TIME-ACCURATE COMPUTATIONAL FLUID DYNAMICS ANALYSIS OF A SUPERSONIC TURBINE TO ASSESS STRUCTURAL MODE EXCITATION

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ABSTRACT

Gas turbines can experience significant unsteady loading during operation which can cause damage such as blade cracking or bearing wear. While computational fluid dynamics (CFD) modeling of full three-dimensional gas turbine flow to verify meanline design performance is standard practice within the industry, the use of time-accurate CFD makes it possible to assess the unsteady loading which can be especially problematic at operating conditions where unsteady fluid loading aligns with structural modes. The Fluid Dynamics branch (ER42) at NASA Marshall Space Flight Center has developed a time-accurate CFD analysis methodology using the unstructured, density-based, Loci-CHEM solver which is capable of simulating the relative motion required for turbomachinery applications through sliding interface meshes. The highly-parallel unstructured solver allows for full three-dimensional, time-accurate simulation of turbines including upstream and downstream components such as manifolds, nozzles, and stators, any of which could excite a turbine structural mode. Recently, Loci-CHEM was used to analyze the FASTRAC supersonic turbine to assess the loading on the rotor. Overall performance and time-averaged loading on the rotor was computed, including the axial force over the entire rotor disk which is required for force balance calculations on the turbopump. The FASTRAC turbine has supersonic nozzles upstream of the rotor that result in significant unsteady loading on the rotor blades at multiples of the nozzle pass frequency. The unsteady blade pressure loading was decomposed into the frequency domain for direct use in structural forced response analysis. Utilizing this type of CFD analysis coupled with structural analysis has proven to be a valuable tool in identifying structural modes that are being excited by unsteady fluid loading.

INTRODUCTION

Gas turbines, such as those used in rocket engine turbopumps, can experience significant unsteady loading during operation. If the alternating fluid loading aligns with the rotor structural modes, the structure can easily become excited and produce large alternating stresses that can generate or grow cracks. Turbine blade cracking due to low- and high-cycle fatigue is a common failure in gas turbines, with an example cracked turbine blade shown Figure 1. Avoiding operation of the turbine at structural mode crossings or changing the design to alter the structural mode frequencies or fluid loading is important for safely operating turbines, especially for human rated launch vehicles.

Assessing which specific turbine structural modes are being excited can be difficult. Optical probes exist that can be used to measure turbine blade vibrational response but require optical access, which is a significant challenge. Structural analysis can be used to predict the structural modes, including the modal frequency, which can be used to assess if the turbine is operating at rotational speeds with Campbell crossings. However, the actual structural response, including stresses and strains, can only be assessed analytically using a forced response analysis. A forced response analysis applies an alternating fluid loading onto the structural modes as a forcing function to determine the degree to which the structural modes will be excited. To complete a forced response analysis the alternating fluid loading on the rotor blades is required. Determining the fluid loading is difficult to do experimentally and to resolve analytically requires capturing the coupling between rotors, stators, and other components.

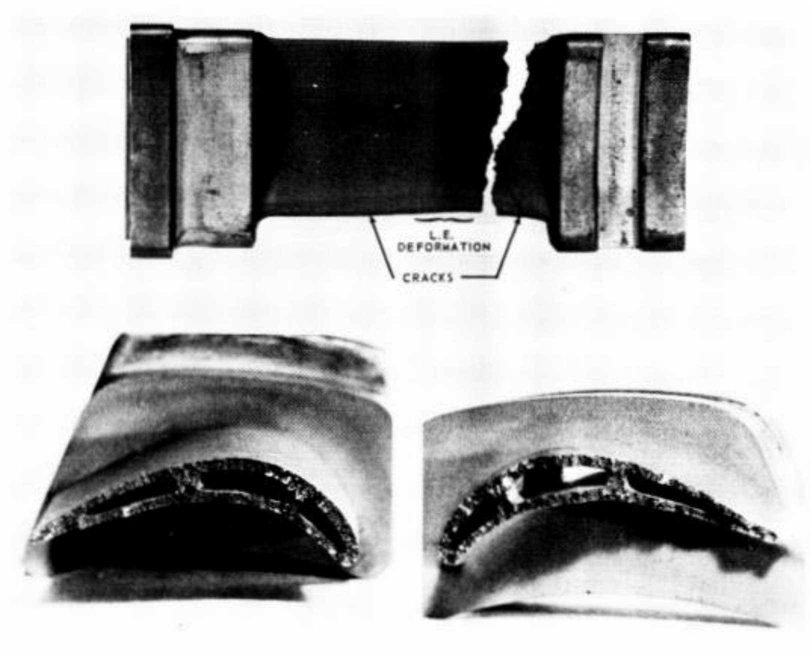

Figure 1. Example of turbine blade cracking and failure from [1].

Three-dimensional computational fluid dynamic (CFD) simulation of turbines is often used to assess time-averaged loading and performance as verification of mean-line analysis tools. Axial and side loading on the rotor can be predicted and used as inputs into load balance and rotor-dynamics models for the turbopump. In order to assess the alternating loading on the rotor for forced response analysis to determine if structural modes will be excited, high-fidelity, time-accurate CFD can be used. The Fluid Dynamics branch (ER42) at NASA Marshall Space Flight Center (MFSC) has developed a full three-dimensional time-accurate CFD analysis methodology using the unstructured, density-based, Loci/CHEM solver. This methodology is used to predict alternating loading on the turbine blades due to rotor-stator interactions. Part of this methodology includes a procedure to transform the time-accurate alternating pressures into the frequency domain for direct used in forced response analysis. Forced response analysis is used to determine the alternating stresses on the rotor and is an input into fatigue life calculations. Multiple harmonics, at least 8 for some turbines, of stator pass frequencies have been identified as having appreciable alternating loading and have been identified as modes that have caused turbine cracking. By using full 3D CFD models, complex interactions between components can be resolved, such as coupled modes developed by multiple stator rows and non-uniform inlet flow causing lower frequency alternating loading.

In the current work, CFD analysis is used assess the main stage loading on the FASTRAC supersonic gas turbine. FASTRAC is a LOX-RP rocket engine developed at NASA MSFC in the late 1990s as a low cost and easy to manufacture engine with 60,000 lbf of thrust. FASTRAC has a single turbopump with one turbine that drives both the fuel and oxygen single stage pumps. The turbine has axisymmetric converging-diverging supersonic nozzles upstream of the rotor that deliver a supersonic flow over Mach 2 to the rotor, which is not a typical nozzle configuration. The impulse turbine has symmetric rotor blades, which, due to the supersonic nozzles, are subjected to high alternating fluid loading. The alternating loading on the rotor blades is assessed using CFD analysis and the alternating pressures over the entire rotor blade surface are decomposed into frequency space using a Fourier transform. The Fourier coefficients of the alternating loading can be used directly in a forced response analysis to assess the alternating stresses and fatigue life. This methodology has been used for many programs to gain insight into alternating loading on turbomachinery and other components that encounter highly unsteady fluid loading.

ANALYSIS MODEL

The FASTRAC turbine geometry model used for analysis is shown in Figure 2 and includes an upstream volute, 24 inlet converging-diverging supersonic nozzles, the rotor with 147 blades, and 67 downstream exit guide vanes (EGVs). The turbine disk is included in the model along with the fluid gap upstream and downstream of the rotor to allow predication of the total axial force on the turbine bladed disk.

The geometry model surfaces are meshed with triangular elements using the ANSA software [2], with regions of the surface mesh shown in Figure 2. The unstructured volume meshing package AFLR3 [3, 4] is used to create the three-dimensional volume mesh, which contains tetrahedral, prism, and pyramid cells. All solid wall surfaces have prismatic boundary layer meshes with normal growth rate of 1.2. A two-dimensional, planar slice of the volume mesh through the center of one of the inlet nozzles is presented in Figure 3. The volume mesh generated contains 416 million cells.

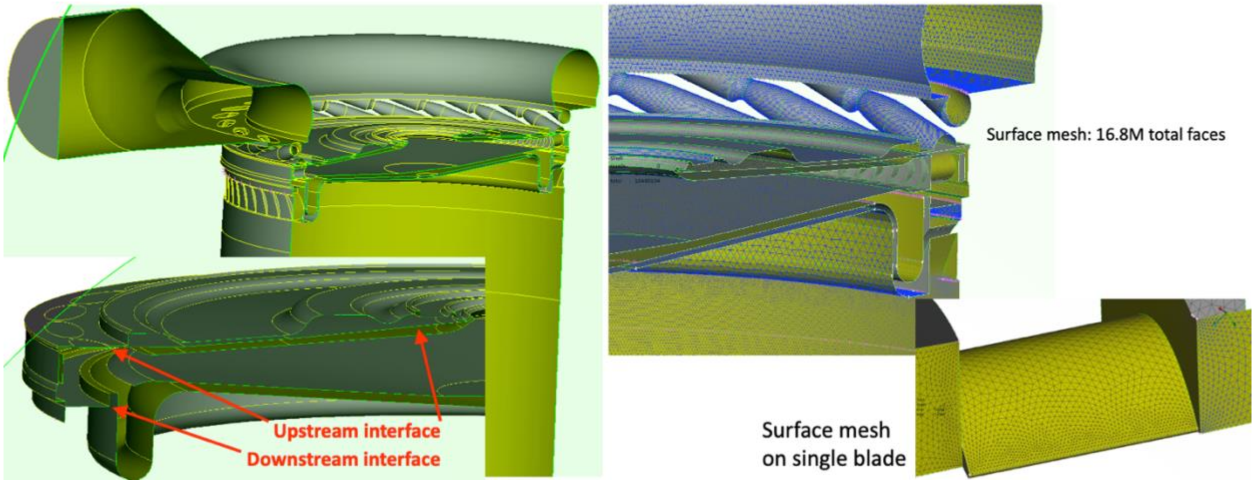

Figure 2. Geometry model of the FASTRAC turbine used for CFD analysis. Left: Slice through geometry model with inset of sliding interfaces shown. Right: Surface mesh on geometry with inset of surface mesh on a single rotor blade.

Loci-CHEM is a density-based finite-volume CFD solver built upon the Loci framework [5, 6, 7, 8]. Loci is a framework that performs the coordination and interaction of a collection of numerical kernels and methods. This collection of numerical kernels and methods support the different capabilities in the Loci-CHEM program. Among the current capabilities in the Loci-CHEM program are: support for arbitrary meshes, several different time integration schemes, and variable time step for steady-state calculations, different turbulent models such as Menter's baseline and Menter's Shear Stress Transport (SST) model, pre-conditioning for low Mach number flows, finite-rate chemistry, and conjugate heat transfer. Also, through the Loci framework, Loci-CHEM supports the use of distributed memory computers for parallel computing. A detailed documentation of the governing equation formulation and numerical approaches may be found in the Loci-CHEM User's manual [5].

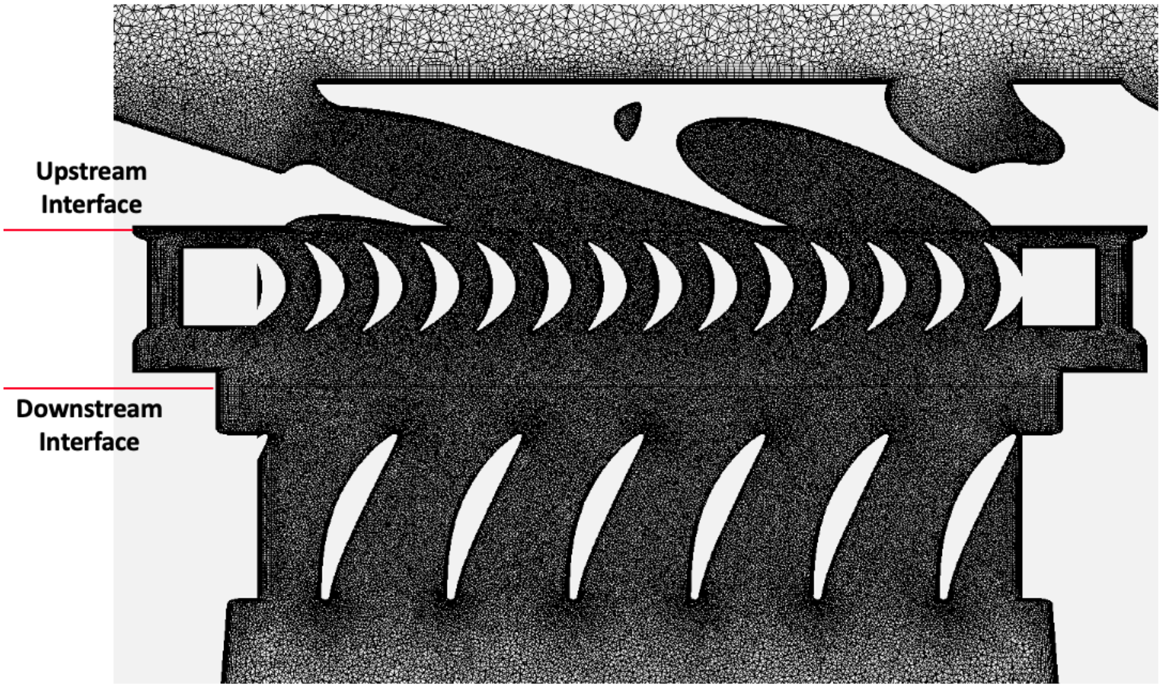

Figure 3. Slice through the volume mesh on a plane at the centerline of an inlet nozzle.

Loci-CHEM has the capability to simulate turbomachinery with rotating components using relative motion and sliding interfaces. The current simulation requires two sliding interfaces between the rotating rotor components and the stationary upstream (nozzles) and downstream (EGVs) components. The two interfaces are shown in Figure 2 and Figure 3. The upstream interface between the nozzles and rotors goes all the way from outer turbine housing through the upstream disk gap and terminates at the turbine shaft. The downstream interface is a planar face in the passage to the EGVs.

The Loci-CHEM simulation of the FASTRAC geometry is completed with a single species ideal gas with fluid properties from NASA CEA [9, 10] to represent the equilibrium combustion products of the gas generator just upstream of the turbine. The ideal gas molar mass is 35.5 g/mol and ratio of specific heats is 1.1. Transport properties are also taken from NASA CEA, with dynamic viscosity of 3.8E-5 Pa-s and thermal conductivity of 0.15 W/m-K. The inlet to the domain has a fixed mass flow rate of of 7.10 lbm/s with gas entering at a temperature of 1600 R. The outlet boundary condition is a fixed pressure of 60.6 psia. These turbine conditions simulate the maximum power level with a rotational speed of 20,000 RPM.

The time-accurate CFD simulation is second order accurate in space and time, using the Roe scheme for the inviscid flux with the Venkatakrishnan limiter. The simulation time step size is set so that 4000 time steps are completed each revolution of the rotor, and the simulation is run until all oscillations are repeating (stationary). The turbulence model used for the simulation is a hybrid RANS-LES model implemented in Loci-CHEM, with Mentor’s Baseline k-omega-SST model for RANS and Sarkar’s compressibility correction (see [5] for details).

RESULTS AND DISCUSSION

FLOW FIELD

Instantaneous static pressure and Mach number contours are shown in Figure 4 and Figure 5 on cylindrical slices through the rotor blade mid-span. Flow exits the supersonic nozzles at approximately Mach 2. The oblique shock at the rotor leading edge is unsteady as the blades rotate, with regions in between the nozzles where flow expands up to Mach 2.5 with static pressure much lower than the average static pressure of the nozzle exit flow. The variation in flow caused by the region between the nozzles causes a significant fluctuation on the rotor inlet flow.

Significant flow separation on the rotors is observed, starting at approximately one third of blade chord. This flow separation was also predicted by CFD analysis of the FASTRAC during the development and testing of the turbopump [11]. The leading-edge oblique shock on the pressure surface of the rotors interacts with the flow separation of the neighboring rotor, resulting in a region of high pressure on the pressure surface. This region of high pressure fluctuates in magnitude as the rotor passes through the nozzle flow, with a peak pressure when the rotor is near the nozzle centerline and a minimum when the rotor is between nozzles.

The flow exits the rotor highly unsteady, with many eddies generated at the rotor which travel downstream into the transonic EGVs. The influence of the nozzles can be observed downstream of the rotor and through the EGVs, with regions of higher pressure and lower Mach number through the EGVs that are downstream of the gap between nozzles.

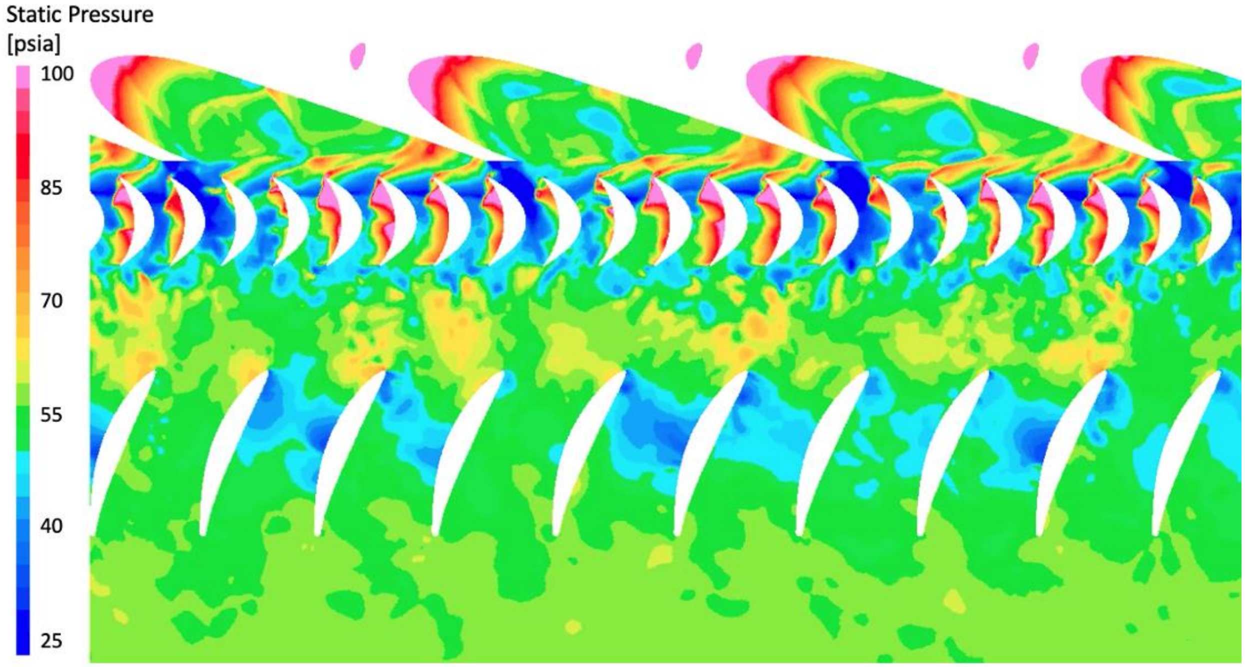

Figure 4. Static pressure contour on a cylindrical slice through the rotor blade mid-span at one instant in time.

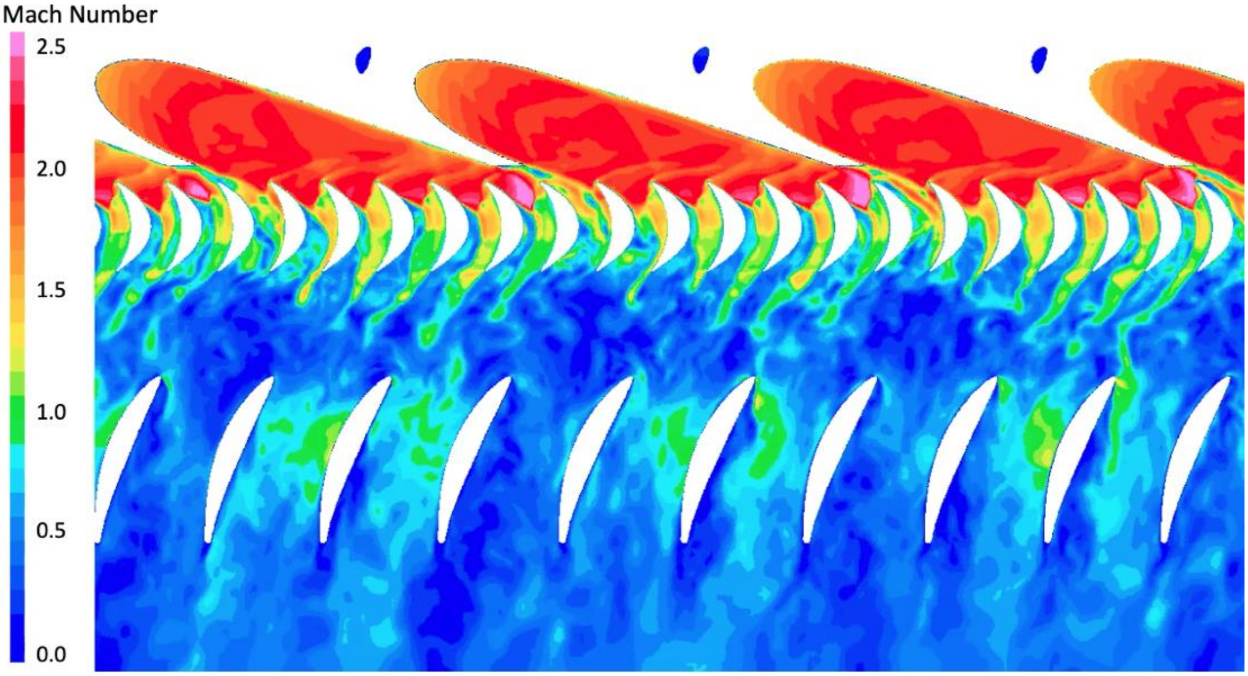

Figure 5. Mach number contour on a cylindrical slice through the rotor blade mid-span at one instant in time.

Time-averaged static pressure and Mach number on the same cylinder slice are shown in Figure 6. Note the discontinuity at the interfaces caused by time-averaging in the rotational reference frame for the rotor and the stationary reference frame for the nozzles and EGVs. Mach diamonds are observable in the nozzles, and the low pressure, high Mach number region is clear in the region between nozzles. A sharp suction peak occurs on the rotor suction surface just upstream of the flow separation location. On the pressure surface, a double peak pressure occurs, one near the quarter chord downstream of the leading edge oblique shock, and the second near the three-quarter chord after a secondary expansion and shock downstream of the first peak.

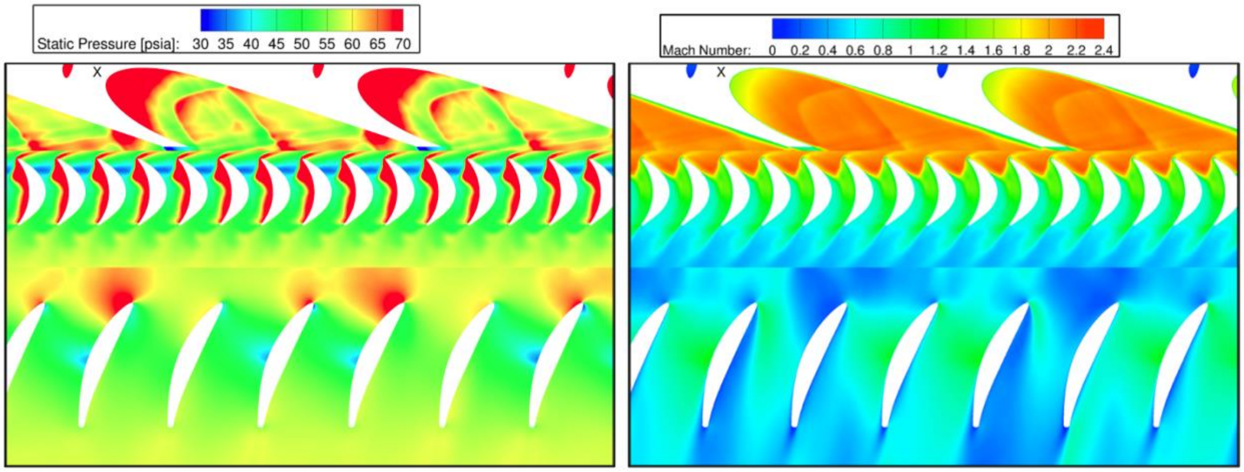

Figure 6. Time-averaged static pressure (left) and Mach number (right) contours on a cylindrical cut at rotor blade mid-span.

The time-averaged static pressure on a planar slice through the center of the turbine is shown in Figure 7. The pressure in the cavity upstream of the rotor is lower than the pressure in the downstream cavity, resulting in a net axial force on the rotor in the upstream direction. The upstream cavity has a lower pressure due to an ejector-like effect that occurs as the high velocity flow exiting the nozzle expands and results in a low pressure at the inner diameter of the rotor blades. This can be observed in time-averaged planar slices between the nozzles and rotor in Figure 8.

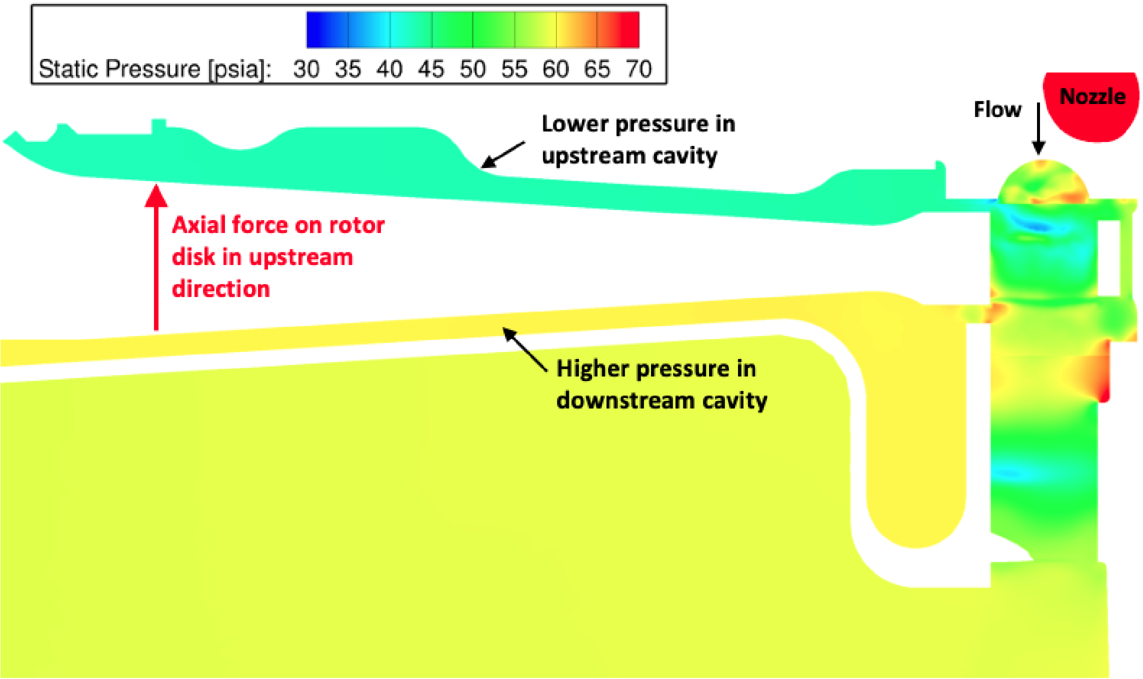

Figure 7. Time-averaged static pressure contour on planar cut through the center of the turbine.

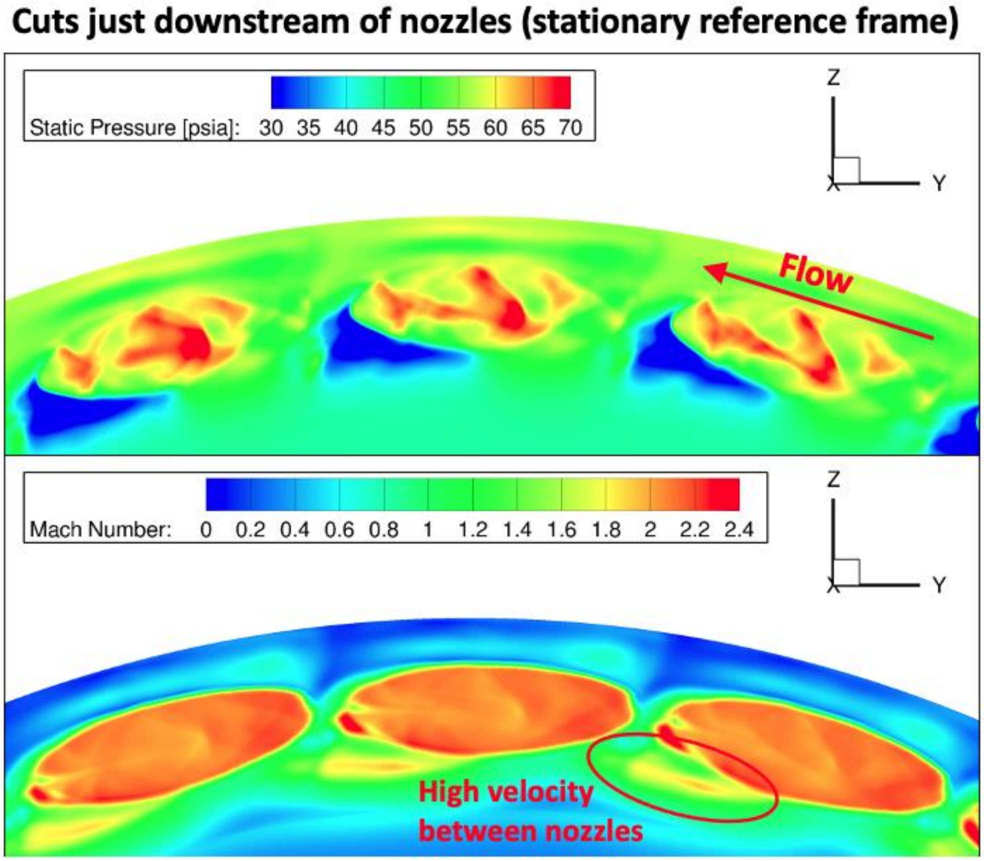

Figure 8. Time-averaged static pressure (top) and Mach number (bottom) contours on an axial plane downstream of the nozzles.

ALTERNATING PRESSURES

The alternating pressures on a single rotor at mid-span leading and trailing edge locations are presented in Figure 9 over one full revolution. At the leading edge, the pressure significantly fluctuates 24 times over one revolution, equal to the number of nozzles. A Fourier transform of the time history of these pressure traces results in the responses in Figure 10. Note that the responses in Figure 10 are half-amplitude, i.e., one-half of the mean-to-peak amplitude. The leading-edge location produces responses well above the noise for the nozzle pass frequency, 8000 Hz, up to 8x the nozzle pass frequency (higher frequencies were not resolved for this analysis). The amplitude of the response decreases from the nozzle pass frequency to 4x nozzle pass frequency but remains at a similar amplitude for the higher nozzle pass frequencies. The reason for significant number of nozzle-pass harmonics is due to the very sharp low-pressure region between the nozzles.

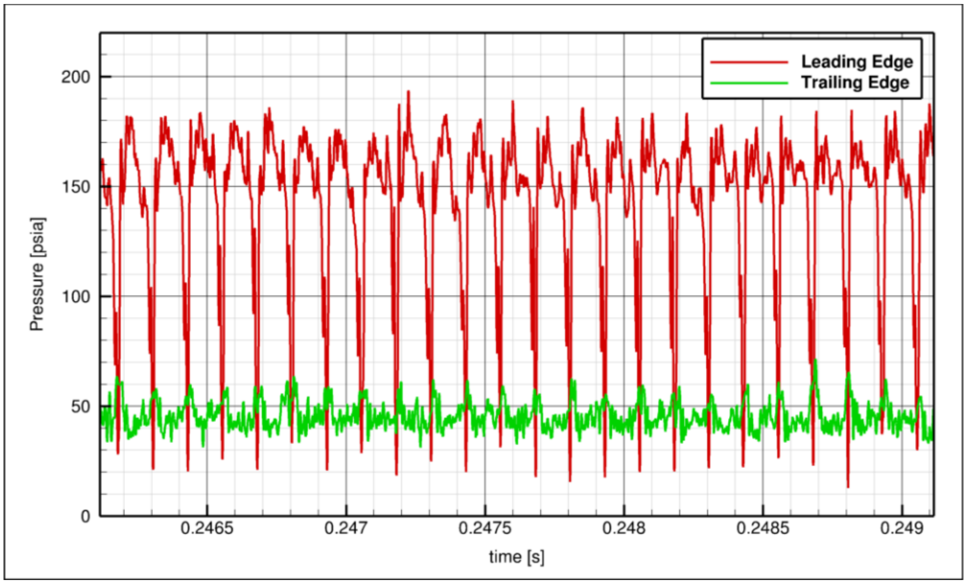

Figure 9. Time history of pressures on a rotor blade at leading and trailing edge locations.

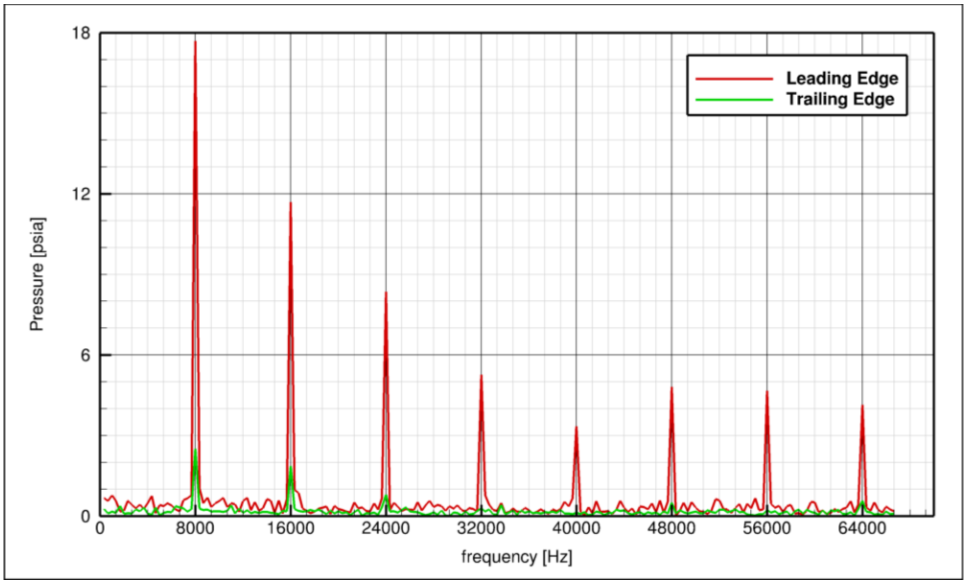

Figure 10. Fourier transform pressure response half-amplitude on a rotor blade at leading and trailing edge locations.

A forced response analysis is a structural analysis which uses a fluctuating fluid loading profile and the dynamic structural modes of a structure to compute alternating stresses. Forced response analyses are used to determine if modal excitation will occur for a structure, which is especially vital for turbomachinery applications where many modal crossings can exist. If the alternating fluid loading aligns with a structural mode, modal excitation will occur and can cause fatigue issues like blade cracking. Forced response analysis is completed in the frequency domain. A procedure has been developed to decompose the time domain alternating pressures on rotor surface into the frequency domain using Fourier transformation. This is the same procedure for calculating the frequency content of pressure traces as shown above at each grid point on the surfaces of interest.

The CFD predicted alternating pressures for the FASTRAC turbine are decomposed into the frequency domain using this Fourier transformation procedure. The time-averaged pressure on a rotor blade is given in Figure 11, and the fluctuating pressure response magnitude at frequencies from 1x nozzle pass frequency up to 8x nozzle pass frequency are given in Figure 12 through Figure 19. Note that the contour scale for each frequency differs and ranges from zero to the peak magnitude of each mode. The peak response magnitude decreases with higher frequency but remains significant through the 8x nozzle pass frequency. The shape of the alternating pressure loading is unique for each frequency, but regions with appreciable alternating pressure are common between modes. The peak response locations for most modes are at the leading edge and on the pressure surface near the peak pressure location and outer shroud. There are also regions of alternating pressure response on the suction surface at the location where flow separation occurs and interacts with the leading-edge oblique shock.

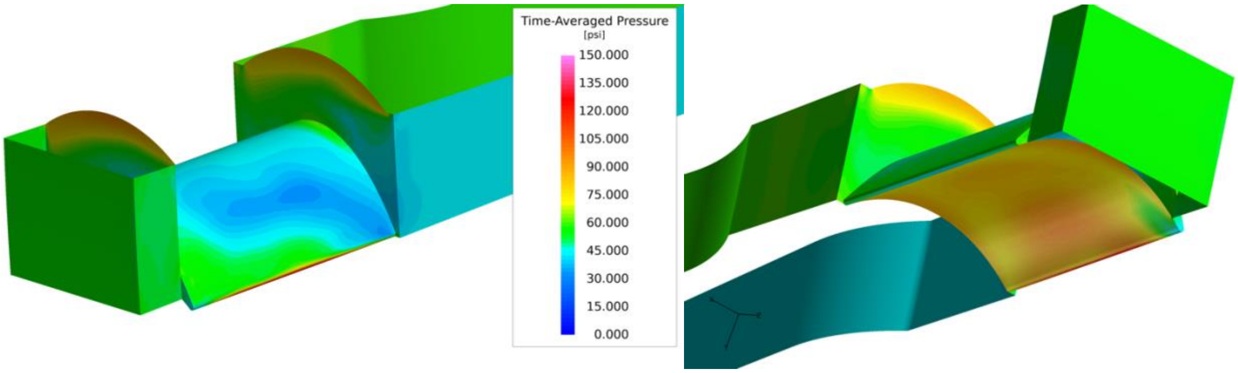

Figure 11. Time-averaged surface pressure on a single rotor blade. Left: leading edge and suction surface. Right: Trailing edge and pressure surface.

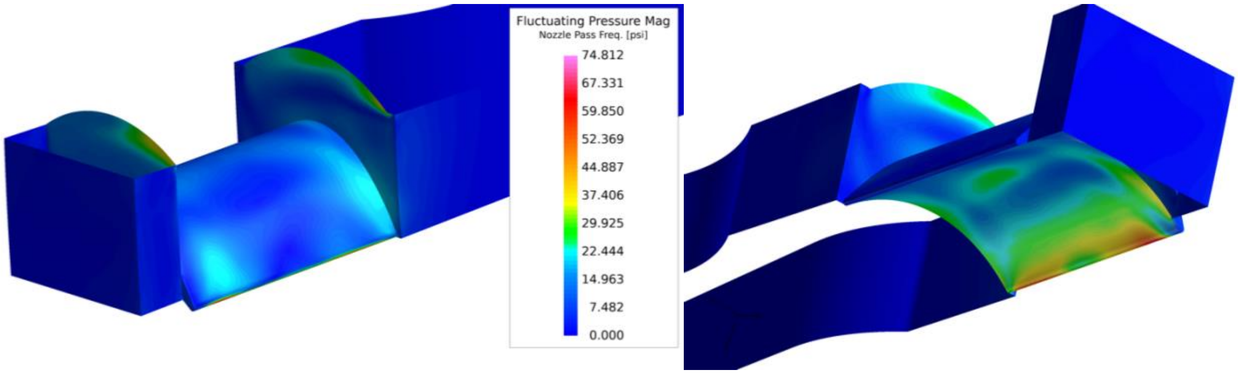

Figure 12. Fluctuating pressure response magnitude at nozzle pass frequency. Same orientation as Figure 11.

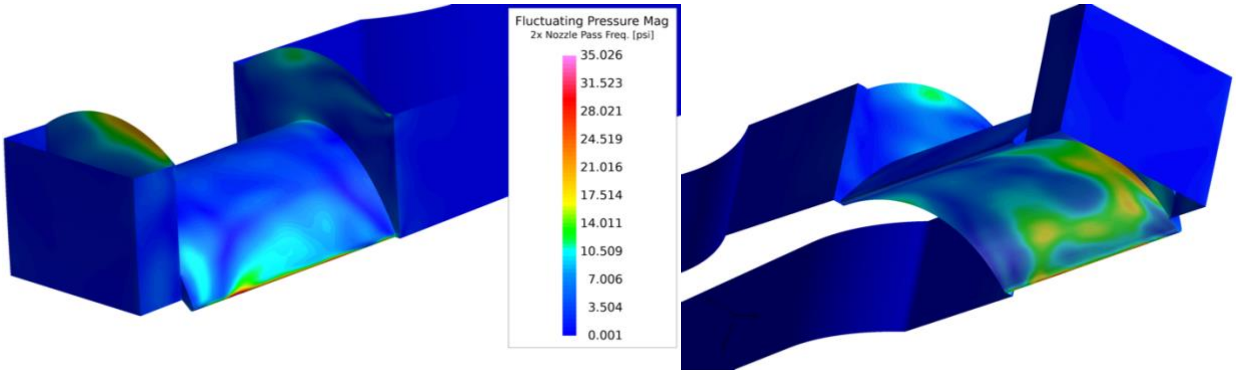

Figure 13. Fluctuating pressure response magnitude at 2x nozzle pass frequency. Same orientation as Figure 11.

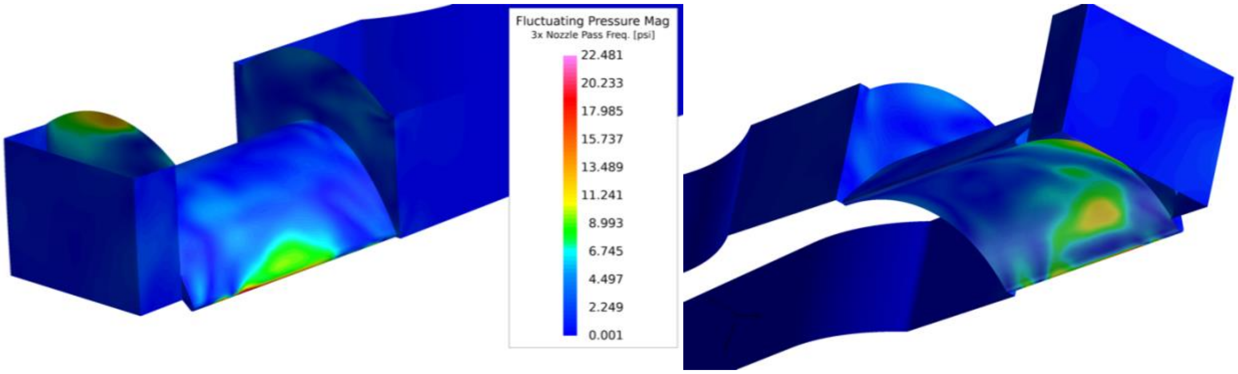

Figure 14. Fluctuating pressure response magnitude at 3x nozzle pass frequency. Same orientation as Figure 11.

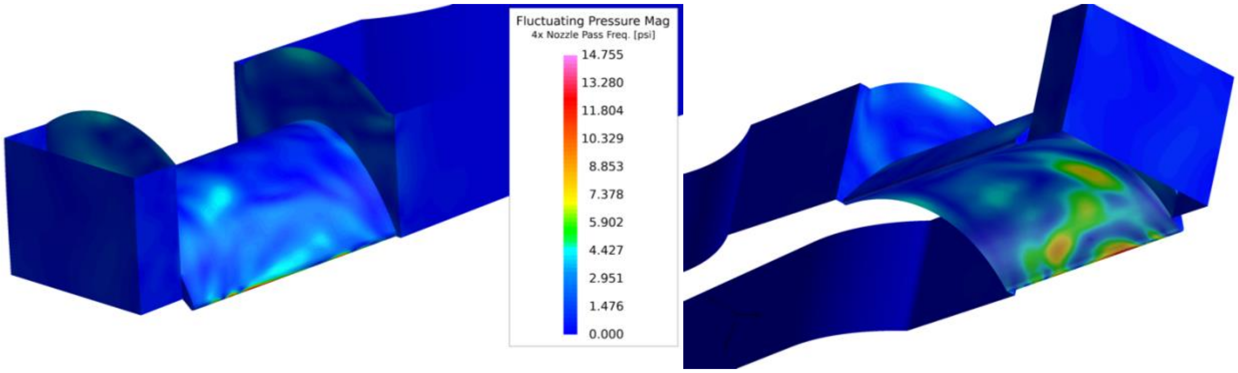

Figure 15. Fluctuating pressure response magnitude at 4x nozzle pass frequency. Same orientation as Figure 11.

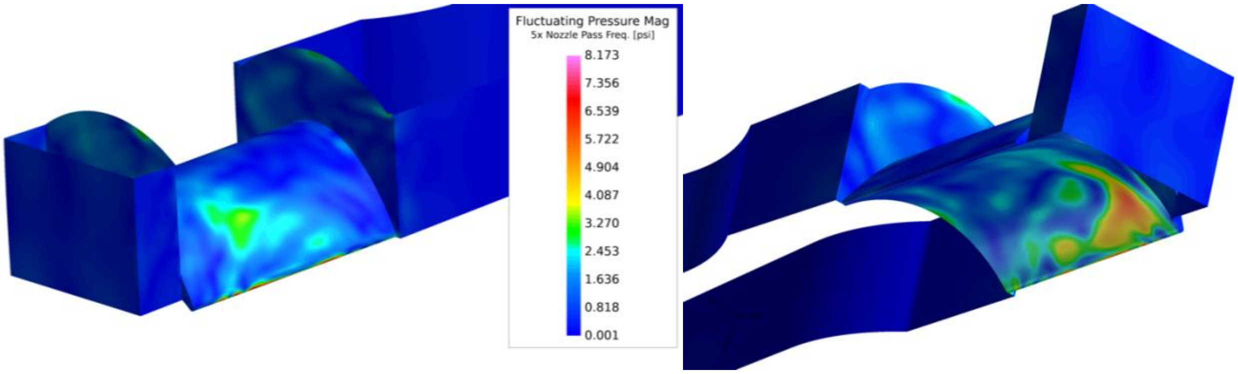

Figure 16. Fluctuating pressure response magnitude at 5x nozzle pass frequency. Same orientation as Figure 11.

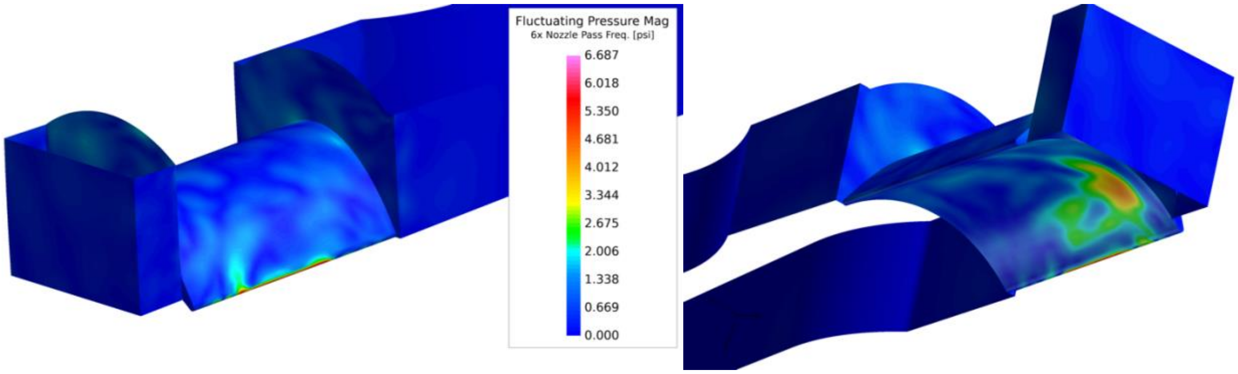

Figure 17. Fluctuating pressure response magnitude at 6x nozzle pass frequency. Same orientation as Figure 11.

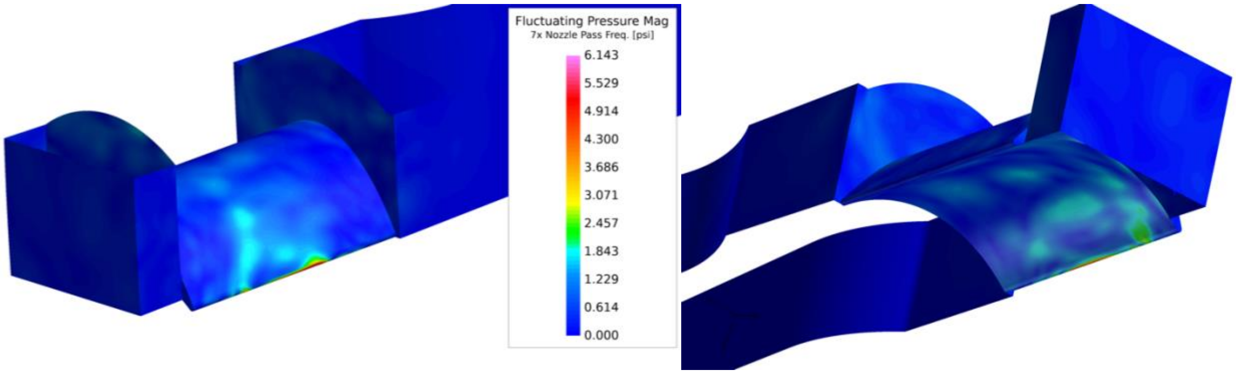

Figure 18. Fluctuating pressure response magnitude at 7x nozzle pass frequency. Same orientation as Figure 11.

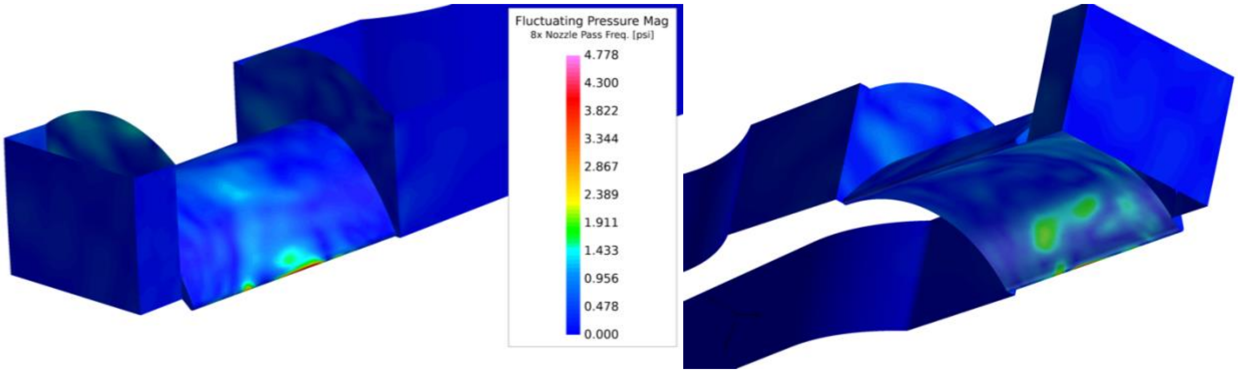

Figure 19. Fluctuating pressure response magnitude at 8x nozzle pass frequency. Same orientation as Figure 11.

The real (cosine) and imaginary (sine) components of the decomposed alternating pressures are shown in Figure 20 and Figure 21 for the nozzle pass frequency. The real and imaginary components contain the phase information of the alternating pressure and are the direct inputs in the forced response analysis. The decomposed alternating pressure functional form for each orthogonal mode is $P_\omega(t) = A_{real}\cos(\omega t) - A_{imag}\sin(\omega t)$ where P_ω is the alternating pressure at frequency ω and A_{real} and A_{imag} are the real and imaginary response coefficients plotted in Figure 20 and Figure 21.

The alternating pressure does not act on the rotor in unison (i.e., in phase), but imparts a positive or negative pressure fluctuation away from the time-averaged pressure at different locations at different times. The real and imaginary components capture that phase information. Real and imaginary components are 90-degrees out of phase from each other. A negative real component is 180-degrees out of phase from a positive real component, meaning that a location with a negative real component will feel a pressure below the average pressure at the same instant in time when a location with a positive real component will feel a pressure above the average pressure. The same is true for negative and positive imaginary components. This fluctuating pressure "pushing" or "pulling" and phase information directly affects the structural response which depends on the direction and phasing of the alternating loading.

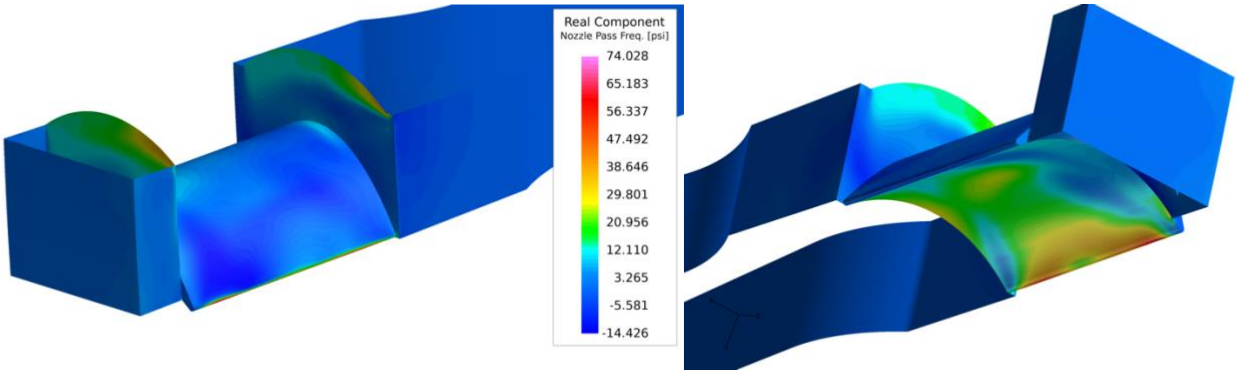

Figure 20. Fluctuating pressure response real (cosine) component at nozzle pass frequency. Same orientation as Figure 11.

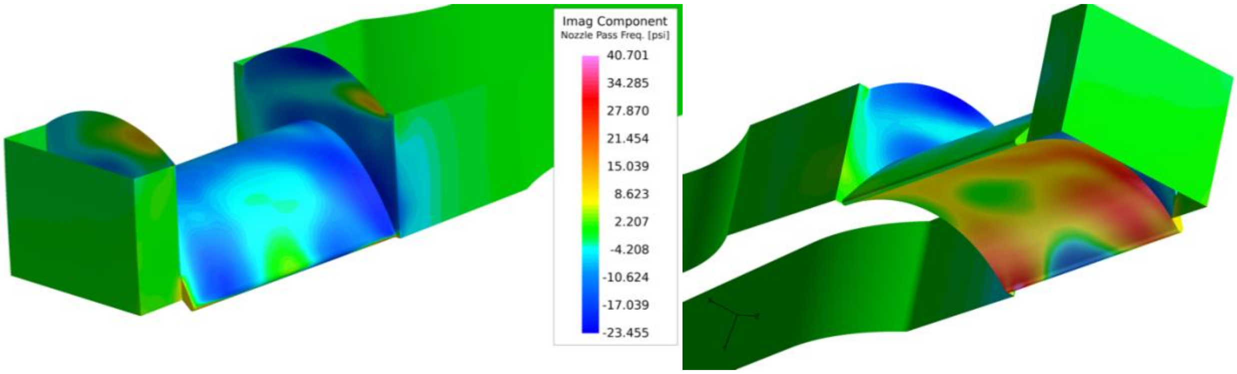

Figure 21. Fluctuating pressure response imaginary (sine) at nozzle pass frequency. Same orientation as Figure 11.

SUMMARY AND CONCLUSIONS

Time-accurate CFD analysis of the supersonic FASTRAC turbine was completed using the Loci-CHEM solver with hybrid RANS-LES turbulence model. The configuration of the FASTRAC turbine results in a significant flow separation on the rotors and a net axial force on the rotor disk in the upstream direction. CFD results indicate an alternating flow field is experienced by the rotor blades due to the supersonic nozzles, and in particular the gap between the nozzles. Fourier transformation of the alternating surface pressure on the rotor indicates that responses are present at nozzle pass frequency and multiples of nozzle pass frequency up to at least 8x nozzle pass frequency.

The alternating fluid loading on its own cannot indicate whether modal excitation will occur but is used as an input for forced response analysis, which can determine if modes will be excited and the resulting alternating stresses and strains. CFD analysis provides insight into the source of unsteady loading and can be used to inform design or operational changes. This analysis methodology has been used in failure investigations for multiple programs to identify structural modes that have been excited and resulted in structural cracking and failure.

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