A Numerical Investigation of Turbine Noise Source Hierarchy and Its Acoustic Transmission Characteristics

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Understanding the relative importance of the various turbine noise generation mechanisms and the characteristics of the turbine acoustic transmission loss are essential ingredients in developing robust reduced-order models for predicting the turbine noise signature. A computationally based investigation has been undertaken to help guide the development of a turbine noise prediction capability that does not rely on empiricism.

The investigation relies on highly detailed numerical simulations of the unsteady flowfield inside a modern high-pressure turbine (HPT). The simulations are developed using TURBO, which is an unsteady Reynolds-averaged Navier-Stokes (URANS) code capable of multi-stage simulations. The purpose of this study is twofold. First, to determine an estimate of the relative importance of the contributions to the coherent part of the acoustic signature of a turbine from the three potential sources of turbine noise generation, namely, blade-row viscous interaction, potential field interaction, and entropic source associated with the interaction of the blade rows with the temperature non-uniformities caused by the incomplete mixing of the hot fluid and the cooling flow. Second, to develop an understanding of the turbine acoustic transmission characteristics and to assess the applicability of existing empirical and analytical transmission loss models to realistic geometries and flow conditions for modern turbine designs.

The investigation so far has concentrated on two simulations: (1) a single-stage HPT and (2) a two-stage HPT and the associated inter-turbine duct/strut segment. The simulations are designed to resolve up to the second harmonic of the blade passing frequency tone in accordance with accepted rules for second order solvers like TURBO. The calculations include blade and vane cooling flows and a radial profile of pressure and temperature at the turbine inlet. The calculation can be modified later to include the combustor pattern factor at the turbine inlet to include that contribution to turbine noise.

We shall present preliminary analysis of the results obtained so far in order to assess the validity of such an approach and to seek feedback on improving the approach. This work addresses both Area 1 (Turbine Tone Noise) and Area 5 (Influence of the Turbine on Combustor Noise) topics.

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Outline

- Motivation and Objectives
- Single and Multi-Stage Turbine Geometries
- Simulation Setup
- Noise Generation Mechanisms
- Results
- Future Work
- Summary

Motivation and Objectives

Motivation:

As fan and jet noise are reduced, turbine noise is lurking just below surface. Robust first-principles-based models for turbine noise do not currently exist.

Approach:

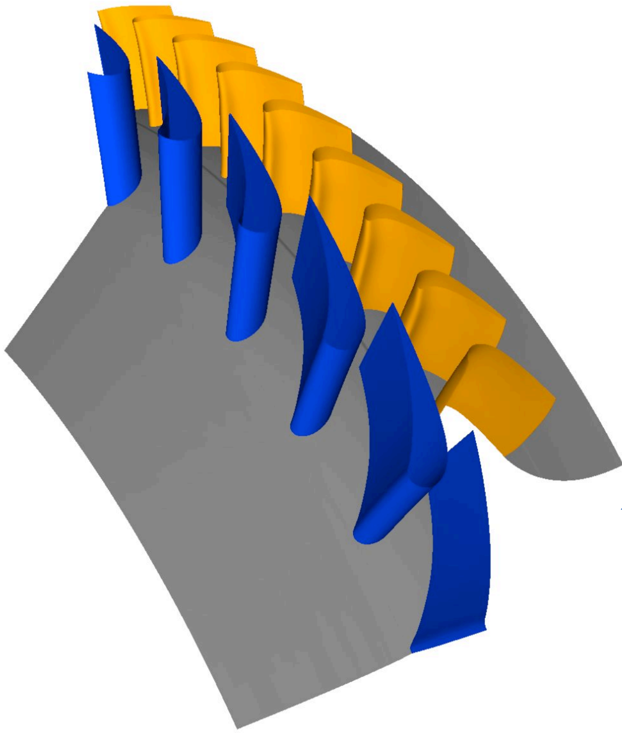
Appropriately apply an aerodynamic solver to produce highly detailed numerical simulations of a modern high pressure turbine.

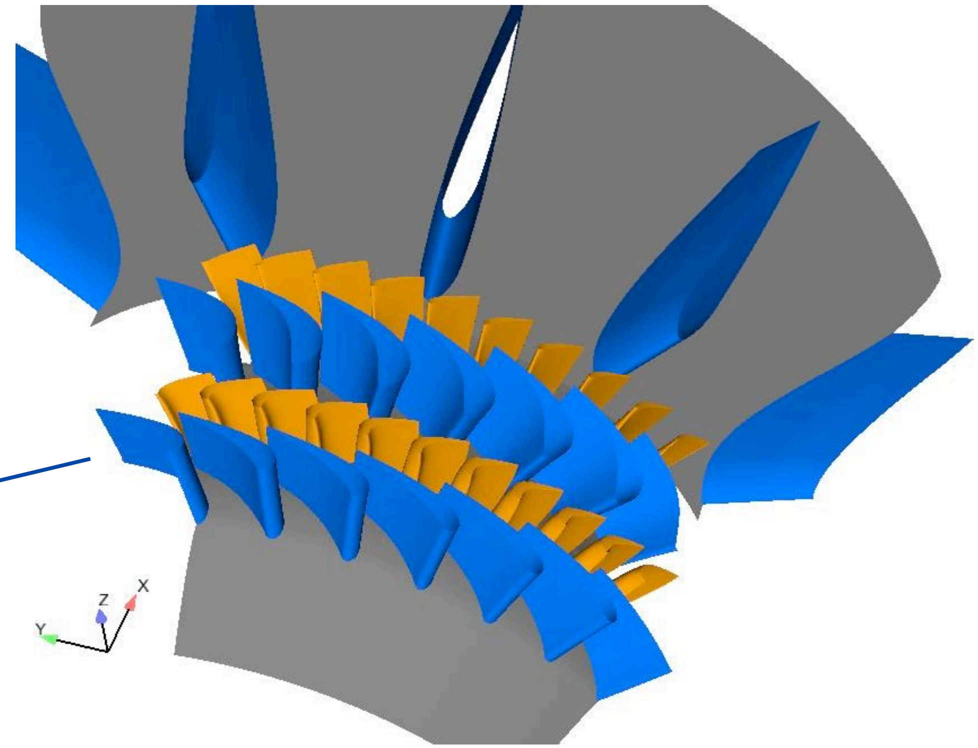
Objectives:

- Estimate of the relative importance of the contributions to the coherent part of the acoustic signature of a turbine from the three potential sources of turbine noise generation; blade-row viscous interaction, potential field interaction, and entropic sources
- Understand the turbine acoustic transmission characteristics
- Develop reduced order models for turbine noise generation and transmission

Preliminary analysis of the results obtained so far is presented in order to assess the validity of such an approach and to seek feedback on improving the approach.

Single and Multi-Stage Geometries





1st stage HPT
1/8 annulus
40-64 blade count (5-8 sector)
Cooling flows are included.

Entire HPT + strut
1/7 annulus
42-70-42-63-2 blade count
Cooling flows are included.
(still converging on RTJones machine)

The Numerical Code

TURBO:

3D multi-stage, turbomachinery URANS solver
Temporal discretization is second-order accurate backward differencing
Spatial discretization is a modified upwind scheme, 3rd order accurate
NASA/CMOTT κ-ε turbulence model

Mesh:

Domain is meshed to resolve 2BPF using 40 nodes per wavelength as accepted practice for a 2nd order code
Total node count is 10x an aero simulation:

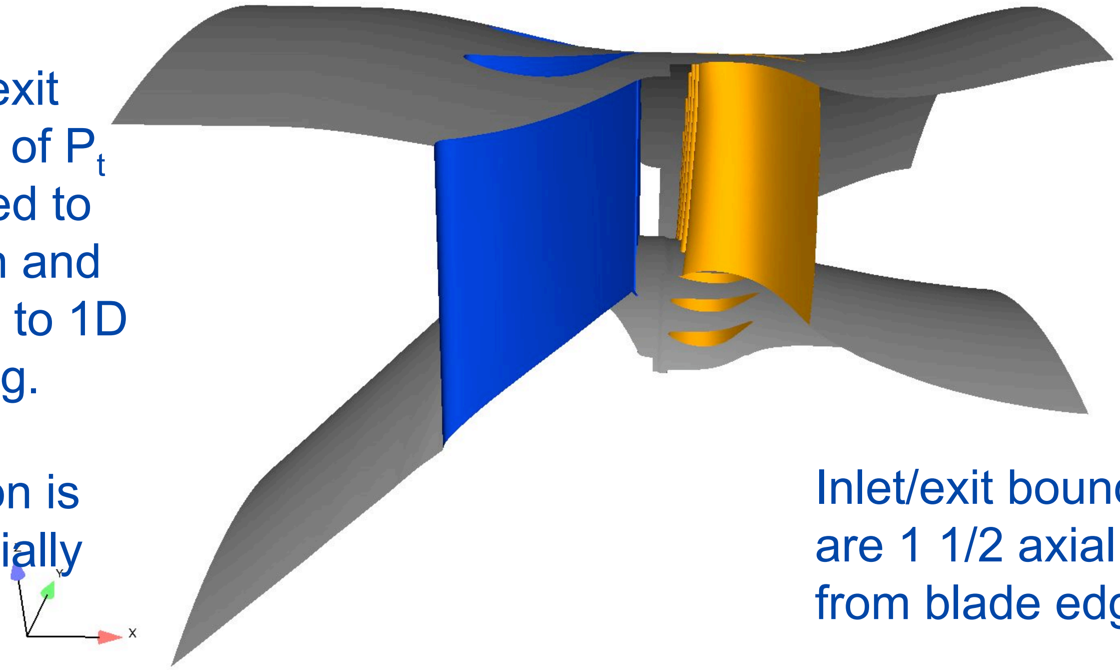
- Single stage case: 80M nodes
- Multi-stage case: 165M nodes

The Computation Domain

Vanes, rotors, hub and casing have cooling flows included using source terms.

Combustor exit radial profile of P_t and T_t applied to start solution and then change to 1D non-reflecting.

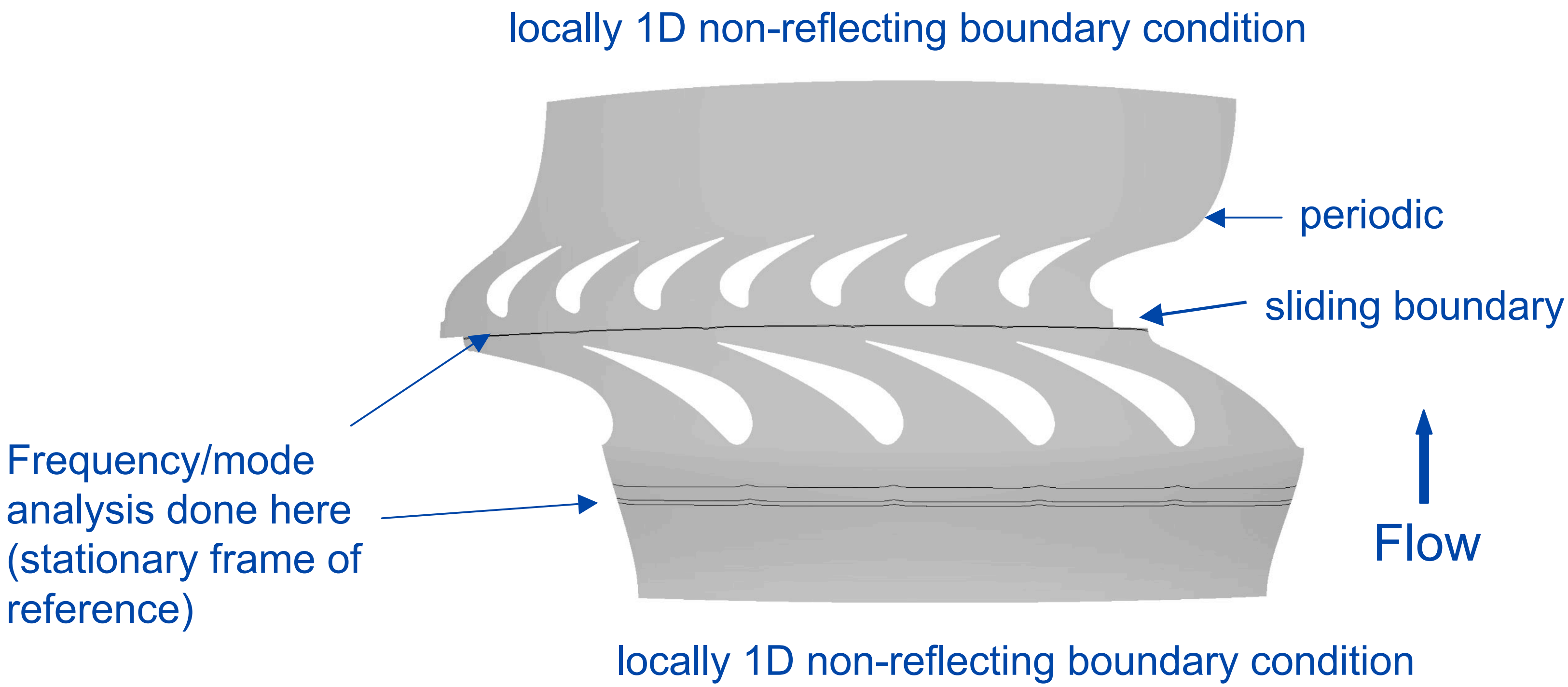
Inlet condition is circumferentially uniform.



Inlet/exit boundaries are 1 1/2 axial chords from blade edges

Side view of domain showing flowpath contraction for single-stage geometry

The Computation Domain



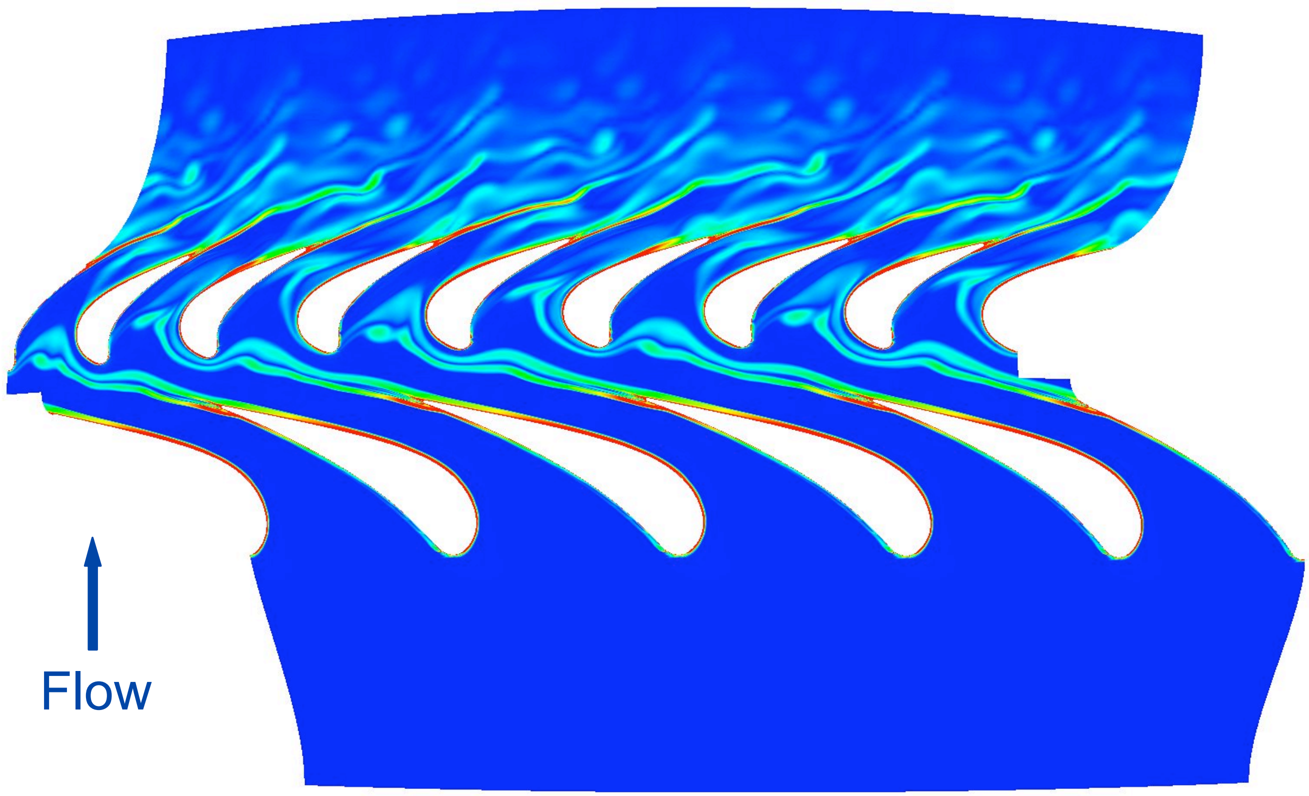
1/8 annulus with 40-64 blade count (5-8 for sector)

Results
Instantaneous views of the flow field

Noise Generation Mechanisms (1)

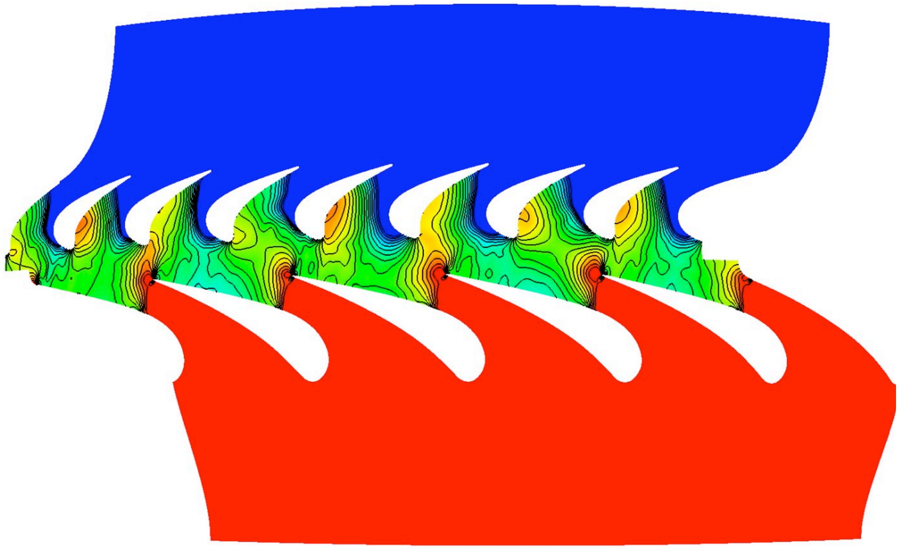
Velocity non-uniformities are the primary tone noise generator for fans but are only one of the mechanisms at work in turbines.

- The vane wakes are highly distorted by the velocity gradients of the rotor
- The potential field of the rotor extends forward to the vane trailing edge

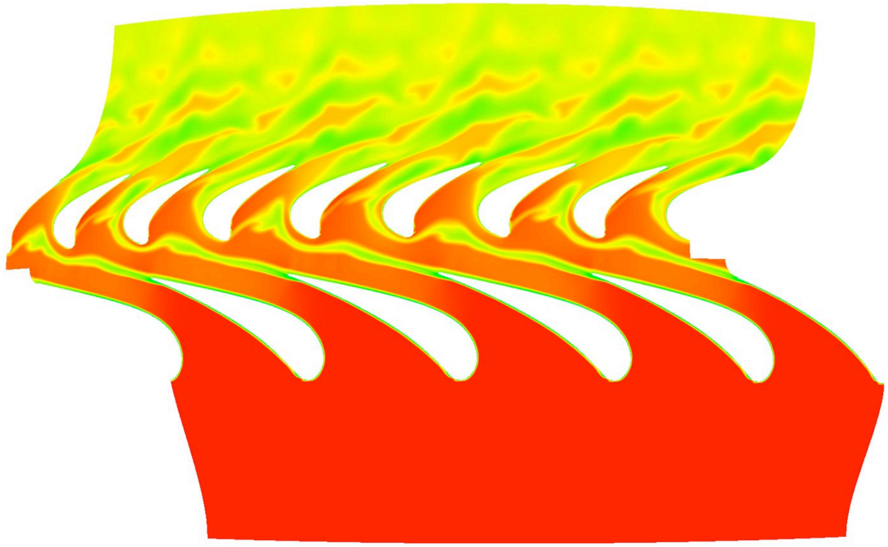


Vorticity magnitude on a 50% span surface.
Vorticity tracks the velocity non-uniformities in the flow.

Noise Generation Mechanisms (2)



Static pressure
(color scale adjusted to highlight blade row interaction)

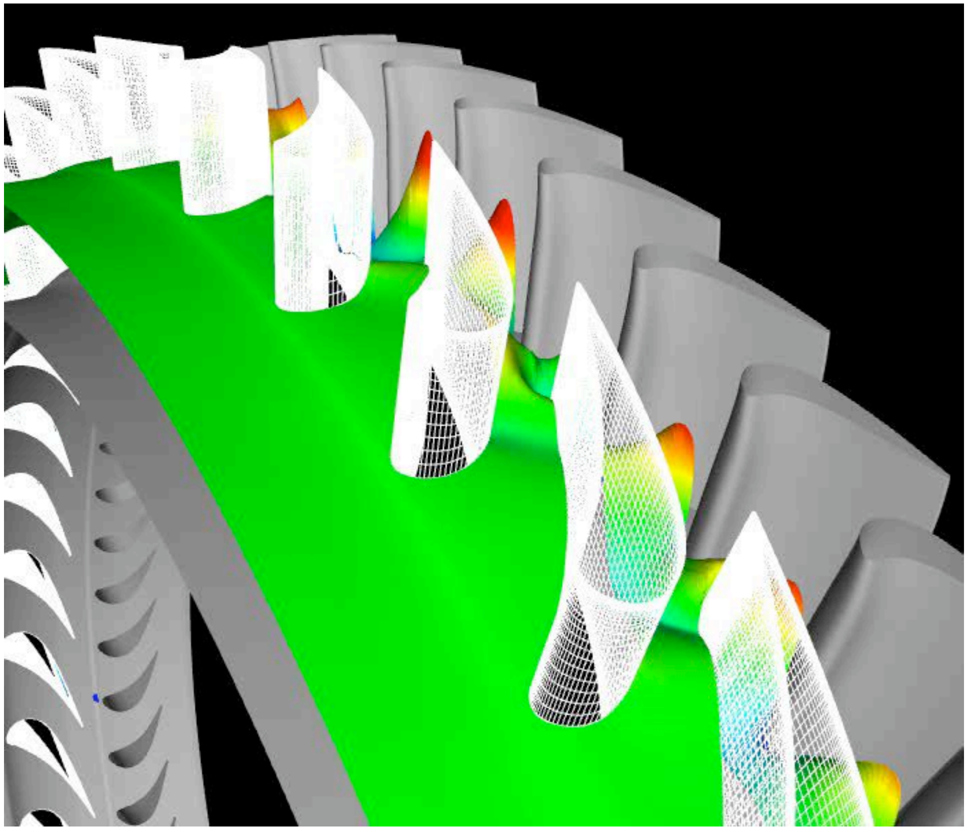


Static temperature

In turbines, tone noise generation mechanisms also include:

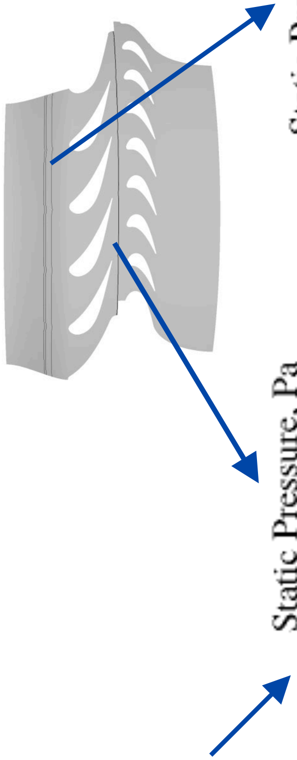
- potential field interactions due to close blade row spacing and large leading edge radii
- entropic interactions due to wake fluid which is hundreds of degrees cooler than the core flow

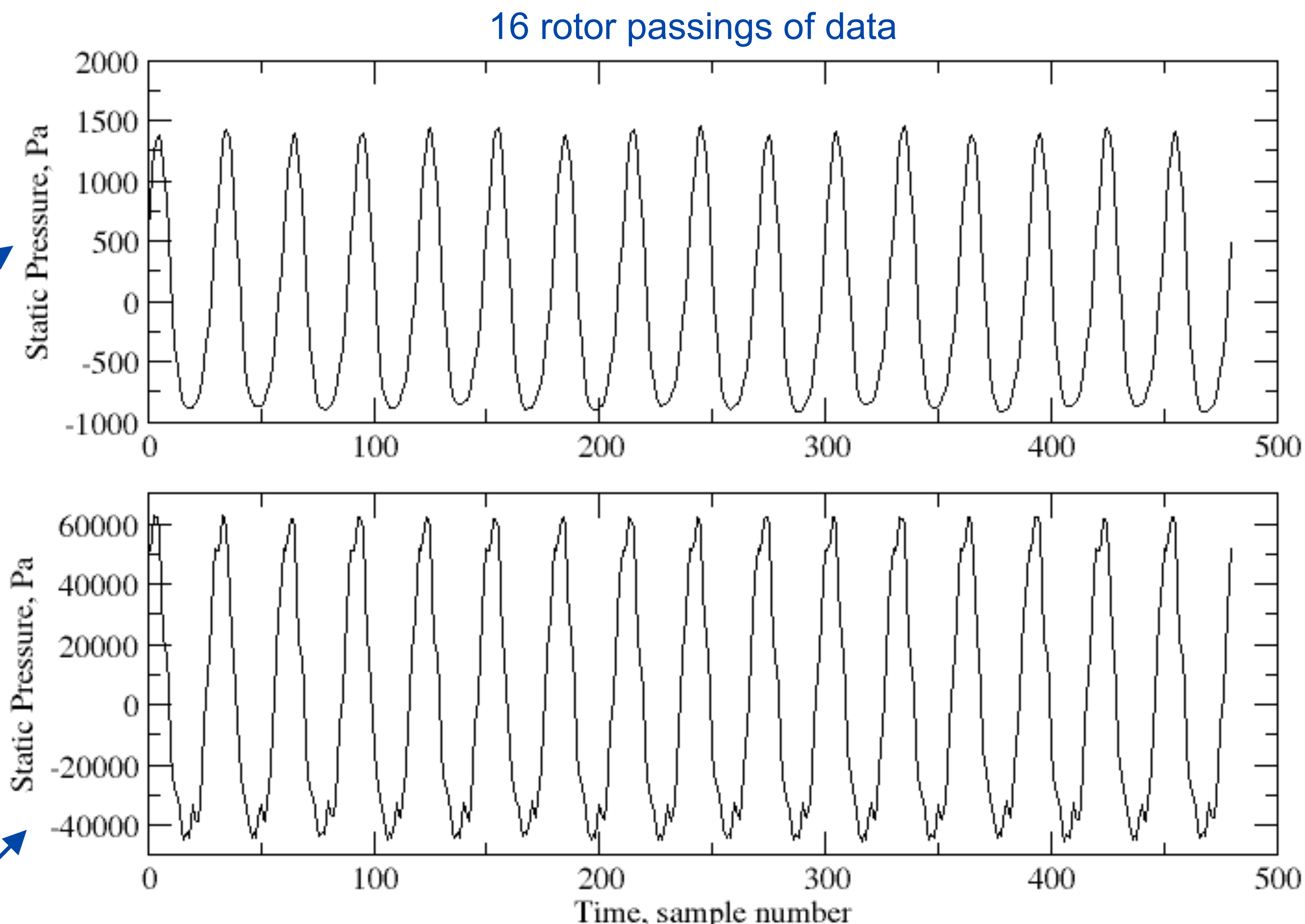
Flow Field Pressure Fluctuations



Animation showing pressure fluctuation propagating forward through vane (coarse mesh solution)

Pressure Time Histories Before and After Vane

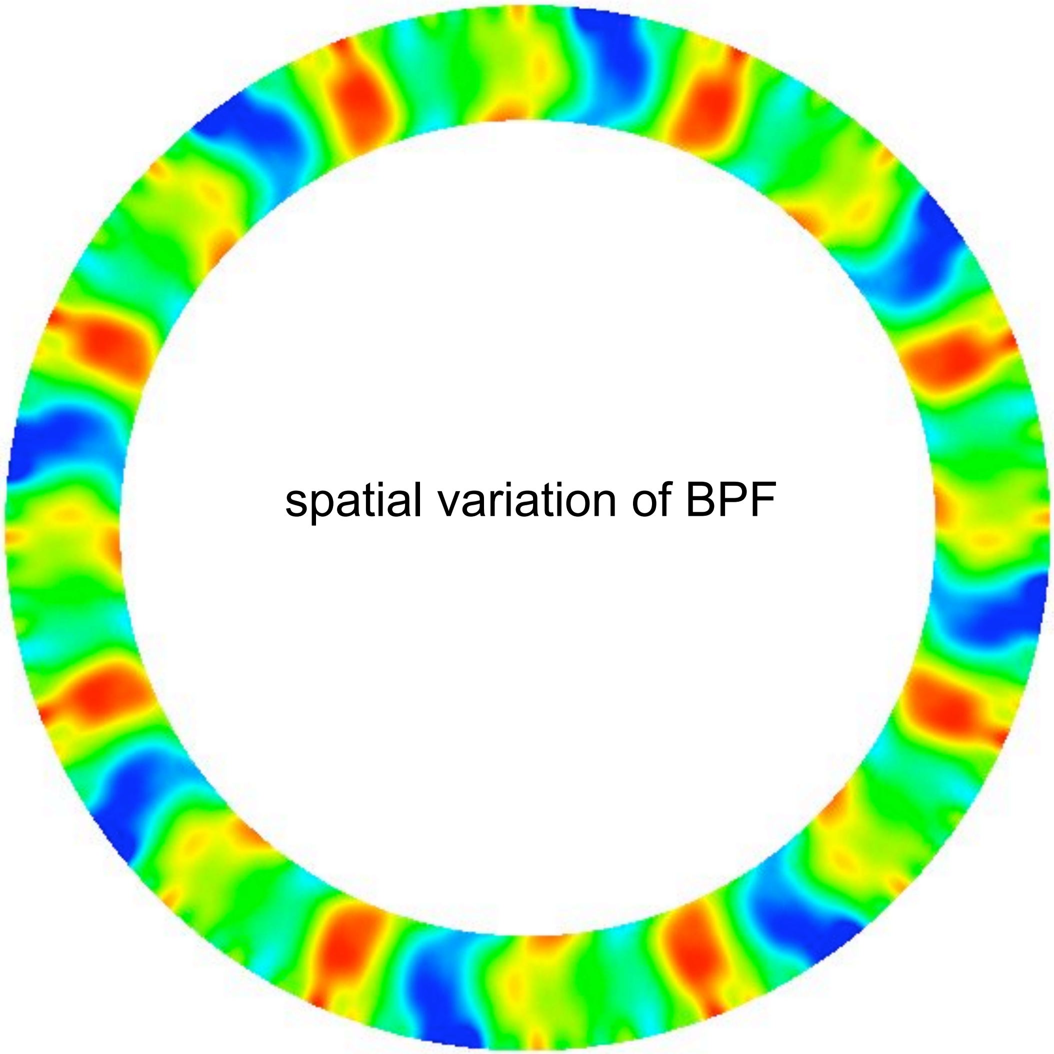




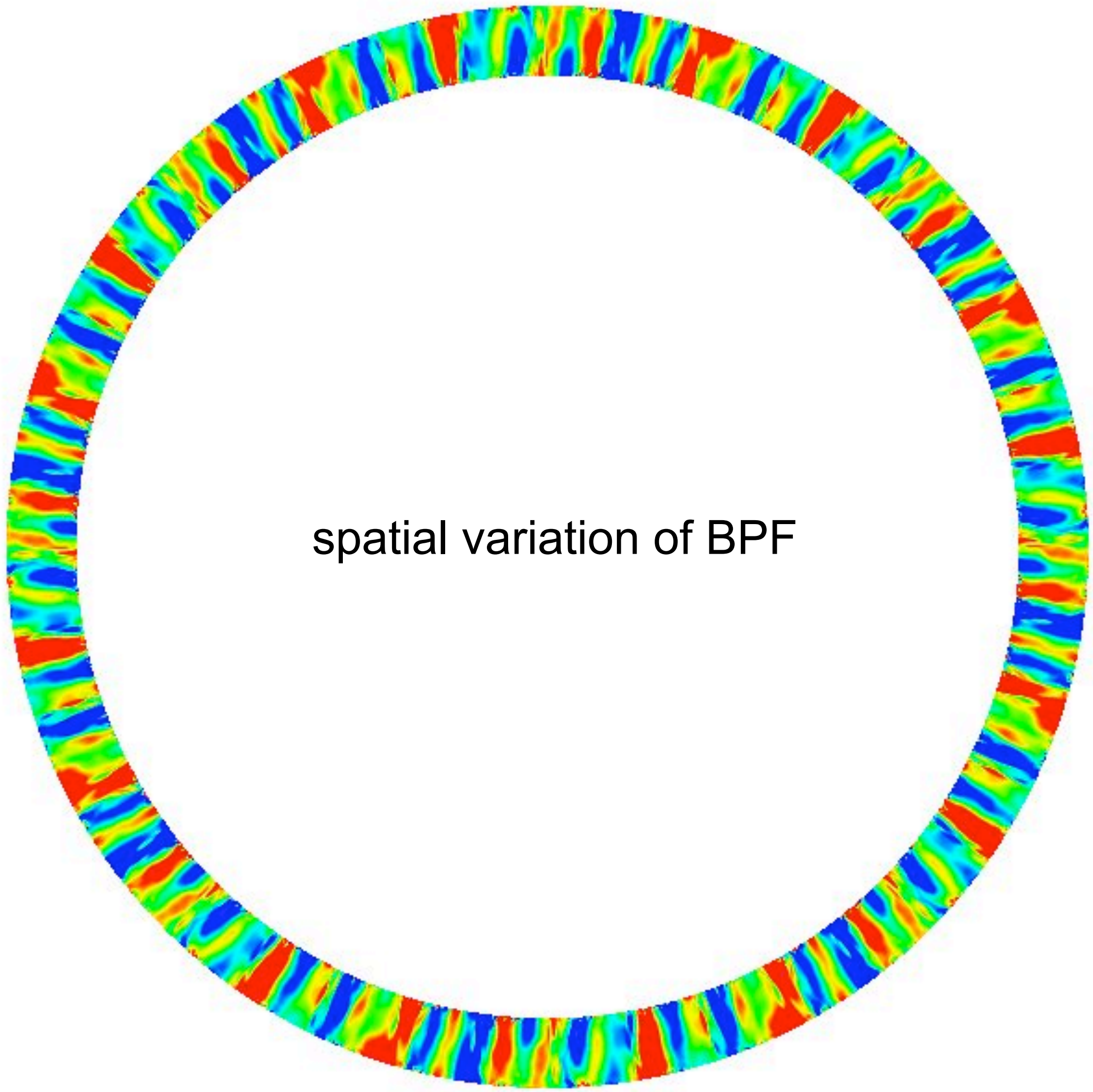
Note the 40x change in scale (>30dB change in level)

Results
Spectral and Modal Analysis

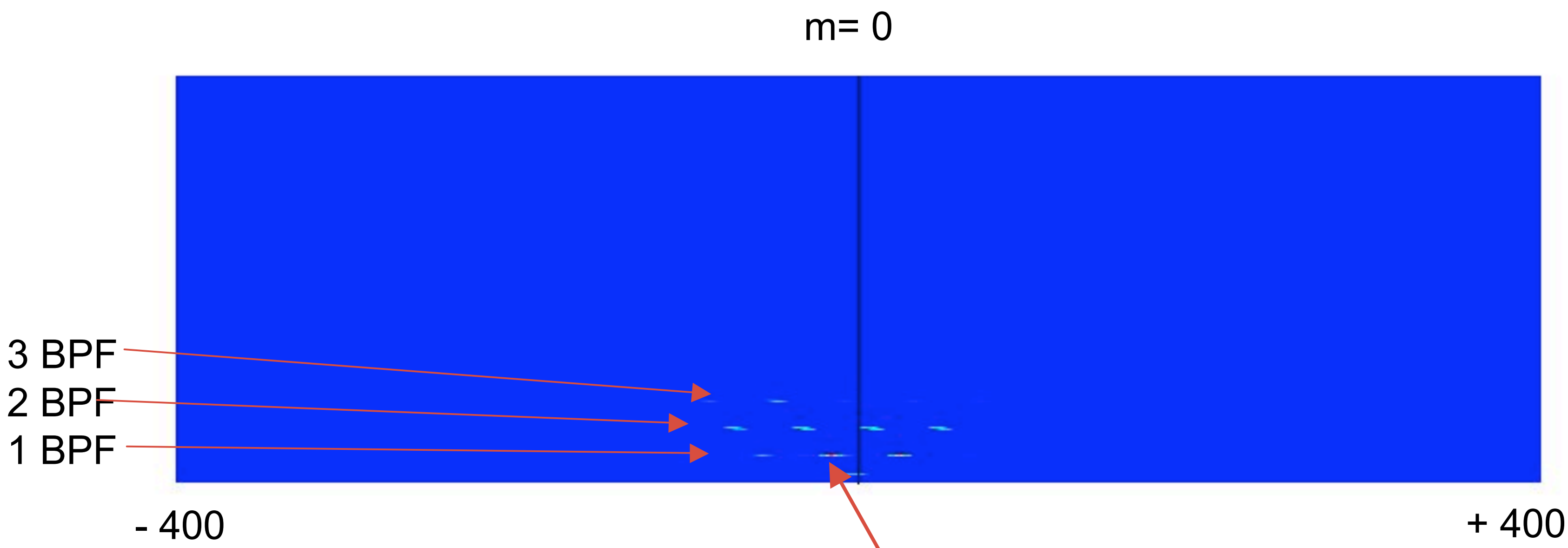
Upstream



Downstream

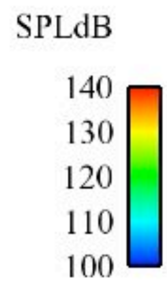


Frequency/Mode Plot Upstream of Vane: 50% Span



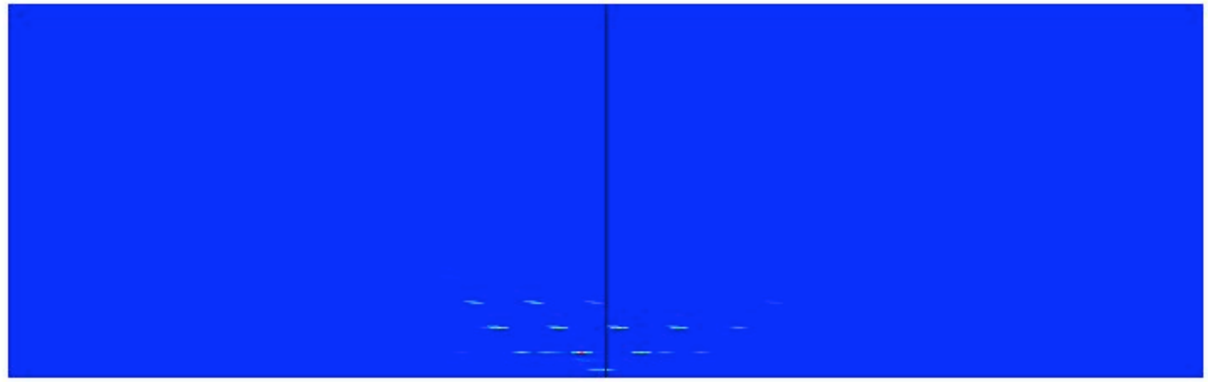
Modes present:
1 BPF: -56 -16 +24
2 BPF: -72 -32 +8 +48
3 BPF: -88 -48

Peak 145.6 dB
at m= -16

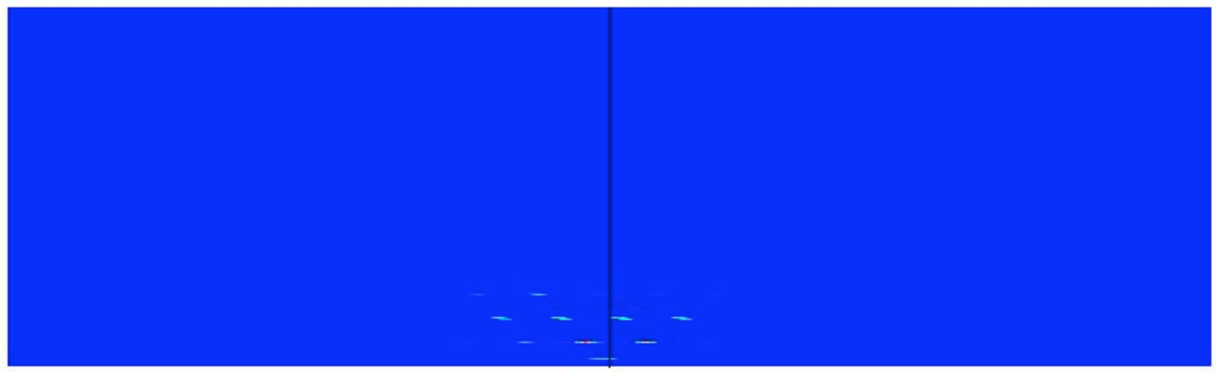


Frequency/Mode Plots Upstream of Vane

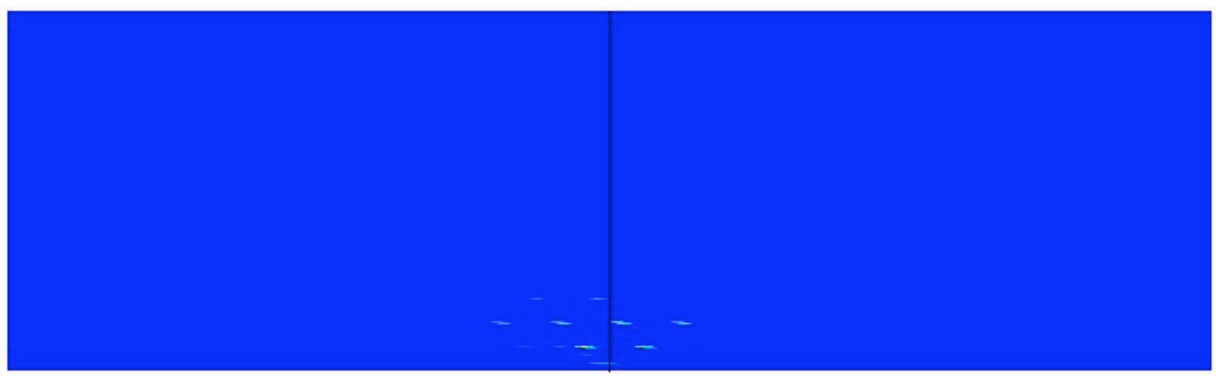
90%
Span



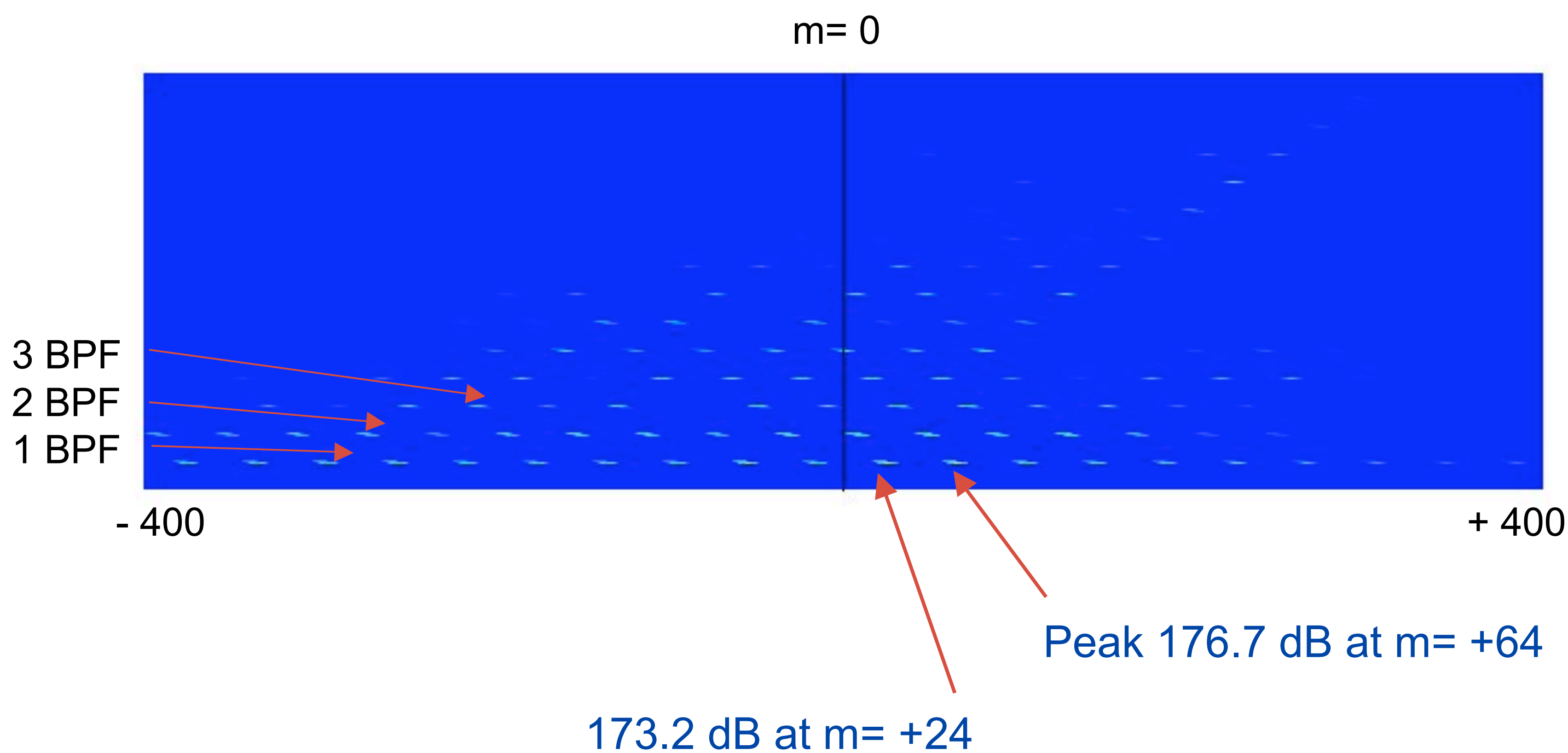
50%
Span

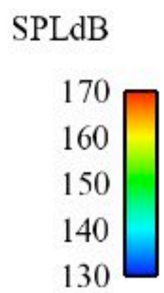


10%
Span



Frequency/Mode Plot Downstream of Vane: 50% Span

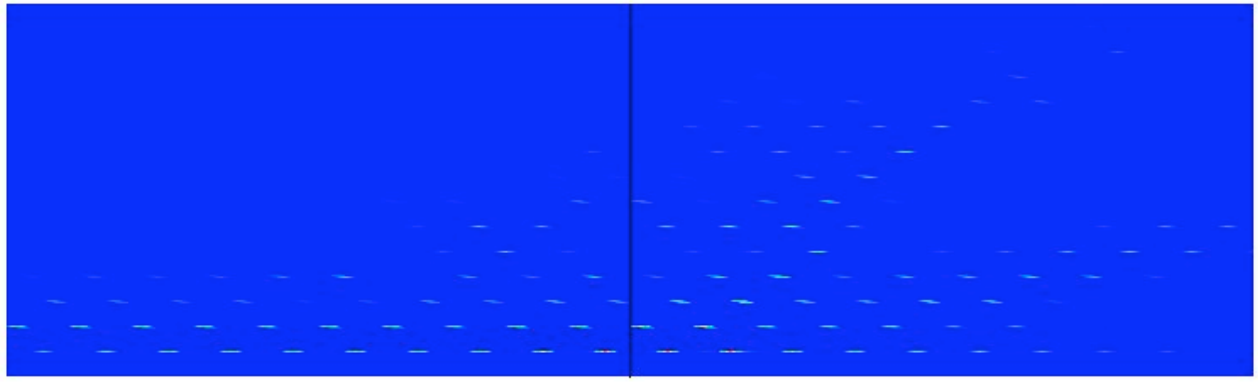




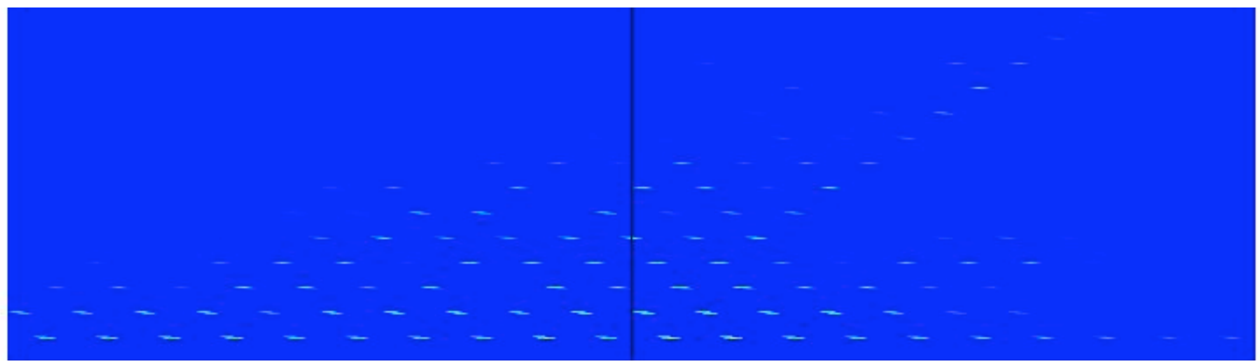
Modes present:
1 BPF: -… -96 -56 -16 +24 +64 +104 …
2 BPF: -… -112 -72 -32 +8 +48 +88 …
3 BPF: -… -48 -8 +32 +72 …

Frequency/Mode Plots Downstream of Vane

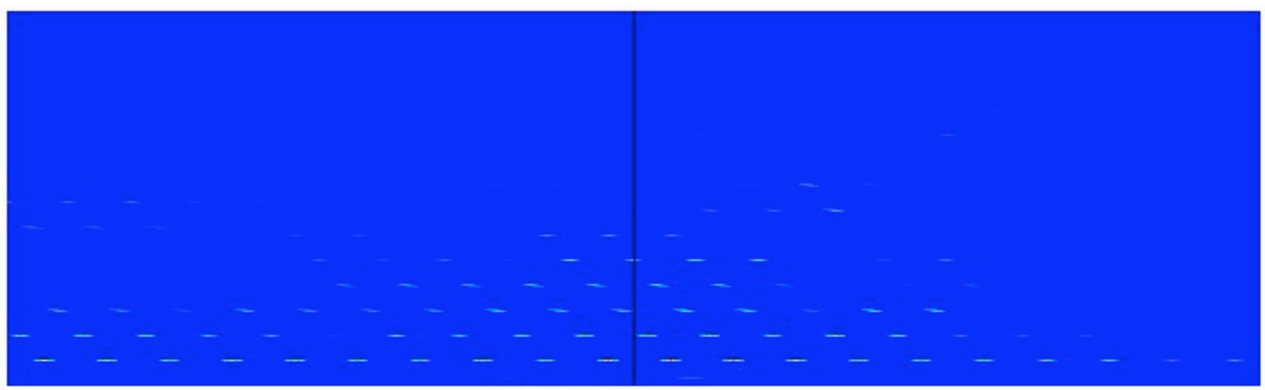
90% Span



50% Span



10% Span



Future Work

Near term work:
- Analysis of pressure wave transmission through the rotor
- Analysis of pressure wave transmission in the multi-stage HPT

Develop:
- Transmission loss estimates
- Transmission loss model

Further simulations:
- Add pattern factor at turbine inlet
- Add combustor unsteadiness at turbine inlet
- Continue simulations through the LPT

Need help with:
- Cooling flow definition (location, flow rate, P,T). Approach now is ad hoc.
- Validation data
- Another turbine geometry with a different aerodynamic design

Summary

Analysis of unsteady pressure data from the TURBO first stage HPT simulation shows reasonable modal content and pressure amplitude.

Analysis will continue with the multi-stage simulation and the development of reduced order generation and transmission loss models based on the simulation results.

Computer time provided by NAS on the Columbia and RTJones supercomputers.