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Active Control Analysis for Aeroelastic Instabilities in Turbomachines

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Introduction

Turbomachines onboard aircraft operate in a highly complex and harsh environment. The unsteady flowfield inherent to turbomachines leads to several problems associated with safety, stability, performance and noise. In-flight surge or flutter incidents could be catastrophic and impact the safety and reliability of the aircraft. High-Cycle-Fatigue (HCF), on the other hand, can significantly impact safety, readiness and maintenance costs. To avoid or minimize these problems generally a more conservative design method must be initiated which results in thicker blades and a loss of performance. Actively controlled turbomachines have the potential to reduce or even eliminate the instabilities by impacting the unsteady aerodynamic characteristics. By modifying the unsteady aerodynamics, active control may significantly improve the safety and performance especially at off-design conditions, reduce noise, and increase the range of operation of the turbomachine. Active control can also help improve reliability for mission critical applications such as the Mars Flyer.

In recent years, HCF has become one of the major issues concerning the cost of operation for current turbomachines. HCF alone accounts for roughly 30% of maintenance cost for the United States Air-Force [1]. Other instabilities (flutter, surge, rotating-stall, etc.) are generally identified during the design and testing phase. Usually a redesign overcomes these problems, often reducing performance and range of operation, and resulting in an increase in the development cost and time. Despite a redesign, the engines do not have the capabilities or means to cope with in-flight unforeseen vibration, stall, flutter or surge related instabilities. This could require the entire fleet worldwide to be stood down for expensive modifications. These problems can be largely overcome by incorporating active control within the turbomachine and its design. Active control can help in maintaining the integrity of the system in unforeseen events and provide for more aggressive designs to reduce the weight and improve efficiency of the turbomachine. Another area where active control can be useful is in controlling and suppressing rotating stall and surge in compressors, thereby increasing its operating range. Although some of these benefits will be offset by the added cost and weight penalty of the control system, the potential benefits in safety, reliability, performance, and noise characteristics are significant enough to warrant research in the area of active control of turbomachines.

There is renewed interest within industry to understand unsteady aerodynamic behavior. This improved understanding not only leads to better design of turbomachines, which avoid instabilities but also which helps in understanding the controllability of the instabilities. The proliferation of micro-electro-mechanical-system (MEMS) devices has made available new tools to designers for employing feedback controls at reasonable costs. MEMS have also made the control devices small and unobtrusive enough to be implemented within the turbomachine without significant obstruction to the flow path. This has made active-control very attractive especially for systems requiring extreme confidence.

Accomplishments

The objective of the proposed effort was to develop a numerical analysis program for active control of aeroelastic instabilities. This was to be done by modifying an existing aeroelastic code TURBO-AE [2] based on a Navier-Stokes solver for turbomachine analysis to allow for modeling air injection from solid surfaces. Unfortunately, however, this was not accomplished because the work was redirected as described below. TURBO-AE is currently under development at NASA Glenn and is capable of calculating flutter, forced response and unsteady aerodynamic characteristics of turbomachinery components.

The scope of the research effort was expanded to include aeroelastic analysis of the second rotor row of the Ultra Efficient Engine Technology (UEET) two-stage Proof of Concept Compressor (POCC). NASA Glenn Research center has undertaken the design, fabrication and testing of the UEET two-stage POCC. In order to support the design phase, aeroelastic analysis of the second rotor row was required. A grant supplement was added to carry out this work. Later, aeroelastic analysis in support of the POCC design effort was performed under a separate contract.

The proposed effort was to be accomplished using the TURBO-AE code. TURBO-AE code is an aeroelastic analysis code applicable to axial flow turbomachine components. The code is based on a three-dimensional unsteady Navier-Stokes code TURBO [3] being developed at Mississippi State University (MSU). During the initial phase of the research effort, an update to TURBO code was provided by the researchers from MSU. This update was implemented in the TURBO-AE code and the code was tested to establish the accuracy of the modified code. During testing of the code it was found that there were problems associated with the convergence characteristics of the new update. The UEET POCC second stage rotor geometry was used for this effort. A steady flowfield generated by APNASA code [4], a benchmark for turbomachinery aerodynamic analysis, was used as a starting solution to obtain a steady flow field from the TURBO-AE code. It was found that the flow would not converge and would separate on the suction side near the hub region. Two sample results are shown in Fig.1. Significant effort was required to understand the reason for the discrepancy between the results obtained from APNASA and TURBO-AE. It became essential to resolve this issue before any further research or analysis could be performed using the TURBO-AE code. After significant effort it was established that the differences were because of turbulence modeling and its effect on providing excessive damping in the transient phase of the analysis. The problem was solved by modifying the inlet velocity profile obtained from APNASA, to remove the effect of boundary layer from the hub region. This information was provided to researchers at MSU. Figure 2 shows the comparison of the flowfield between APNASA and TURBO-AE at one span location after the issue was resolved. Because resolving the discrepancy took significant effort, not enough resources were available to accomplish the originally proposed task.

The TURBO-AE code was next applied to calculate the aeroelastic characteristics of UEET POCC's second stage rotor. During preliminary design, there was concern with the respect to flutter stability of the second stage rotor. The design guidelines being used could not confirm the rotor to be stable. An analysis using the ASTROP2 code, an aeroelastic analysis code based on linear aerodynamics, also showed the rotor to be marginally stable [5]. For this reason the rotor was analyzed using the TURBO-AE code to establish the stability characteristics of the compressor rotor. The aeroelastic analysis of the rotor was carried out at the design speed for several inter blade phase angles. Figure 3 shows the variation of aerodynamic damping with inter blade phase angle. As can be seen the rotor is stable and is not expected to flutter.

References

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2. Bakhle, M., Srivastava, R., Keith, T. Jr., Stefko, G. L., "A 3D Euler/Navier-Stokes Aeroelastic Code for Propulsion Applications," AIAA Paper 97-2749, 33rd Joint Propulsion Conference and Exhibit at Seattle, WA, July 1997.

3. Janus, J. M., "Advanced Three-Dimensional CFD Algorithm for Turbomachinery," Ph.D. Dissertation, Mississippi State University, May 1989.

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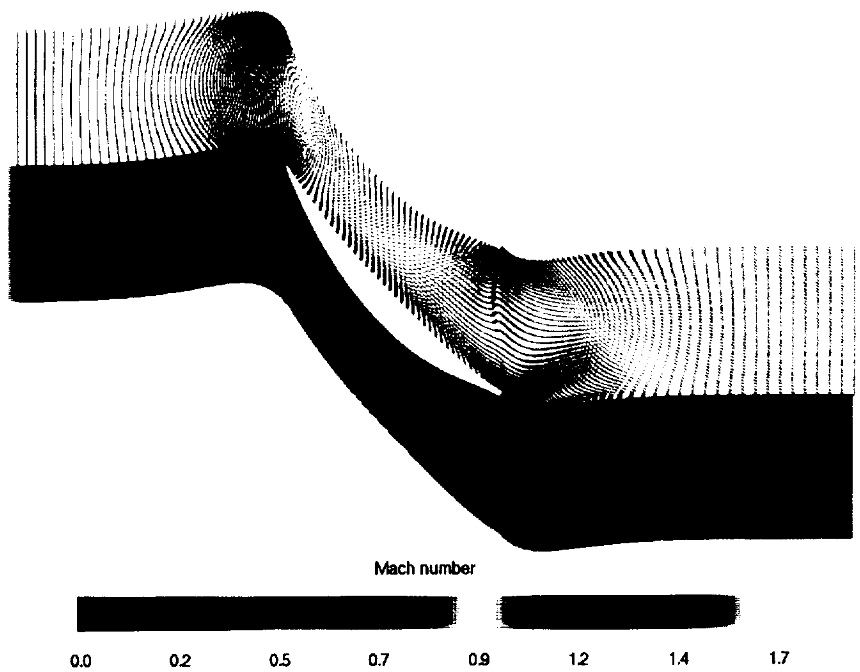
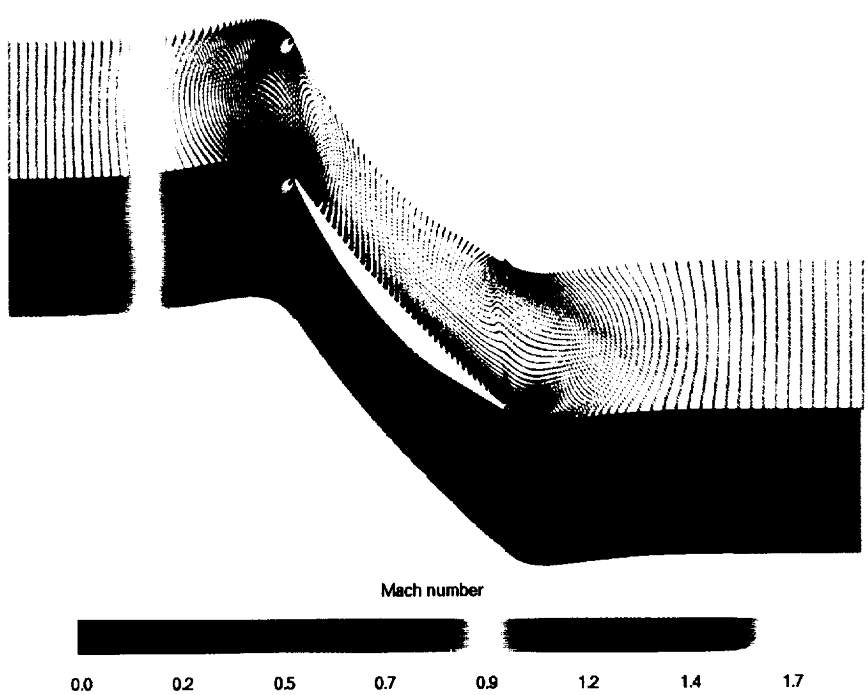
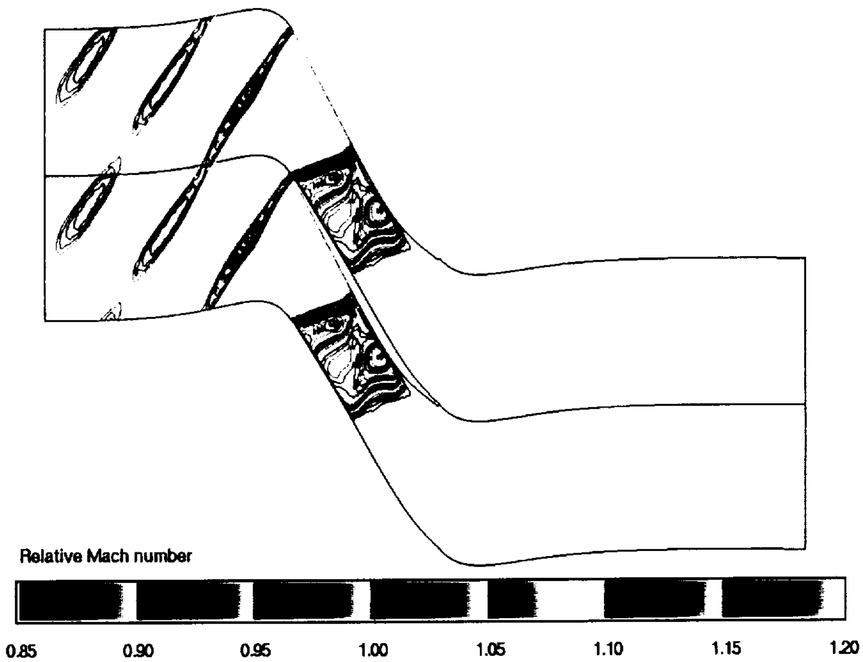


(a) Span station J=7

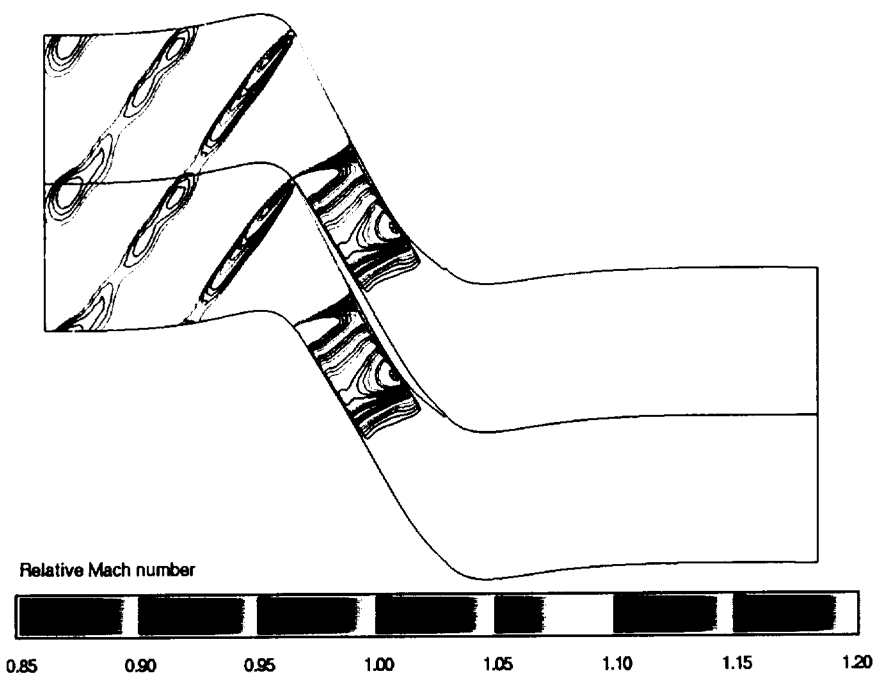


(b) Span station J=17

Figure 1. Mach number contours and velocity vectors showing the flow separation on suction surface of the blade near the hub region.



(a) Mach contours from APNASA at span station J=30



(b) Mach contours from TURBO-AE at span station J=30

Figure 2. Comparison of flowfield between APNASA and TURBO-AE for the UEET POCC second stage rotor after fixing the convergence problem for TURBO-AE

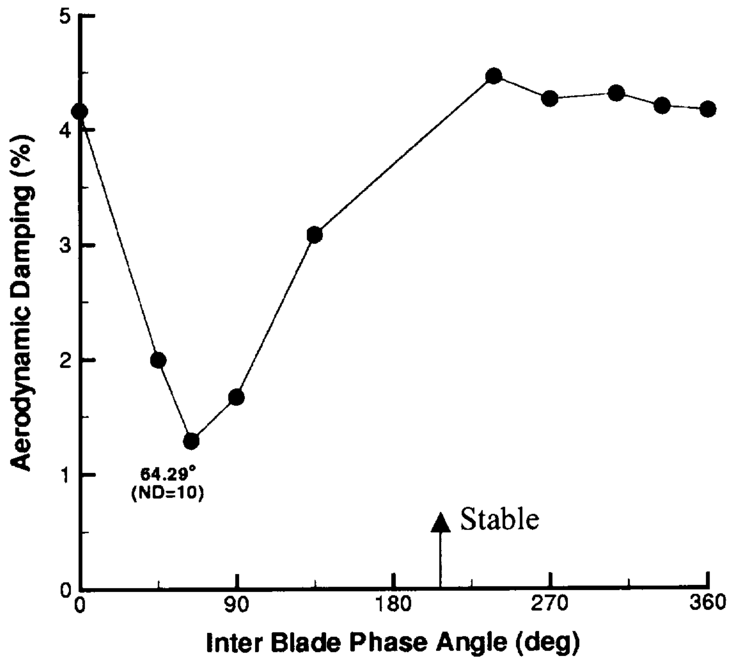


Figure 3. Variation of aerodynamic damping with inter blade phase angle for the UEET POCC second stage rotor at design operating condition