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Rapid low fidelity turbomachinery disk optimization

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ABSTRACT

Turbomachinery disks are heavy, highly stressed components used in gas turbines. Improved design of turbomachinery disks could yield a significant reduction in engine weight. This paper focuses on rapid low fidelity design and optimization of isotropic and transversely isotropic disks. Discussion includes the development of a one dimensional plane stress model, disk parameterization methods, and the implementation of a genetic algorithm for shape optimization. Three traditional geometry definition methods are compared to two new methods that are described and produce more optimum designs. Hardware from the GE E^3 is used as an example. The analysis code is open-source, graphical, interactive, and portable on Windows, Linux, and Mac OS X.

1. Introduction

High fuel costs and the tightening global economy have lead to a renewed push for reliable, highly fuel efficient gas turbine engines. Better engine flow path design and higher engine temperatures will inevitably lead to more efficient designs, but are not the only areas where research should be done. Methods for safely decreasing the overall engine weight must also be investigated. Turbomachinery disks comprise a large part of the structural weight of an engine, making them a perfect target for this investigation. Preferably, disk optimization should not greatly increase the amount of time needed for an engine design. This means that the general disk shape optimization should be completed early in the design process using quick, low fidelity models. Fine tuning of the shape will still be needed later in the design cycle, but proper optimization early on should ease this process. A fast disk optimization method may also be integrated into a larger component or system multi-disciplinary optimization approach.

This paper focuses on disk design and optimization using a plane stress model. The derivation of the governing equations for isotropic and transversely isotropic disks will be described, followed by a description of the process used to discretize the model. Existing design codes often use parameterized disk geometry inputs to simplify the disk definition process [1,2]. Geometry and results using the common Ring, Web, and Hyperbolic parameterization methods will be compared. These three methods will also be compared to a new Continuous Slope (CS) parameterization and an arbitrary control point method. Optimization of the disk shape will be completed using a genetic algorithm with a specially tailored fitness function.

The limitations of the plane stress assumption will be discussed, along with methods to ensure the robustness of the resulting geometry. Further discussion will attempt to rate the effectiveness of each disk geometry definition method considering the weight of the resulting designs, the speed of optimization convergence, and the robustness of the final geometry. Future application of the stress model for the optimization of wound composite disks and flywheels will also be discussed. Throughout this paper hardware from the GE E^3 turbofan engine will be used as an example [3,4].

Effective computer codes for use in engineering design must be robust, user friendly, and highly interactive. A disk analysis and optimization code has been created. The details of the program capabilities and the code design philosophy are described.

2. Analysis code

One dimensional stress models for disks of varying thickness have been in use for some time. Simple models for isotropic disks are available in many sources [5,6,1]. A small number of proprietary codes and commercial packages that implement these models exist. The disk design routine in GasTurb Details is the most widely available of these codes [2]. Free and publicly available disk optimization codes are not common. Code packages designed to support transversely isotropic (composite) materials and advanced geometry definition methods are even less common, even for proprietary applications. A complete disk analysis and optimization code package was needed and has been created. This code was intended to complement and to a small extent interface with the

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Nomenclature

Variables

B	equilibrium equation body forces
C	Hooke's law stiffness coefficients
E	elastic modulus
F, L	genetic algorithm fitness function terms
m	disk mass
r	radial direction or radius at station
t	disk thickness at station
S	slope of the disk thickness profile
T	temperature at station
u	radial disk displacement
α	thermal expansion coefficient
ϵ, γ	normal and shear strains
ρ	density
σ, τ	normal and shear stresses
ω	rotor angular velocity

Superscripts and subscripts

b	blade or dead weight
cg	enter of gravity
m	mechanical stress component
T	thermal stress component
θ	tangential direction

T-Axi axisymmetric flow solver, available from the University of Cincinnati Gas Turbine Simulation Laboratory (GTSL) [7]. For continuity the name of the disk design code was simply chosen to be T-Axi Disk.

T-Axi Disk is a Graphical User Interface (GUI) based application written entirely in Fortran90 with calls to the DISLIN graphical libraries [8]. The code is open-source, freely available, and compatible with Windows, Linux, and Mac OS X operating systems. A version of this code has been released as an educational tool and is described by Gutzwiller et al. [9]. Fig. 1 shows a sample screenshot from the Windows release of T-Axi Disk. Downloads of the code distribution, example analyses, and complete documentation are on the GTSL website [7]. A summary of the code features are:

- Interactive design with an easy to use GUI.
- Detailed 2D and 3D stress contour plots.
- Rapid design optimization using a genetic algorithm.
- Automatic design tracking.
- Five disk definition methods.
- Support for isotropic and transversely isotropic materials.
- Temperature dependent material database with 10 common disk materials, compiled from trusted public sources [10,11].
- Automatic creation of axisymmetric Finite Element data for use with ANSYS (V11.0).
- Automatic blade and total dead weight estimation.

It may have been possible to complete the direct goals of this paper with a much simpler, command line based analysis code. Regardless, creating an easy to use, publicly available program is a worthwhile expenditure of time. One of the primary goals of any research is the transmission of knowledge and information throughout the engineering community. Typically this is done through journal publications, conference presentations, and other similar channels. Dispensing easy to use, well documented, and self contained software is another often overlooked way to transfer knowledge.

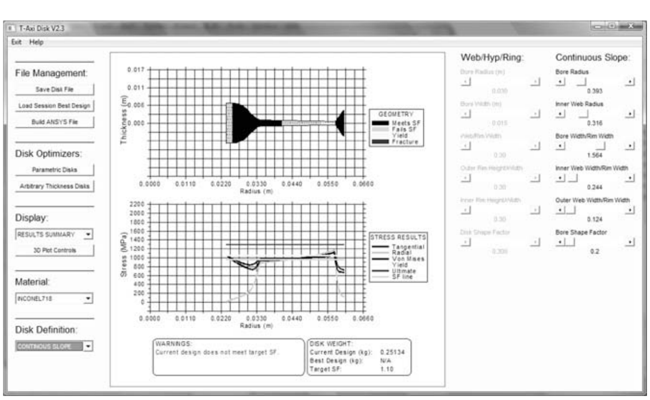

Fig. 1. T-Axi Disk interface – primary design screen.

The main application of T-Axi Disk is as an optimization tool, and therefore needs to be able to execute thousands or millions of analyses without any code failures. Building a GUI around a code tends to expose any holes or bugs, leading to a very robust final product. Also, T-Axi Disk has the ability to output stress and geometry results at intermittent points in an optimization process. This feature allows the user to gain an understanding not only of what the optimized design looks like, but also *how* the algorithm finds the optimum. This type of understanding would be nearly impossible to acquire without a GUI based application. A specific design philosophy has been followed during the development of T-Axi Disk.

- *Open-source*

T-Axi Disk is being released following the GNU General Public License [12]. This allows any end user to modify or expand the source code. Hopefully, this will prevent future engineers from having to recreate the basic analysis code, saving time which would be better spent on application and novel design studies.

- *Modularity*

The T-Axi Disk source code was created with as much modularity as possible, allowing other researchers to easily extract subroutines and graphical procedures from the program.

- *Graphical User Interface*

A clean GUI and well thought out presentation of results is very important. It significantly decreases the learning curve that comes with a new program and decreases the turnaround time for an analysis. The T-Axi Disk GUI was written using the DISLIN graphical libraries, which are very capable for this type of program [8].

- *Availability*

T-Axi Disk is easy to obtain. The code distribution, source files, example analysis files, and documentation are all available for download from the University of Cincinnati GTSL website [7].

- *Ease of installation and portability*

The entire T-Axi Disk distribution is contained within a single compressed file. Effort was taken to ensure that no unnecessary