBL Data Block Structure

The T/STAEBL cooled blade analysis system modules are all stand–alone programs, with no subroutine callable arguments. The analysis modules of the T/STAEBL system communicate among each other through a system of data blocks. The data blocks may contain basic input data, data produced by one program that will be required by another, or system outputs. To aid system development, increase flexibility, and speed new user learning, all data blocks are in ASCII format. Thus, any intermediate inputs and outputs may be edited and interpreted by the user.

The T/STAEBL data blocks are all numbered. A detailed list of the data blocks, their number designations, and their usage is provided in the T/STAEBL Theoretical Manual (Reference 4). In this report, we simply give an overview of the kinds of data blocks required to permit a cooled blade optimization.

Required Input Data Blocks

To run a cooled airfoil optimization, a number of input data blocks are required. These blocks include the necessary data for optimization control, as well as for thermal and structural analysis of a candidate cooled foil design.

Design Variation Procedure

In the Aero/Structural Tailoring of Engine Blades program (Reference 2), which allowed the optimization of fan and compressor blading, basic geometric and aerodynamic parameters were input via design curves. While T/STAEBL still utilizes the design curve principle, the design curves are now inferred from the input geometry and performance data blocks. As such, the optimization inputs of T/STAEBL are a subset of the inputs used in Aero/STAEBL. ABSCISSA and CURVE cards are not permitted. Instead, a blade is defined using five data sections, at 0%, 25%, 50%, 75%, and 100% spans. Thus, the allowable abscissa values are predefined. Additionally, the program automatically builds design curves for a generous number of parameters. Those parameters that may be altered as design variables are listed in Table VIII.

T/STAEBL Design Variables

Within T/STAEBL, those parameters that are to be treated as design variables or constraints for a particular optimization are defined in data Block 503.

As mentioned previously, the T/STAEBL design curves are automatically constructed by the program to allow the set of variables listed in Table VIII. Not all variables lead directly to design curves, however – the first five variables, as noted, are single valued. While tilts could be generalized into design curve formats, they are currently treated as tip tilt values. Tilts at intermediate sections are linearly interpolated from zero at the root to the indicated tip values.

A design parameter is declared to be a variable by being called out on a VARIABLE card in the design optimization input. As the optimizer alters the value of a variable, the design curves are updated, and intermediate station value increments are determined from spline fits. Since the user may want to hold a value at a station constant, a CONSTANT option has been provided. Also, the user may vary one term in direct proportion with another through usage of the DEPEND option.

Table VIII. T/STAEBL Design Variables

Variable	Abbreviation
Single Valued Parameters	
Supply Pressure	SUPPRS
Axial Tilt	AXTILT
Tangential Tilt	TANTILT
Secondary Material Angle	SMATANG
Coating Thickness	COATTHK
Design Curves	
Variable	***Abbreviation***
Rib 1 Thickness	RIB1THK
Rib 2 Thickness	RIB2THK
Rib 3 Thickness	RIB3THK
Cavity 1 Pressure Side Thickness	CV1PTHK
Cavity 1 Suction Side Thickness	CV1STHK
Cavity 2 Pressure Side Thickness	CV2PTHK
Cavity 2 Suction Side Thickness	CV2STHK
Cavity 3 Pressure Side Thickness	CV3PTHK
Cavity 3 Suction Side Thickness	CV3STHK
Cavity 4 Pressure Side Thickness	CV4PTHK
Cavity 4 Suction Side Thickness	CV4STHK
Cavity 1 Trip Strip Height	CAV1TSH
Cavity 1 Trip Strip Pitch	CAV1TSP
Cavity 1 Trip Strip Angle	CAV1TSA
Cavity 2 Trip Strip Height	CAV2TSH
Cavity 2 Trip Strip Pitch	CAV2TSP
Cavity 2 Trip Strip Angle	CAV2TSA
Cavity 3 Trip Strip Height	CAV3TSH
Cavity 3 Trip Strip Pitch	CAV3TSP
Cavity 3 Trip Strip Angle	CAV3TSA
Pedestal 1 Diameter	PED1DIA
Pedestal 2 Diameter	PED2DIA
Pedestal 3 Diameter	PED3DIA
Pedestal 4 Diameter	PED4DIA
Pedestal 5 Diameter	PED5DIA
Pedestal 6 Diameter	PED6DIA
Pedestal 7 Diameter	PED7DIA
Pedestal Spacing	PEDSPAC
Film Hole 1 Diameter	FLM1DIA
Film Hole 2 Diameter	FLM2DIA
Film Hole 3 Diameter	FLM3DIA
Film Hole 1 Spacing	FLM1SPC
Film Hole 2 Spacing	FLM2SPC
Film Hole 3 Spacing	FLM3SPC

Constraints

Two forms of constraints are permitted in T/STAEBL: side constraints, and constraints on calculated values. Side constraints define the upper and lower limits of values which a variable is allowed to take. Since their value relative to the parameter value is known at the start of any function call, gradient values are not required for these constraints.

Within the T/STAEBL analysis procedure, many values are calculated that give important information relating to the life or performance of an airfoil. These values are stored in a data Block 515, with the values arranged as listed in Table IX. By referencing an appropriate address in this data block, the user may prescribe allowable limits for any of these values. This process is accomplished by using a CONSTRNT card. If only a single speed analysis is called for in the finite element control, fields 31–40 in this data block will be meaningless.

Table IX. Calculated T/STAEBL Performance Parameters (Block 0515)

Location	Calculated Value Description
–1– thru –10–	*Natural frequencies, first analysis speed, first ten modes of vibration*
–31– thru –40–	*Natural frequencies, second analysis speed, second ten modes of vibration*
–90–	*Single airfoil weight, lb*
–91–	*Root section P/A membrane stress, psi*
–92–	*Coolant flow rate, lb/sec*
–93–	*Average profile loss, Δ pt/pt*
–94–	*Average film mixing loss, Δ pt/pt*
–95–	*Maximum temperature, °F*
–96–	*Average blade temperature, °F*
–97–	*Percent of life used in 10 hours*

Objective Function

Due to the variability of cost/weight/performance trades depending on aircraft, fuel cost, cost of raw materials, etc., a general objective function has been included in the T/STAEBL system. Through using the OBJECTIV card, the user is allowed to define the objective function as a linear combination of stored performance parameters, including the airfoil weight, stress, coolant flow, losses, maximum temperature, average temperature, and life consumption.

Using this procedure, the user is able to supply the cost sensitivities to the program. If no OBJECTIV card is provided, T/STAEBL will default to a minimum airfoil weight optimization.

Thermal Analysis Input

To allow the performance of a complete cooled airfoil thermal analysis, as performed by T/STAEBL, numerous input data blocks, detailed in Reference 3, are required. These blocks include:

Block Number	Airfoil Sections	Block Description
1	1–5	Section Geometry – airfoil cross-section coordinate definition
12	0	Materials Data
16	0	Thermal Cycle Definition
17	1–5	Blade Thermal Analysis Breakup
22	1–5	Creep Cycle Definition
23	1–5	Film Hole Geometry
24–26	1–5	Gas Convective and Thermal Properties
27–28	1–5	Coolant Convective and Thermal Properties
29–30	1–5	Pedestal Convective and Thermal Properties
31–32	1–5	Film Hole Convective and Thermal Properties
37	1–5	Pedestal Geometry
93	1–5	External Pressure Ratios
95	0	External Total Pressures
96	0	Internal Total Pressures
97	0	External Total Temperatures
99	0	Internal Cooling Reference Data
101–102	1–5	Boundary Layer Data
104	1–5	Film Effectiveness
400	1–5	Conduction and Network Analyses Base Input
401	0	Network Analysis Input
501	0	Coating Thickness
504	0	Network Analysis Post–Processing
505	0	Network Analysis Iteration Control
506	0	Network Analysis Post–Processing Control
507	0	1–D Heat Transfer Control
512	1–5	Thermal Analysis Flag Point Definition
513	0	Global Section Radii
514	0	Network to Cavity Cross Reference
520	0	Oxidation Life Parameters

Vibration Analysis Input

T/STAEBL includes a finite element analysis that has both static and modal analysis capabilities, to perform the vibrations analysis of a rotating airfoil. The finite element code has an element library that includes spring, beam, and shell (both triangular and quadrilateral) elements. To model the hollow cooled airfoils applicable to T/STAEBL, beam elements are utilized in the airfoil neck. Quadrilateral plate elements are used to model both walls of the cooled airfoil, as well as modelling the ribs that tie the walls together. Trailing edge pedestals are modelled using links to tie the offset airfoil walls.

To perform the T/STAEBL finite element frequency analysis, three separate input blocks are required:

1. Block 502, Finite Element Mesh Control, to interface between the cooled blade coordinate descriptions and the finite element mesh generation

2. Extended neck geometry definition

3. Block 516, finite element analysis control.

8.2 Materials Data Base

To aid in the generation of the T/STAEBL input data, an interactive materials data base has been created. This data bank will take materials data in several forms, including tabular data, estimation equations, and spline coefficients. From this input, the data base prepares the Block 12 materials block required to execute the T/STAEBL program. Property data that are processed include: specific heat, thermal conductivity, coefficient of expansion, elastic modulus, yield strength, density, creep and stress rupture data.

Besides Block 12 generation, the materials data base also allows graphic review of the material property curves. The user may edit the properties for any material and also may add materials to the data base.

8.3 Program Execution

Execution of the T/STAEBL system has been facilitated on the NASA–Lewis Research Center CRAY through the use of an interactive shell program. Prior to execution, the user must have generated all of the required input data blocks, detailed in Reference 3. The T/STAEBL job submitter will ask the user how many design iterations he/she would like performed.

Upon completion of the job submitter, a batch job is submitted to the CRAY. All needed data blocks are then accessed. Outputs are disposed to the user's CMS account on run completion.

Several output files are created by a T/STAEBL execution. If run–time errors are encountered, a diagnostics file is created. Additionally, an ADS output file reports the optimizer interactions; a T/STAEBL report file summarizes the variables, constraints, objective function, frequencies, and thermal performance parameters for each function call; and finite element mesh and frequency output files detail the current vibration analysis.

9. T/STAEBL VALIDATION

A comprehensive test case has been conducted to demonstrate the cooled airfoil optimization capabilities of the T/STAEBL system. The test case derives from the Energy Efficient Engine (EEE) design, which was designed under NASA Contract NAS3–20646, and consists of a full Thermo–Structural optimization of the first turbine blade, which is a cooled, triple pass airfoil. This blade configuration includes trip strips, cooling holes, pedestals, and every other complication common to modern, cooled airfoils.

9.1 EEE First Turbine Blade Optimization

The inputs for the turbine blade optimization test case include all those data blocks required for running the T/STAEBL system, as detailed in the T/STAEBL User's Manual (Reference 1).

The first turbine blade finite element structural model was built as detailed in Section 2.5, and contained 68 nodal points, serving as vertices for 83 quadrilateral shell elements. Each of the cavity walls and each of the ribs are modelled. At the trailing edge of the airfoil, pedestal groups are modelled using additional quadrilateral rib elements. Five radial stations are employed for this approximate model.

Design Variables

For this cooled blade optimization, 14 design variables were employed. As will be seen, the constraints are frequency constraints. As such, the design variables utilized were ones which could have a frequency impact on the blade. Six of the design variables were assigned to the thickness of the ribs between cavities. A variable thickness was assigned to the thickness of each of the three ribs at the root and at the tip of the airfoil. The curve splining algorithm of T/STAEBL thus allows for linear thickness change variations for each rib between root and tip.

The remaining eight design variables were assigned to variations in the thickness of the wall of each side of each cavity at the tip of the blade. As such, the T/STAEBL blade optimizer had a lot of freedom for varying the structural design of the EEE first turbine blade. A complete list of the design variables employed for this optimization is:

RIB1THK1	–	Rib 1, thickness at station 1 (root)
RIB1THK5	–	Rib 1, thickness at station 5 (tip)
RIB2THK1	–	Rib 2, thickness at station 1 (root)
RIB2THK5	–	Rib 2, thickness at station 5 (tip)
RIB3THK1	–	Rib 3, thickness at station 1 (root)
RIB3THK5	–	Rib 3, thickness at station 5 (tip)
CV1PTHK5	–	Cavity 1, pressure side thickness, tip
CV1STHK5	–	Cavity 1, suction side thickness, tip
CV2PTHK5	–	Cavity 2, pressure side thickness, tip
CV2STHK5	–	Cavity 2, suction side thickness, tip
CV3PTHK5	–	Cavity 3, pressure side thickness, tip
CV3STHK5	–	Cavity 3, suction side thickness, tip
CV4PTHK5	–	Cavity 4, pressure side thickness, tip
CV4STHK5	–	Cavity 4, suction side thickness, tip

For a cooled blade design and optimization, nearly any reasonable structural configuration can be designed to have adequate life, simply by providing high volumes of cooling air. Thus, airfoil life is not usually considered as a design constraint, but is most often included in the objective function, as a cost of prematurely replacing an airfoil, to be traded against the higher fuel cost associated with utilization of increased amounts of cooling air to enhance the life of the airfoil. However, if a blade is operating at a low integer multiple of its natural frequency, its life will be limited by this resonant condition, and will not be enhanced by increased cooling air flows.

Thus, in a cooled airfoil optimization, it is desirable to have frequency constraints included. Indeed, it is possible that these will be the only constraints imposed on the optimization. For the current test case, the T/STAEBL system evaluated the first two frequencies to be 1799 cps and 2620 cps for the base airfoil. For purposes of the optimization demonstration, it was decided to constrain the first frequency to be greater than 1850 cycles per second, and the second frequency to be less than 2700 cycles per second. Thus, for this demonstration, the first frequency constraint was violated by the base design. The geometry must be modified by the T/STAEBL system to achieve a feasible configuration.

To demonstrate the capabilities of the T/STAEBL system, the first test case consisted of a weight minimization of the EEE first turbine blade airfoil. As evaluated by T/STAEBL, the foil for the base blade has a weight of .208 lb.

Optimization Results

Recalling that the first frequency of the base blade is too low, one would be inclined to expect the T/STAEBL system to add mass to the root of the blade, to increase airfoil stiffness, and raise the frequency. Table X documents the actual design moves performed by the optimizer. Note that, while the airfoil weight increases for moves 2 and 3, the T/STAEBL system quickly finds a lighter design to be superior. It takes T/STAEBL until design 6 to reach a blade design that satisfies the frequency constraints. At this time, the foil weight is .1990 lb.

Table X. Turbine Blade Optimization Design Moves

DESIGN MOVE:	*1 (BASE)*	*2*	*3*	*4*	*5*	*6*	*7*
OBJECTIVE FUNCTION VALUE:							
WEIGHT:	*.2079*	*.2046*	*.2164*	*.2104*	*.2030*	*.1996*	*.1999*
CONSTRAINT VALUES:							
FREQ 1:	*1799*	*1833*	*1816*	*1822*	*1843*	*1872*	*1871*
FREQ 2:	*2620*	*2611*	*2583*	*2596*	*2607*	*2598*	*2599*
DESIGN MOVE:	*8*	*9*	*10*	*11*	*12*	*13*	*FINAL*
OBJECTIVE FUNCTION VALUE:							
WEIGHT:	*.1982*	*.1926*	*.1815*	*.1808*	*.1815*	*.1813*	*.1808*
CONSTRAINT VALUES:							
FREQ 1:	*1873*	*1874*	*1863*	*1863*	*1866*	*1865*	*1863*
FREQ 2:	*2599*	*2604*	*2637*	*2638*	*2628*	*2631*	*2638*

The final design selected by the system, which occurred on design move 11, has a weight (.1808 lb) that is 13 percent lighter than the weight of the base blade. Full details for the base and final designs are listed on Table XI. The details of Table XI come from the optimization report summary file, created for each run by the T/STAEBL system. This file is most useful in enabling the user to follow the progress of the run. The file includes the results of each function call. Gradient evaluations are given the flag (GE), while design moves are tagged (DM), to help the user understand the trends of the system.

Table XI. Base and Final Designs

	BASE	FINAL
OBJECTIVE WEIGHT:	.20786	.18079
DESIGN VARIABLES:		
RIB1THK1	0.00	−.01
RIB1THK5	0.00	−.01
RIB2THK1	0.00	−.01
RIB2THK5	0.00	−.01
RIB3THK1	0.00	−.01
RIB3THK5	0.00	−.01
CV1PTHK5	0.00	−.00243
CV1STHK5	0.00	−.01
CV2PTHK5	0.00	.00360
CV2STHK5	0.00	−.01
CV3PTHK5	0.00	−.00165
CV3STHK5	0.00	−.00929
CV4PTHK5	0.00	−.01
CV4STHK5	0.00	−.01
CONSTRAINTS:		
FREQ1	.02772	−.00718
FREQ2	−.02976	−.02298
FREQUENCIES:		
1ST MODE	1798.7	1863.3
2ND MODE	2619.6	2638.0
THERMAL ANALYSIS PARAMETERS:		
ROOT P/A STRESS	52311	51251
CFLRATE	3.661	3.856
AVPRLOSS	.004574	.004569
AVFMLOSS	.009598	.009598
MAXTEMP	1641	1649
AVBLTEMP	1210	1200
PLIFEUSE	.0044	.0173

Within the summary file are listed the design parameters both in the form used by the ADS optimizer, and in a form understandable by the user. Thus, design variables are listed in both native and scaled forms. Constraints are listed in ADS form (i.e., $G(x) < 0$ for a satisfied constraint), but the constrained values, such as frequencies, are also listed. Additionally, the relevant thermal analysis parameters for the design are listed.

Note that for this design optimization, many of the design variables have reached their lower limit, suggesting that further weight reduction may still be possible. In only one instance, the pressure side of cavity 2, was material actually added to the blade. By removing mass from the tip of the blade, the T/STAEBL system has reached its frequency goals, while significantly reducing foil weight. To do this, cooling flow rates have increased, as well as foil temperatures. This increased temperature results in a much higher fractional life use for the airfoil, from .0044 to .0173. Should this life use become excessive, the benefits of the weight optimization could be lost.

10. CONCLUSIONS AND RECOMMENDATIONS

The T/STAEBL cooled airfoil optimization program has successfully applied mathematical optimization to the complex, multidisciplinary process of cooled airfoil design. T/STAEBL's design optimization procedure provides the capability to simultaneously evaluate the effect of changes to many design variables to the minimization of a comprehensive objective function, while responding to numerous design constraints.

The T/STAEBL design process demonstrates the benefit of improved data communications among analysis modules employed in the cooled blade design process, even when optimization procedures are not being employed.

A benefit of the cooled blade automation process is the involvement of the structural aspects (vibratory forced response) of the design process on a concurrent, rather than on a delayed, basis. Thus, the airfoil's frequency characteristics can now provide a contribution to the blade design process, instead of the delayed, reactive effect, currently encountered.

The T/STAEBL process develops a cooled airfoil design by coupling many analysis packages through a design data base. As a result of this diversity, long run times are often encountered for a blade design, even on CRAY supercomputers. In a design optimization, however, there are great potential benefits for parallel processing. For gradient evaluations, for example, the next several design variable sets are already known. Thus, is would be very beneficial to have parallel CPU's each processing one of these design sets. This same logic could be taken to a second level – some of the analysis modules can work independently of others, so a benefit could be achieved through parallelization within the evaluation of a single design. Thus, it is recommended that the T/STAEBL architecture be generalized and expanded to allow for parallel processing on multiple CPU's, to reduce computer expense and speed run turn–around time.

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13. ABSTRACT ***(Maximum 200 words)***

The Thermal/Structural Tailoring of Engine Blades (T/STAEBL) system is a computer code that is able to perform numerical optimizations of cooled jet engine turbine blades and vanes. These optimizations seek an airfoil design of minimum operating cost that satisfies realistic design constraints. This report documents the organization of the T/STAEBL computer program, its design and analysis procedure, its optimization procedure, and provides an overview of the input required to run the program, as well as the computer resources required for its effective use. Additionally, usage of the program is demonstrated through a validation test case.

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