STRUCTURAL TAILORING OF ADVANCED TURBOPROPS*

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ABSTRACT

The Structural Tailoring of Advanced Turboprops (STAT) computer program was developed to perform numerical optimizations on highly swept propfan blades. The optimization procedure seeks to minimize an objective function defined as either; (1) direct operating cost of full-scale blade or, (2) aeroelastic differences between a blade and its scaled model, by tuning internal and external geometry variables that must satisfy realistic blade design constraints.

The STAT analysis system includes an aerodynamic efficiency evaluation, a finite element stress and vibration analysis, an acoustic analysis, a flutter analysis, and a once-per-revolution forced response life prediction capability. STAT includes all relevant propfan design constraints.

The STAT system has been applied to three large scale advanced propfan applications. The STAT program made significant improvements in all three cases and demonstrated the great potential for design enhancements through the application of numerical optimization to turboprop fan blades of composite construction.

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THE HIGHLY COMPLICATED PROCESS OF THE SWEPT PROPFAN DESIGN

The swept turboprop design process involves the application of state-of-the-art interdisciplinary engineering technologies. Numerous design iterations are required between several work disciplines, including aerodynamics, acoustics, structures, and aeroelastic analysis groups. Using these current design procedures, it is very difficult to arrive at a satisfactory turboprop design, much less an optimum one, because of multi-iterative, manual intergroup design process that is required.

The penalties of this process include less than optimum designs, long design times, low performance, and high noise and weight levels.

MANY DISCIPLINES MUST BE TIED TOGETHER
- **AERODYNAMICS**
- **ACOUSTICS**
- **STRUCTURES**
- **AEROELASTIC (FLUTTER)**
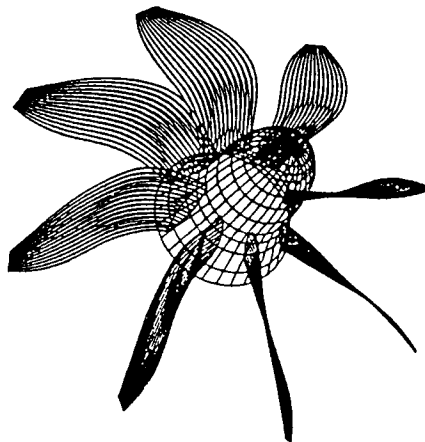
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SR-7 PROPFAN DESIGN HISTORY -- CONFLICTS BETWEEN
FLUTTER AND STRESS CONSTRAINTS

In the design process for the SR-7 Propfan, a satisfactory aerodynamic configuration was reached by design iteration number 40. The final, acceptable design, however, was not reached until design number 100. Thus, 60 configuration changes were required before all structural design constraints could be met. The cost and labor required to complete this process is obviously very high.

For the SR-7, the increased sweep tended to improve the flutter stability margin, at the expense of higher foil stresses. The final 20 iterations in the design process proved to be little more than a fine-tuning of the blade sweep.

- **HIGHER SWEEP IMPROVES FLUTTER MARGIN.**

- **INCREASED SWEEP INCREASED AIRFOIL STRESS.**

- **THE FINAL SR-7 BLADE IS DESIGN ITERATION NUMBER 100.**
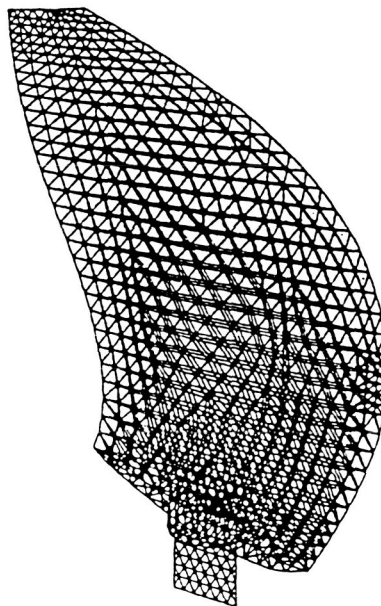
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MULTIDISCIPLINARY ANALYSIS CAPABILITIES OF STAT

STAT is a highly modular software package, consisting of an executive system, an optimizer, a design preprocessor, a set of approximate analyses, and a set of refined analyses. Currently, STAT uses the ADS optimization package, which is quite versatile, and also publicly available.

STAT's design preprocessor uses design curves to define both geometric and construction blade properties. Based on input from the optimizer, a new geometry is defined, and appropriate numerical models constructed.

STAT's approximate and refined analyses include aerodynamic, acoustic, flutter, finite element stress and vibrations, and 1-P forced response analyses.

- **OPTIMIZER:**
  ADS

- **DESIGN PROCESSING:**
  BASELINE DESIGN CURVES
  DESIGN CURVE PERTURBATIONS

- **MODULAR APPROXIMATE, REFINED ANALYSES:**
  AERODYNAMICS
  ACOUSTICS
  FLUTTER
  STRESS
  VIBRATIONS
  FORCED RESPONSE

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THREE PROPFAN APPLICATIONS OF STAT

The STAT program has successfully demonstrated the potential of design optimization when applied to turboprop fan blades of composite construction. STAT produced improved designs for both the SR-7 and 18-E LAP blades. Additionally, the optimizer proved to be capable of constructing an improved aeroelastic scaled model propfan.

The final SR-7 blade was design number 100 in a long, expensive development process. STAT was able to demonstrate further improvements available from this finely tuned design. The 18-E Propfan was an early infeasible design candidate in the SR-7 development program. STAT showed the capability to take an early configuration and significantly improve it, thus greatly reducing the expense of the design process.

By applying STAT to an aeroelastic scaled model blade, STAT shows the potential for increasing the relevance of wind tunnel testing, while aiding design of these test configurations.

- **SR-7 PROPFAN—CAN WE IMPROVE ON THIS DESIGN (100th ITERATION)?**

- **PROPFAN 18-E—CAN WE GET TO A FEASIBLE PROPFAN FASTER THAN HSD'S ENGINEERS DID?**

- **AEROELASTIC SCALE MODEL—CAN STAT BE USED TO DESIGN AEROELASTICALLY SIMILAR SCALE MODELS FOR WIND TUNNEL TEST?**

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DEMONSTRATIONS OF STAT UTILIZED TWO DIFFERENT OBJECTIVE FUNCTIONS

For conventional swept propfans, STAT uses aircraft direct operating cost as the objective function. Thus, a weighted function including aircraft fuselage noise level, propeller efficiency, and propeller weight is minimized, subject to appropriate design constraints.

For economical evaluation of candidate propfan designs, wind tunnel tests of scaled models are conducted. For effective wind tunnel testing, it is necessary to have aerodynamic, aeroelastic, and modal similarities between the full scale blade and the scaled model. In STAT, a weighted overall measure of full scale to scaled model configurations is minimized. A properly scaled blade will have similar flutter, resonance, efficiency, acoustic, and static and modal deflection characteristics.

- **FOR FULL SIZE PROPFANS, DIRECT OPERATING COST IS MINIMIZED.**

- **FOR THE AEROELASTIC SCALE MODEL, A WEIGHTED SIMILARITY FUNCTION MEASURES DIFFERENCES IN VIBRATORY, MASS, MODE SHAPES AND UNTWIST DEFLECTIONS.**

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STANDARD PROPFAN DESIGN CONSTRAINTS USED BY STAT

STAT includes all design constraints normally considered in the propfan design process. Side constraints limit the movement available on the various components of geometry. Vibratory frequencies are limited according to prescribed resonance margins. Stresses are limited via a Goodman diagram construction including both steady stress and once per revolution forced response stresses. Both classical unstalled and stalled flutter are constrained. Finally, rotor power is held constant through an equality constraint.

BLADE GEOMETRY
- **THICKNESS/CHORD**
- **ROOT STACKING POSITION**

FLUTTER
- **CLASSICAL FLUTTER**
- **STALL FLUTTER**

POWER

RESONANCE MARGINS
- **1st MODE 2E**
- **2nd MODE 4E**
- **2nd MODE 5E**
- **3rd MODE 5E**

STRESSES
- **STEADY STRESS**
- **1-P FORCED RESPONSE**

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STAT IMPROVES DOC FOR SR-7 PROPFAN BY 3.0 PERCENT

The SR-7 Propfan utilizes a complex composite construction. A nickel sheath edge layer protects a fiberglass outer shell. Also utilized are an internal aluminum spar, and foam to fill the gaps between the spar and the shell.

The initial optimization pass, using 38 design variables, reduced DOC by 5.0 percent. When design space was unscaled, however, the 1-P life was found to be unacceptable.

Using just 12 design variables to optimize the blade stacking, an improvement of 5.3 percent over the base blade was found. Subsequent refined analysis found that all constraints were satisfied, but that the actual DOC reduction was 3.0 percent.

- **INITIAL OPTIMIZATION PASS, USING 38 DESIGN VARIABLES, REDUCED DOC BY 5.0 PERCENT, BUT THE 1-P FORCED RESPONSE LIFE CONSTRAINT WAS VIOLATED.**

- **USING TWELVE STACKING VARIABLES, STAT IMPROVED APPROXIMATE DOC BY 5.3 PERCENT**

- **REFINED ANALYSIS INDICATED:**
  ALL CONSTRAINTS WERE SATISFIED.
  ACTUAL DOC IMPROVEMENT WAS 3.0 PERCENT.

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THE 18-E LAB DESIGN WAS AN EARLY, INFEASIBLE
DESIGN IN THE SR-7 HISTORY

The 18-E Propfan design was a candidate in the SR-7 design evolution that was unacceptable because of stress considerations. An interesting study performed with STAT was to see how this design would evolve relative to the manually designed SR-7.

Using 12 stacking and twist variables, STAT was able to improve the approximate DOC by 5.3 percent, which is a 4.4 percent improvement over the final SR-7 configuration.

- STEADY, 1-P STRESSES OF THE 18-E DESIGN ARE UNACCEPTABLE.

- BY ALTERING THE BLADE STACKING AND STAGGER, STAT WAS ABLE TO FIND AN IMPROVED DESIGN.
  - TWELVE DESIGN VARIABLES EMPLOYED.
  - ALL CONSTRAINTS SATISFIED.
  - DOC REDUCED BY 5.3 PERCENT (OR, 4.4 PERCENT IMPROVED OVER FINAL SR-7 DESIGN).

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THE SR-7A IS AN AEROELASTIC PROPFAN SCALE MODEL

The SR-7A is a 2/9 size aerodynamic scaled model of the SR-7 LAP blade design. The blade is composite in construction, made up with 12 layers. For the STAT optimization, the exterior shape was fixed to the scaled SR-7. The composite construction was tailored using 37 design variables to better match the aero-structural performance of the blades, including: scaled frequencies, mode shapes, untwist static deflections, and mass distribution.

As the objective function, a summation of squared differences for all the above parameters was minimized. STAT was successful at reducing this objective function by 32 percent over the existing scaled model configuration.

- 2/9 SIZE SCALE MODEL, LAMINATED COMPOSITE CONSTRUCTION.

- EXTERIOR GEOMETRY IS FIXED BY THE SR-7, BUT COMPOSITE CONSTRUCTION WAS TAILORED TO BETTER MATCH AEROSTRUCTURAL SCALING REQUIREMENTS (37 DESIGN VARIABLES).
  FREQUENCIES
  MODE SHAPES
  DEFLECTIONS
  MASS DISTRIBUTION

- COMPONENT STRESSES WERE THE ONLY DESIGN CONSTRAINT.

- DIFFERENCES SQUARED OBJECTIVE FUNCTION WAS REDUCED BY 32 PERCENT

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Currently, STAT is being expanded to allow the tailoring of counter rotation propfans. This effort involves extensive improvements to the aerodynamic and acoustic modules, including an upgrade of the approximate acoustic analysis, to improve correlations with refined analysis.

Enhancements to STAT include an improved optimization scaling algorithm, and also improved flexibility in initial design selection.

- **APPLICATION TO COUNTER ROTATION PROPFANS.**
  AERODYNAMICS
  ACOUSTICS

- **INCREASED AIRFOIL DEFINITION FLEXIBILITY.**

- **IMPROVED OPTIMIZATION SCALING ALGORITHMS**

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CONCLUSIONS

The STAT propfan optimization system has shown that design tailoring can be effectively applied to large, multidisciplinary systems, showing great potential for manpower requirement reductions, relative to present, manual design procedures.

STAT has been successfully applied to the optimization of two full scale propfans, and also to an aerostructural scaled model. With the exception of the approximate acoustic analysis, all approximate analysis modules have shown very good accuracy.

- **DESIGN OPTIMIZATION HAS BEEN SUCCESSFULLY APPLIED TO THE COMPLEX PROPFAN DESIGN PROCESS.**

- **STAT HAS BEEN SUCCESSFULLY APPLIED TO THE OPTIMIZATION OF TWO PROPFANS, AND ALSO TO AN AEROSTRUCTURAL SCALE MODEL.**

- **THE APPROXIMATE ACOUSTIC ANALYSIS NEEDS IMPROVEMENT.**

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