Improved Modeling Techniques for Turbomachinery Flow Fields

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Abstract

Objectives and Method of Approach

The objective of the program is to develop improved methodology for modeling turbomachinery flow fields. Specifically, it will address the deficiencies of the stress tensor models in steady-state 3-D Navier-Stokes models used for the design of turbomachinery components. Since the derivation of the average-passage equations clearly shows that the deterministic features of the turbomachinery flow contribute to the mixing stress tensor and stress tensor modeling does not address these contributions, the approach is to directly measure the mixing stress tensor in a high-speed turbomachinery component. Advanced analysis tools will be used to resolve the random and the deterministic components of the mixing stress tensor and a model will be developed from the governing equations with an appropriate change in the frame of reference. These models will be tested in Navier-Stokes solvers available at Rolls-Royce Allison. The overall objective is to provide models and tools for improved methodology for the design of high efficiency turbomachinery and drastically reduce the time required for the design and development cycle. This methodology will replace present day approach based on empiricism and extensive testing.

Results and Accomplishments

The experimental and computational studies performed during this study were based on the Pennsylvania State University Research Compressor (PSRC). The PSRC employs a 3-stage axial flow compressor consisting of an inlet guide vane row and three stages of rotor and cantilever-mounted stator blading with a rotating hub. An area traverse mechanism is used for detailed area traverse of 1-½ passages downstream of stator 2, and downstream of rotor 3. Five different types of probes (five-hole probe, aspirating probe, single sensor slanted hot wire, unsteady pressure probe, and thermocouple probe) can be traversed radially and tangentially using the mechanism. Additionally, the area traverse mechanism can be replaced such that unsteady casing pressure measurements can be made at one tangential and thirteen axial positions. The PSRC facility is unique in that the blade loading (average blade section diffusion factor near 0.438) and the rotational speed (tip Mach number near 0.5) are roughly equivalent to an embedded portion of a modern, high speed gas turbine compressor. This makes the PSRC facility a unique vehicle through which realistic studies of multistage compressor aerodynamic mixing can be performed.

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The unsteady pressure measurements carried out at the exit of the rotor 3 indicate that the stator 2 wakes still persist and the defect and the width of the stator wakes are appreciable. Time-averaged hot-film measurements at the exit of rotor 3 corroborate the unsteady pressure measurements in indicating that the width of the stator wakes are appreciable, but show that the wakes are much deeper than previously measured, and thus the wake decay is less than previously determined. A new wake correlation for the decay of the stator wake through a rotor blade row has been developed. Correlations are presented which accurately model the decay of the maximum defect in total velocity of the stator wake as it passes through the rotor passage. Unsteady hot-film measurements indicate that the rotor 3 flow is highly unsteady and three-dimensional with large wake defects and widths.

Based on these measurements, it was observed that the rotor wakes, tip leakage flow regions, hub endwall suction surface corner region and hub and casing endwall regions were areas of highly three-dimensional flow. The presence of considerable upstream stator wakes downstream of the rotor will cause the downstream stator to see, not only temporally fluctuating inlet flow from the passing rotor, but spatially non-uniform inlet flow as well.

The unsteady hot-film measurements also indicate that the temporal fluctuations in the flow field due to a passing rotor give rise to 'apparent' stresses. The 'apparent' stress correlations were significant in the rotor wake, near the hub suction and pressure surfaces, and near the suction surface at 85% radial span. The unsteady flow near the endwall is not correlated with the rotor blade or shaft frequency, hence the 'apparent' stresses were found to be small. The 'apparent stress correlations were zero elsewhere. The $\overline{\tilde{V}_z \tilde{V}_z}$ normal stress component was one order of magnitude greater than all the stress components, which were of the same magnitude.

Unsteady casing pressure measurements indicates a low-pressure region near the blade suction surface from about 50% to 90% axial chord. This indicates the presence of a tip leakage vortex being formed near mid-chord and moving radially inwards towards the core region. Revolution periodic measurements indicate that there is no correlation between rotor tip clearances and static pressure intensity and fluctuations.

The Rolls-Royce Allison personnel have predicted the flow in the multistage compressor. The predicted results for the 3-½ stage Penn State research compressor were obtained using two different inter-blade row coupling techniques. The first technique, referred to as a mixing plane, was employed to characterize the overall performance of the compressor and to evaluate the ability to predict detailed flow features such as blade wakes, endwall flows, clearance vortices, etc. The second technique, referred to as rotor/stator interaction, provides detailed evaluations of the time-dependent flow features resulting from the relative motion of adjacent blade rows in turbomachines. These time-dependent fluctuations form the basis for the deterministic mixing stresses, which are believed to be of significant importance in multistage compressor flows. The deterministic stresses resulting from the time-dependent solution were computed and compared with experimental results. These calculations and the detailed time-dependent test data taken from the PSRC facility have led to the development of a preliminary computational model designed to incorporate the time-averaged effects of multistage turbomachinery deterministic unsteadiness into a rapid 3-D Navier-Stokes solution algorithm.

The focus of the numerical modeling effort under this project has concentrated on evaluating sources and magnitudes of deterministic aerodynamic unsteadiness in modern turbomachines. Three-dimensional time-dependent flow predictions were performed for the Penn State Research compressor Rotor 2/Stator 2/Rotor 3 blading. The results from these simulations quantified the time-averaged effects of deterministic flow unsteadiness on compressor performance. Based on this data, time-dependent flow features affecting compressor performance were correlated with wake-based and potential-based aerodynamic interactions between adjacent blade rows. A preliminary model for wake-based flow unsteadiness was developed and has been successfully applied to a number of compressor configurations.

The next step in this research is to identify an appropriate model for potential-based interactions between adjacent blade rows. By selectively removing and/or repositioning blade rows in the numerical simulations, the effects of wake-based and potential-based interactions between blade rows can be isolated. These simulations, coupled with the guidance provided by the test data from the Penn State Compressor rig, will lead to the development of a complete model for deterministic unsteadiness in turbomachines suitable for incorporation into the design process. Through this methodology, the effects of deterministic flow unsteadiness on compressor performance can be evaluated during the design process, resulting in improved aerodynamic efficiency and stability for the final product.

Numerical simulations of rotor/stator/rotor aerodynamic interaction for the Rotor 2/Stator 2/Rotor 3 segment of the PSRC have been compiled. These simulations evaluate the influence of sequential positioning of Rotor 3 relative to Rotor 2 (airfoil indexing) as well as evaluating variations in blade row potential interactions when Rotor 3 is removed from the simulation. These data, which are currently being processed, will contribute to a better understanding of the role potential field interactions play in the makeup of the deterministic stress environment, and will ultimately lead to improved models of the time-averaged effects of deterministic unsteadiness in multistage compressor flows.

Application and Benefits

The results of this program are of great interest to the Gas Turbine Industry and have potential benefits in several manners. If suitable modeling procedures for multistage compressor flows were available, then it is likely that significant improvements in multistage compressor (and turbine) performance and design cycle cost and time could be achieved. Given the ability to accurately account for these multistage mixing effects, an estimated 2 - 3% improvement in compressor adiabatic efficiency and a 5% or greater improvement in compressor surge margin over current compressor designs might be achieved. Perhaps of greater importance is that the ability to rapidly analyze and alter compressor design with confidence using multistage CFD tools would result in an estimated reduction of one year in compressor development time and a savings of over $1,000,000 in compressor development cost. Clearly then, on the basis of economics alone, there is a strong industry motivation to develop accurate multistage compressor flow modeling tools.

Future Activities

Future activities will include the replacement of the cantilevered stator blades with shrouded ones. This data will be used to determine the multistage effects of corner tip leakage, and corner separation flows for different blade configurations, and to improve the current mixing stress models.

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