Time Accurate Unsteady Simulation of the Stall Inception Process in the Compression System of a US Army Helicopter Gas Turbine Engine

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Abstract

The operational envelope of gas turbine engines such as employed in the Army Blackhawk helicopter is constrained by the stability limit of the compression system. Technologies developed to improve the stable operating range of gas turbine compressors lack fundamental understanding beneficial to design guidance. Improved understanding of the stall inception process and how stall control technologies mitigate such will provide compressors with increased tolerance to stall, thereby expanding the operational envelope of military gas turbine engines.

Compressors which consist of multiple stages of stationary and rotating blade rows can include shocks, vortices, separations, secondary flows, shock/boundary layer interactions, and turbulent wakes, all of which grow in severity as a compressor approaches stall. As a compressor nears stall the flow field is no longer periodic from passage to passage so all blade passages must be computed. For a typical multistage compressor this becomes a formidable computational challenge requiring access to massively parallel machines in order to meet the computational and memory demands of the problem.

We are using a time-accurate CFD code to simulate the unsteady stall inception process, both with and without stall control technology, in the compression system of an Army gas turbine engine. This work will provide the first-ever 3-dimensional viscous time-accurate simulation of the stall inception process in a multistage compressor, providing insight into the causal link between compressor blade design parameters and the stable operating limit, which will be used to guide new design practices leading to compressor designs with increased tolerance to stall. This paper presents progress to date on this challenge project.

1. Introduction.

Gas turbine engines are the prime movers in a large number of combat vehicles for the Army, Navy, and Air Force including surface ships, tanks, manned and unmanned fixed-wing and rotary-wing combat aircraft, and logistic aircraft. These engines must perform reliably in harsh operating arenas while maintaining a high degree of operational availability. The stable operating envelope of gas turbine engines is dictated in large part by the aerodynamic stability (tolerance to stall) of the engine compression system.

Factors that reduce compression system tolerance to stall are erosion due to ingestion of debris during takeoff and landing from damaged and unimproved fields and during low-altitude maneuvers, distorted intake flows during combat maneuvers and due to ingestion of hot gas during munitions firing. In addition, the increasing use of stealth technology is generating requirements that conceal engine intakes and exhaust streams from direct observation, further reducing intake flow quality and thus degrading compressor stability.

Researchers at the ARL Vehicle Technology Directorate and NASA Glenn Research Center have developed compressor stall control technologies that have been successfully demonstrated in compressor component tests[1-5]. These stability enhancement technologies have been developed through parametric experimental studies. Their effectiveness is based on altering the unsteady flow field near the compressor blade tips[1-5]. However, there is a lack of fundamental understanding of the fluid mechanic processes of stall inception and how these stall control technologies mitigate stall to achieve increased compressor stability. Improved understanding of the stall inception process will guide the further development of stall control devices and of compressor blading with increased tolerance to stall, thereby expanding the operational envelope of military gas turbine engines.

During the last ten years steady-flow computational simulations have provided an increasingly accurate prediction of the flow up to the point of compressor stall. However, attempts to study stall through unsteady simulations of a subset of the blades in a compressor blade row[6] or through reduced-order unsteady flow models[8] have been unsuccessful to date. Since the temporal flow field variations that occur during stall inception are not harmonics of blade passing frequency the unsteady flow in each blade passage within a blade row must be simulated in order to study the transition from a steady flow state into the unsteady stalled flow state. Such simulations have been done two-dimensionally[7], but stall is an inherently three-dimensional unsteady phenomena[8]. We have realized major improvements in the ability to accurately simulate *steady* flows near the blade tip in axial compressor rotors through improved gridding techniques[9] and have concurrently improved the accuracy of an *unsteady* flow solver for turbomachinery blading (TURBO) through improvements in grid generation and turbulence modelling[10].

The TURBO code is fully parallelized and has been successfully used as a production code for unsteady simulations of near design point conditions of multistage compressors. The present effort utilizes the time-accurate CFD code TURBO to simulate the unsteady stall inception process, both with and without stall control technology, in the compression system of an Army gas turbine engine. This exercise will provide the first-ever 3D viscous full annulus unsteady simulation of the stall inception process, providing insight into the causal link between compressor blade design parameters and the stable operating limit.

This will be a significant contribution to the Army/DoD community which utilizes gas turbines in a large number of combat vehicles (Comanche, Apache, Black Hawk, M1, FCS, manned and unmanned fixed and rotary-wing aviation platforms) that typically must operate under the most severe conditions. The benefits of improved understanding of the stall inception process will yield compressor designs that are able to operate closer to their maximum efficiency operating point while still providing adequate stall margin. *This would yield a significant reduction in logistics support due to the considerable fuel savings that could be achieved resulting in substantial enhancement of force mobility, survivability, and sustainability.*

2. Problem and Methodology.

Stall detection schemes and stall controllers rely on the presence of smallamplitude stall precursive disturbances (which are measured with high-response transducers and form the inputs to stall warning and stall control systems). The uncontrolled growth of these disturbances leads to stall. We do not currently understand the causal link between these disturbances and the fluid mechanic processes occurring within the compressor blade row just prior to stall. Furthermore we don't understand the fundamental fluid mechanics of how stall control technology extends the stable operating range of a compressor. Determining this causal link and how stall control technology beneficially affects such to extend the stable operating range of a compressor are the key objectives of this effort.

Typical flow phenomena involved in rotating machinery can include shocks, vortices, separations, secondary flows, shock and boundary layer interactions, and turbulent wakes. Any CFD simulation of turbomachinery must be capable of resolving the multiple length and time scales found in these flows. A consistent research effort toward the development of such a CFD code has been underway for some time at Mississippi State University. The TURBO code, whose development has been supported by NASA, DOD, and industry, is a flow solver that approaches the goal of a high fidelity simulation of multi-stage turbomachinery flow physics[10].

The TURBO code was developed to simulate the highly complex flow fields generated by rotating machinery. This code is a finite volume, implicit scheme for unsteady, three-dimensional, compressible, viscous flows. It solves the Reynolds averaged Navier-Stokes equations. Flux vector splitting is used in evaluating flux Jacobians on the left hand side while Roe's flux difference splitting is used to form a higher-order TVD scheme for the evaluation of convective fluxes on the right hand side. Newton sub-iterations are applied to obtain a converged solution within one time step. Numerical instability problems can occur as the grids are clustered on the walls in order to resolve the viscous effects. Therefore, a modified two-pass scheme similar to Gauss-Seidel is used to reduce the errors brought about by the approximate factorization of the old two-pass scheme, and hence allow larger CFL numbers for the Navier Stokes type grids.

The steady Navier-Stokes Turbomachinery solver APNASA[11] is used to compute an initial guess at the time-accurate flow field for the TURBO code. Starting the TURBO computation from this high quality initial flow field makes it easier to overcome the initial transient phase during the computation and in some cases results in an order of magnitude reduction in the CPU time that is required to reach a converged time-accurate solution[12]. This procedure is well demonstrated and is the standard method for beginning a time accurate calculation.

Both TURBO and APNASA use an advanced two-equation turbulence model that was developed specifically for turbomachinery flows by ICOMP at NASA Glenn Research Center[13]. This model has demonstrated superior ability to accurately simulate important viscous effects, such as shock/boundary layer interaction, in turbomachinery environments.

APNASA is a fully operational production code that is in common use by most US engine manufacturers. There is a large experience base at NASA Glenn for the setup and execution of simulations using APNASA. The code is well validated for the compressor geometries that are the focus of the unsteady computations presented herein.

The TURBO code is also a fully operational production code that has been released to industry. There is an experience base at NASA Glenn Research Center in the use of this code for turbomachinery geometries. TURBO has been validated with single and multi-blade row turbomachinery cases. An isolated rotor (one blade row), and a compressor stage (two blade rows) cases have been run on the DoD Naval Oceanographic Office MSRC Cray T90 machine. A multistage compressor (5 blade rows) case has been run on the DoD Naval Oceanographic Office MSRC Origin machine. Resource estimates for this project are based on scaling these cases to full annulus multistage simulations.

Computational issues that arise for this Challenge project include both portability and scalability of the flow solvers, as well as the spatial resolution and time steps needed for accurate simulations of stall characteristics. The parallel TURBO code is implemented in a portable, scalable form for distributed-memory parallel computers using MPI message passing[14]. The parallel implementation employs domain decomposition and supports general multiblock grids with arbitrary grid-block connectivity. The solution algorithm is an iterative implicit time-accurate scheme with characteristics-based finite-volume spatial discretization. The Newton sub-iterations are solved using a concurrent block-Jacobi symmetric Gauss-Seidel (BJ-SGS) relaxation scheme. Unsteady blade-row interaction is treated either by simulating full or periodic sectors of blade-rows, or by solving within a single passage for each row using phase-lag and wake-blade interaction approximations at boundaries. A scalable dynamic sliding-interface algorithm is used here, with an efficient parallel data communication between blade rows in relative motion.

The parallel version of the TURBO code has a parallel algorithm and software structure similar to that of an incompressible flow solver (UNCLE) developed at MSU under ONR sponsorship and used in a current DoD Challenge project on submarine maneuvering. Portability has been demonstrated for numerous parallel platforms including T3E, IBM SP-2, Sun Enterprise ULTRA 10000, SGI-O2K and PCA Arrays, as well as workstation clusters. The parallel TURBO code to be used is an evolution of the sequential version that has been validated very extensively over the past ten years. The parallel version has been validated by repeating selected flow cases previously validated using the sequential version.

The parallel TURBO code has been run on different platforms, including SGI O2K, PC-based Linux clusters, with good portability. The parallel implementation uses a domain decomposition strategy with general blocking capability designed to handle complicated geometry. This implementation has also been shown to give reasonable parallel efficiency on distributed-memory parallel machines. Support for the domain decomposition is provided through the GUMBO[15] software that is available from Mississippi State University. Static load balancing is done either at the grid generation stage or using a graphical repartitioning tool developed for preprocessing of existing grids. The parallel solutions typically have communications overhead of only 10-15%. Scalability studies using heuristic performance estimates indicate that on current-generation hardware, parallel efficiencies (percent CPU utilization) of 80 percent and more can be achieved on up to 400 processors and 50 million points, using appropriately sized grids. Figure 1 shows that close to linear speedup performance was demonstrated for up to 60 processors on a Linux cluster, for an advanced 1.5 stage high-speed compressor with 1.1 million grid points. Super-linear speedup performance (Fig. 1) was achieved on NAVO's IBM SP3 for up to 136 processors, for another 1.5 stage

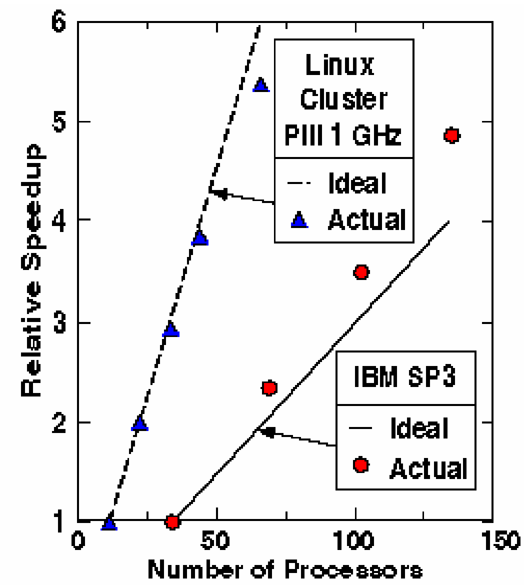

Figure 1 Scalability of TURBO code.

compressor with 2 millions grid points. The super-linear speedup is most likely achieved through the better cache utilization on the SP3. The approach to parallelization for large-scale complex problems is discussed in further detail in References 16-18.

The overall objective of this effort is to predict and characterize the stall inception process in the compression system of the T700 engine used in the U.S. Army Blackhawk helicopter. The T700 engine includes both a high speed multistage axial and a centrifugal compressor stage. The capability of the TURBO code to predict stall range extension and for simulating the flow fields in both high speed axial and centrifugal compressors will be assessed by comparison to experimental measurements obtained both with and without stall control technology in both a high speed axial compressor, Stage 35, and a high speed centrifugal compressor, CC3.

The solution methodology is as follows.

1) Use APNASA to generate a steady state solution for the multiple blade rows to be simulated at a near stall operating condition. Use the APNASA solution results to build the initial starting flow field for TURBO.
2) TURBO is then used to obtain time-accurate solutions with phase-lag boundary conditions to predict the flow field at various flow conditions along the compressor speed line up to the near stall condition. The near stall solution then serves as the starting point for full annulus simulations to predict the stall inception process.
3) The static pressure, which forms the downstream boundary condition for the solution, is then perturbed slightly in order to push the calculation toward stall. The simulation will be closely monitored for the appearance of stall precursive disturbances. Detailed flow field information will then be extracted at the desired portions of the stall inception event.

3. Results.

The results presented herein reflect progress to date on time accurate unsteady 3D full annulus simulations of the stall inception process in the compression system of the Army Blackhawk helicopter engine. The time accurate simulations of both a high speed single stage axial, Stage 35[1-4,19], (Figure 2) and a high speed centrifugal compressor, CC3[5,20], (Figure 3) for which detailed experimental data are available provide assessment of the capability of the TURBO code for predicting the stall inception processes in a multistage axi-centrifugal compressor (see Figure 4) as employed in the Army Blackhawk helicopter.

The high-speed single-stage axial compressor, Stage 35, operating at 17189 RPM at design speed conditions (20.2 kg/sec) produces 1.82 total pressure ratio. This axial compressor consists of 36 rotor blades followed by 46 stator blades. The

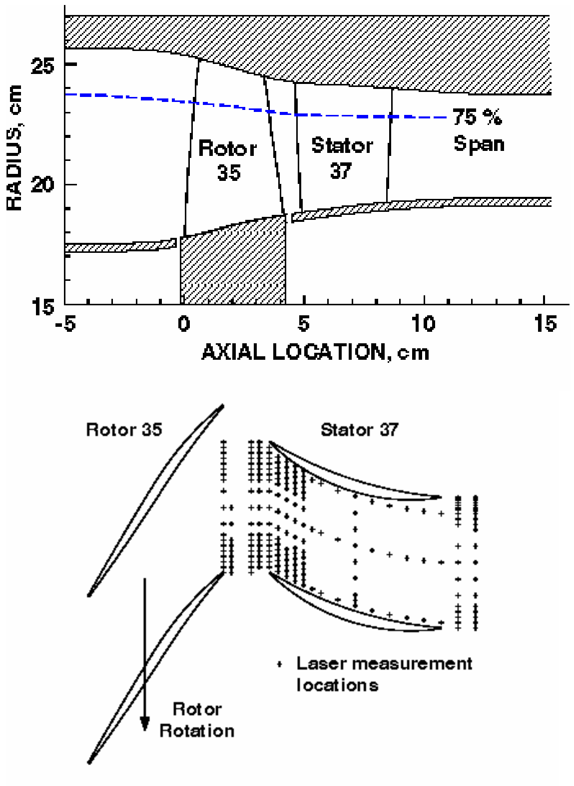

Figure 2 High-speed single stage axial compressor, Stage 35, validation case and location of laser measurement points along 75% span.

high-speed centrifugal stage, CC3, operating at 21,789 RPM at design speed conditions (4.54 kg/sec) produces 4:1 pressure ratio. This centrifugal compressor consists of 15 main blades, 15 splitter blades for the impeller, followed by 24 diffuser vanes.

A comparison of the TURBO predictions using phase-lag boundary conditions to the experimentally measured design speed lines for both the axial and centrifugal compressors are shown in Figure 5. The overall performance compares favorably, including good prediction of the compressor stall point. The discrepancy in the predicted stall point from the measurements is most likely a result of using the wrong tip clearance in the simulations. The rotor tip clearance has a significant effect on compressor stall point,

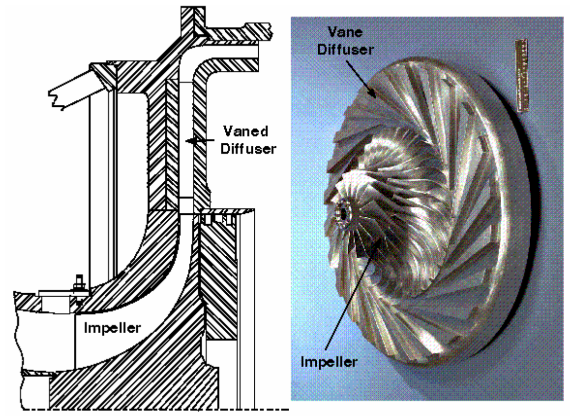

Figure 3 High-speed centrifugal compressor (CC3) validation case.

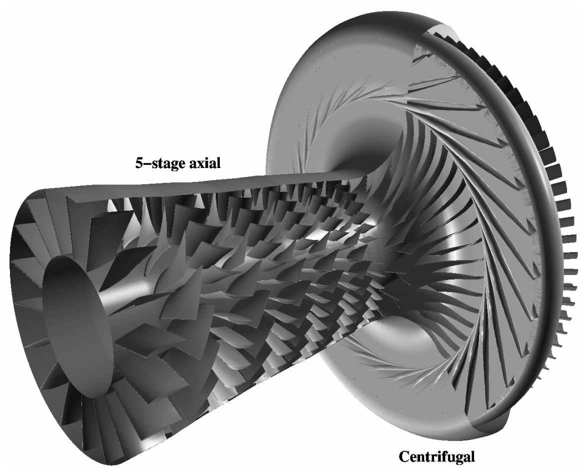

Figure 4 Compression system of T700 engine that powers the Blackhawk helicopter.

and for the tested stage the tip clearance was not documented.

Figure 6 shows a comparison of spanwise distributions of TURBO predictions of mass-averaged total pressure and total temperature downstream of the stage to experimental measurements. The agreement is within experimental uncertainty indicating the suitability of TURBO for predicting the time-averaged flow in high-speed compressors.

Figure 7 shows the capability of the TURBO simulations to predict the blade periodic flow field downstream of the rotor of a high-speed compressor. The rotor

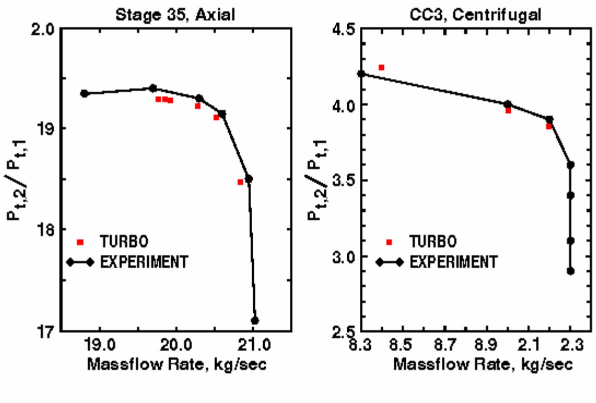

Figure 5 Comparison of TURBO prediction to experimentally measured speed lines for both the axial and centrifugal compressor validations cases.

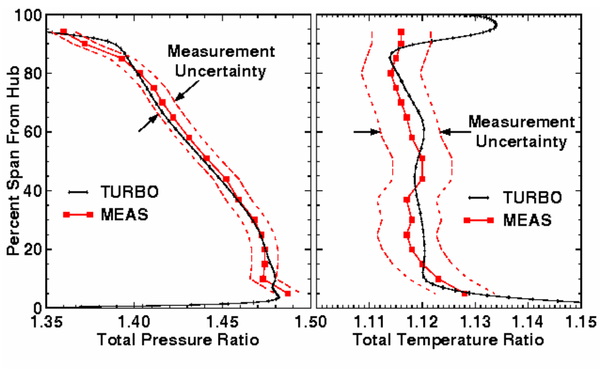

Figure 6 Comparison of predicted and measured spanwise distribution of mass averaged total pressure and temperature for the Stage 35 validation case.

wakes passing through blade row interface and entering the stators are shown as the axial velocity deficit. The agreement with experimental measurements is quite good providing reasonable confidence of the simulations capability for predicting the unsteady flow features relevant to high speed turbomachinery flow fields.

Figures 8 and 9 show the complexity of flow structures present in high-speed turbomachinery flow fields that must be resolved for accurate predictions. For both axial and centrifugal compressor flow fields there are 3D shocks, wakes, and blade tip leakage vortical flows, as well as strong

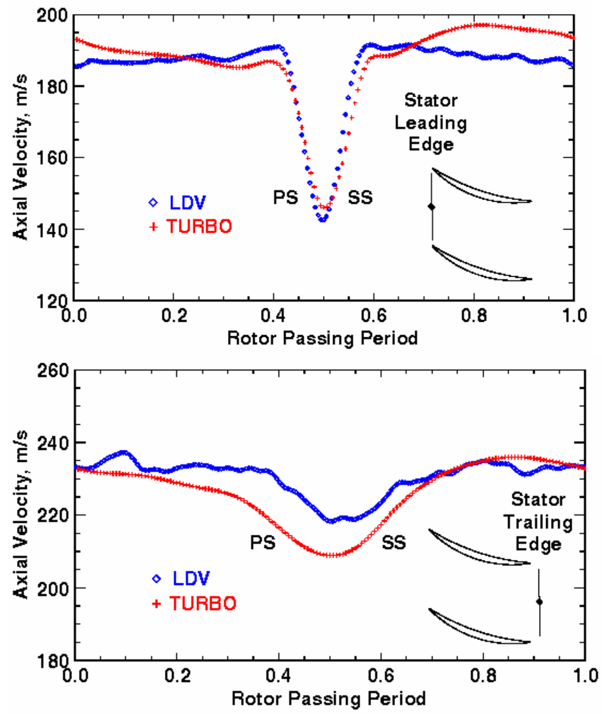

Figure 7 Comparison of predicted and measured blade periodic flow variations for Stage 35.

secondary flows that drive low momentum fluid to regions of lower pressure. Resolving these effects is necessary in addition to resolving viscous layers near the blade and endwall surfaces. It is essential that such fluid dynamic features that are characteristic of turbomachinery flow fields be reasonably predicted for meeting the intended objectives of this Challenge Project.

An important capability of the TURBO code is the ability to predict the non-blade-periodic nature of the stall inception process. In a real compressor it's not possible for all blade passages to be absolutely identical in every way. There are necessarily differences due to manufacturing tolerances if for no other reason. The TURBO simulations however are essentially identical, in that the geometry and mesh are replicated identically around the annulus. As such, there are no geometric disturbances that can give rise to an instability that could occur in one or more

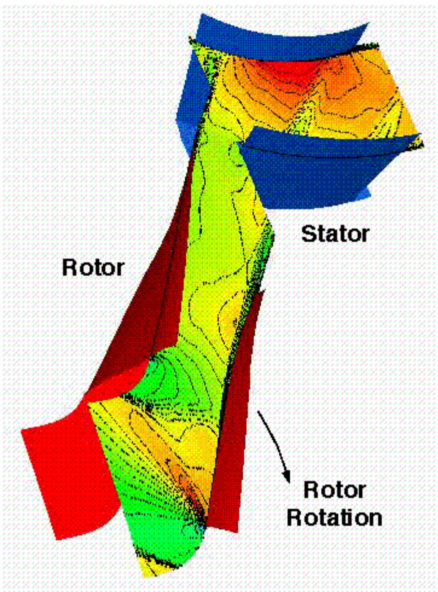

Figure 8 Stage 35 TURBO result at one instant in of rotor/stator position.

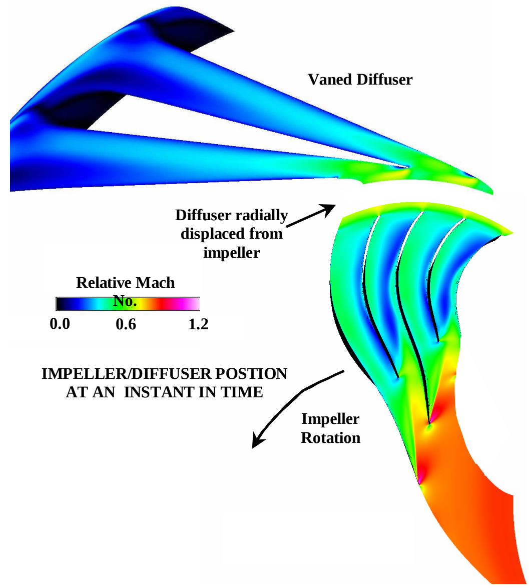

Figure 9 CC3 centrifugal compressor result at an instant of impeller/diffuser position.

passages, but not in all passages. Since the stall inception process must arise from disturbances generated by the flow field that are not necessarily multiples of blade passing frequency it is necessary to assess the TURBO codes ability to simulate a non-periodic flow structure as stall is approached. Figure 10 shows two instances in time of the TURBO results for a 12-passage (1/3 annulus) simulation that is very near the compressor stall point. As evident from these results the TURBO code is predicting a non-periodic structure that changes with time.

Away from the compressor near stall condition the simulations results are essentially periodic from rotor passage to passage, as is shown in Figure 11. Also shown in Figure 11 is the interaction of the rotor tip leakage flow with the passage shock that is believed to be a critical factor in defining the stall limit of the compressor. It has been demonstrated experimentally that the injection of high velocity air upstream of the rotor blade tip parallel to the rotor endwall extends the stable operating range of compressors. However, what's lacking

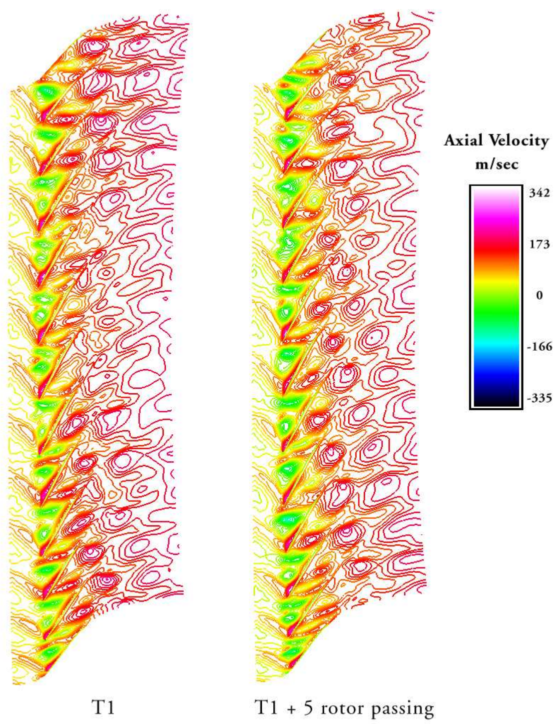

Figure 10 Rotor 35 at 92% span showing passage-to-passage time-varying non-periodic structure at near stall condition.

from the experimental investigations is a fundamental understanding of the stall inception process, how the stall control technology mitigates such, and what the pertinent design parameters are for applying this technology to any compression system. Figure 12 shows the impact of the stall control technology as modeled by discrete injection of high velocity air upstream of the rotor blade tip. As is shown in Figure 12 the injection of high velocity air modulates the rotor tip leakage flow as well as the rotor shock. Subsequent full annulus simulations are expected to provide insight into how the stall control technology delays the inception of stall.

The T700 engine compression system includes five high-speed axial stages followed by a high-speed centrifugal stage. Ideally all the blade passages of this compression system should be computed to adequately capture the temporal and spatial harmonics associated with stall inception. The estimated computing resources for such a full-scale calculation would be on the order of 800-3000 processors, each of 1GB core memory, depending on the required turn-around times. This requirement soon rules out all the existing platforms available for the Challenge Projects. A more conservative approach is to compute the full annulus only in the stages where stall inception is most likely to occur, in this case the first axial stage, for low speed operating conditions, and the radial stage, for high speed operating conditions. Because of the time needed for the wave to travel from one end to the other of the computational domain, it is expected to require a minimum of 20 rotor revolutions to capture the stall precursors and the stall event. To achieve convergence within a reasonable time frame the simulations are “boot strapped” from an initial steady flow simulation, using APNASA, to an unsteady TURBO simulation using phase lag boundary conditions to simulate only one passage for each of the 11 blade rows of the T700 multistage axial. Figure 13 shows time average results from an unsteady TURBO simulation using phase lag boundary conditions. This approach however eliminates relevant spatial and temporal harmonics pertinent to include for simulation of the stall inception process.

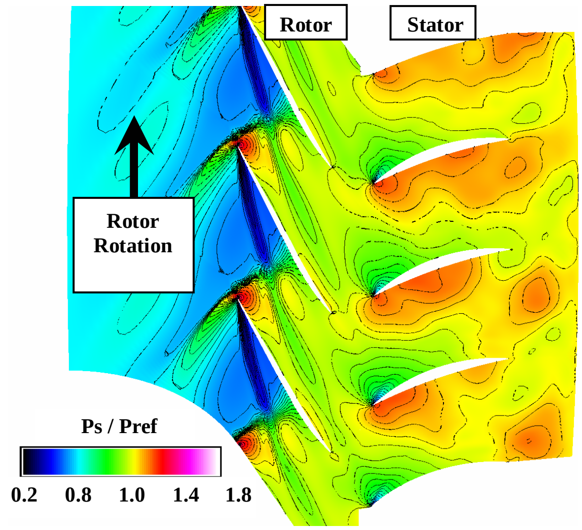

Figure 11 TURBO simulation of Stage 35 at an instant of rotor stator relative position at design point conditions near the rotor tip, showing contours of static pressure ratio.

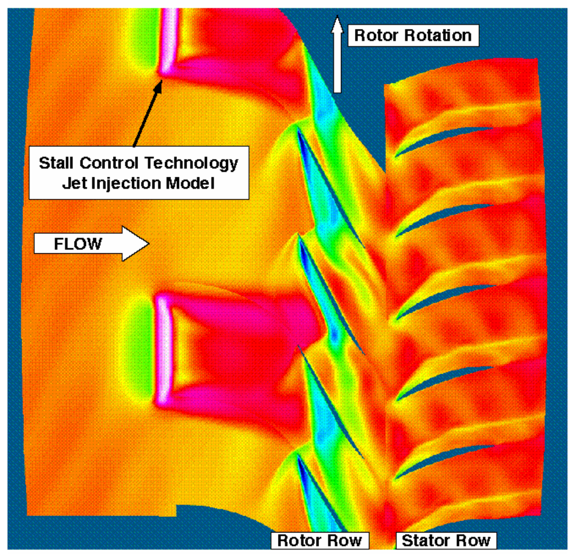

Figure 12 TURBO predictions of Stage 35 with stall control technology modeled, showing color contours ranging from blue, low to red, high axial velocity

A comparison of the APNASA and TURBO predictions of the overall performance for the 98 % speed line characteristic of the T700 multistage axial compressor to the experimentally measured performance are in reasonable agreement (not shown due to proprietary concerns). This comparison indicates the suitability of the TURBO code for predicting multistage compressor flows. Future results will entail full-annulus simulations of the stall inception process for the axial (Stage 35) and centrifugal (CC3) compressor validation cases for which detailed experimental results are available both with and without the stall control technology. These results will provide insight into the fundamental fluid mechanics of the stall inception process in high-speed turbomachinery as well as providing useful insight into the mitigating effects of the stall control technology. Subsequent full annulus unsteady simulations of the T700 five-stage axial and centrifugal compressors and the complete T700 compression system will yield useful insight into the interactions between multiple stages and their effect on the stall inception process.

The aforementioned comparisons provide evidence of the suitability of the TURBO code for the intended purposes of this Challenge Project providing insight into the fundamental fluid mechanics of the stall inception process of both high-speed axial and centrifugal compressors.

The level of computational resources required for the T700 simulations is provided in Table 1, and the computational resources in terms of CPU hours used to date is given in Figure 14. At the present rate of consumption we will exceed our FY03 allocated resources before the end of the fiscal year. The largest computational resource requirements for the T700 compression system simulations are yet to be realized and will entail a considerable increase in the number of processors used to date, see Table 1.

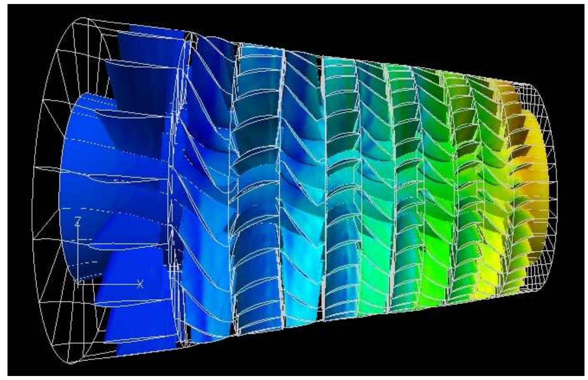

Figure 13 Time averaged results of an unsteady TURBO simulation of the T700 multistage axial using phase lag boundary conditions.

4. Significance to DoD.

All military and commercial gas turbine engine systems can benefit from the proposed work. In the future, this work could lead to new gas turbine engine designs with resistance to compressor stall and thus improved combat capability.

Compressors of gas turbine engines do not currently achieve their ultimate performance (pressure rise and fuel efficiency) because they must be de-rated to provide adequate margin from the compressor stall limit which if exceeded can lead to catastrophic engine failure. The level of de-rate, referred to as stall margin, can be as high as 35% of the total operating envelope of the compressor. Excursions towards the compressor stall limit are incurred as a result of distorted inflows encountered during military operations such as combat maneuvers and munitions release, and the stall margin is degraded over time due to erosion, rubs and normal engine wear. A 5% reduction in required stall

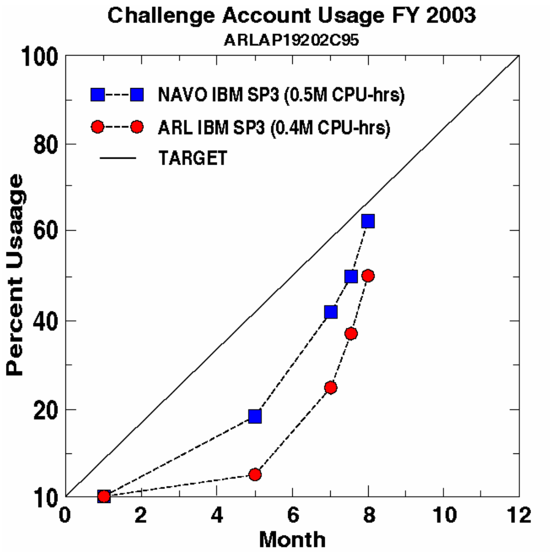

Figure 13 Computational resources used to date on the NAVO and ARL MSRC computers compared to linear burn rate of allocated resources.

margin will provide increased range/payload thereby significantly reducing the total logistics burden over the life cycle of the rotorcraft fleet, and could dramatically increase the vehicle operational envelope thereby enhancing combat mobility, survivability, lethality and sustainability of the objective force.

Stall control technology is applicable to all gas turbine engine powered combat and logistics support vehicles including the Comanche, Apache, Black Hawk, and Cobra rotorcraft, as well as all other manned and unmanned fixed- and rotary-wing aviation platforms, M1, and some surface ships powered by gas turbine engines. Given the pervasive applicability of this work to the vast array of gas turbine powered air and ground platforms that will comprise the objective force, operational benefits to the Army/DoD would be major, and include substantial increase in mobility, survivability, and sustainability.

5. Systems Used

ARL SP3, NAVO SP3, NAVO SP4, ARL Origin 3000

6. CTA. CFD

7. Acknowledgements

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Table 1 Computational resource requirements for T700 simulations.

These resources are the minimum requirements for a single operating point on IBM SP3. For multiple operating points or better turn-around time, the required resources would increase.

T700 Component and TURBO Configuration		Total No. Processors	Total Memory	Permanent Storage	CPU-Hours
Axial	Phase-lag B.C.	33	33 GB	20 GB	30 E03
	Full Annulus**	132	132 GB	76 GB	120 E03
	All Blade Rows Full Annulus	664	664 GB	406 GB	604 E03
Centrifugal	Phase-lag B.C.	8	8 GB	13 GB	7 E03
	Full Annulus	152	152 GB	122 GB	133 E03
Axial and Centrifugal	Phase-lag B.C.	41	41 GB	33 GB	37 E03
	Full Annulus**	284	284 GB	198 GB	253 E03
	All Blade Rows Full Annulus	816	816 GB	528 GB	737 E03

** Full annulus for only those blade rows of the stall critical stages with phase-lag B.C.’s for all other blade rows.