NUMERICAL AEROACOUSTICS INVESTIGATION OF THE EFFECT OF AXIAL GAP LENGTH BETWEEN THE ROTOR AND STATOR OF A TRANSONIC COMPRESSOR STAGE

STUDENT NAME: BORA YAZGAN
STUDENT ID: 503151103

THESIS ADVISOR: PROF. DR. ERKAN AYDER

07.06.2018

CONTENTS

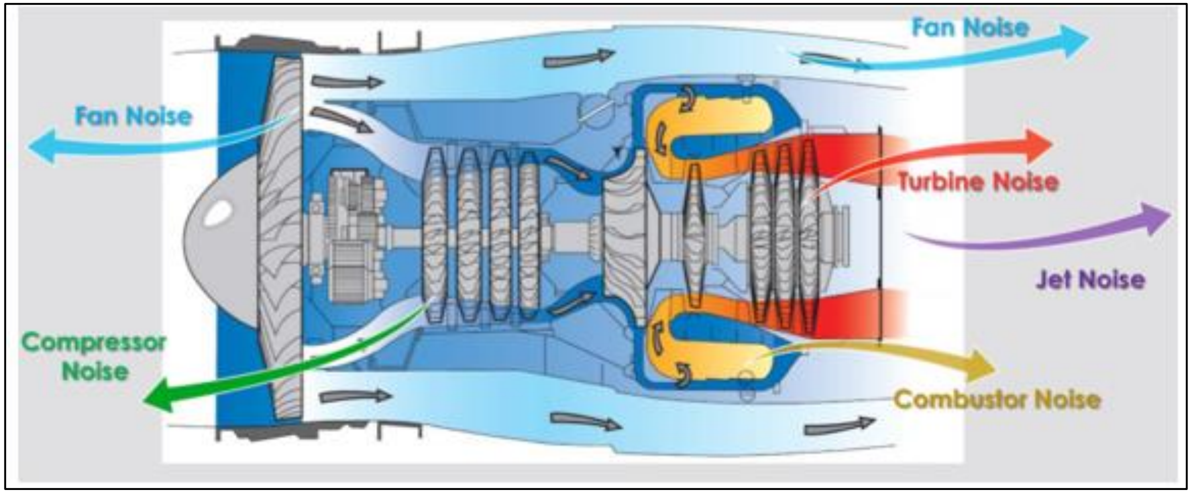
CONTENTS

1. INTRODUCTION

PURPOSE OF THESIS

- **Main objective :** Learning turbomachinery aeroacoustics.

- Turbomachinery noise generation mechanisms.
- Fundamentals of aeroacoustics.
- Noise propagation calculations.
- Utilizing the modern computational methods.
- Developing methodology for turbomachinery aeroacoustics calculations.

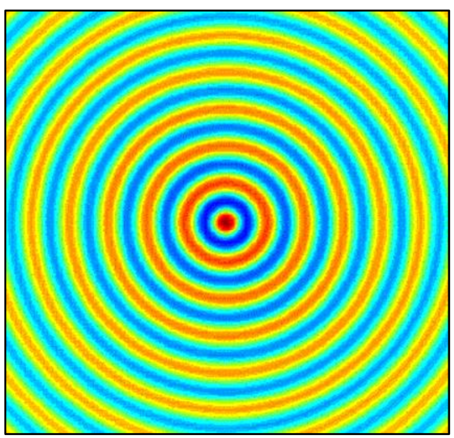


INTRODUCTION

TURBOMACHINERY NOISE SOURCES

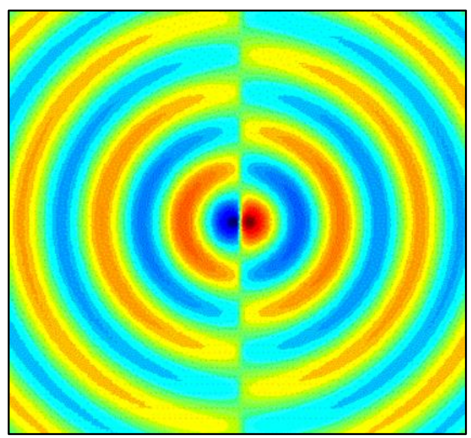
Monopole Noise Sources

- Radiates equally in all directions.
- Blade thickness noise.
- Periodic replacement of the blade and surrounding fluid volume.



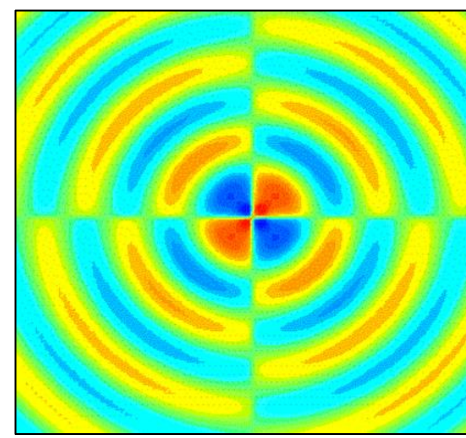
Dipole Noise Sources

- Two contrary monopoles with same strength.
- Fluctuation aerodynamic forces on solid surfaces.
- Tonal noise at blade passing frequency, flow separation etc.



Quadrupole Noise Sources

- Two dipole sources.
- Turbulent structures and shear flow.
- Vortex shedding from trailing edge.



TURBOMACHINERY NOISE TYPES

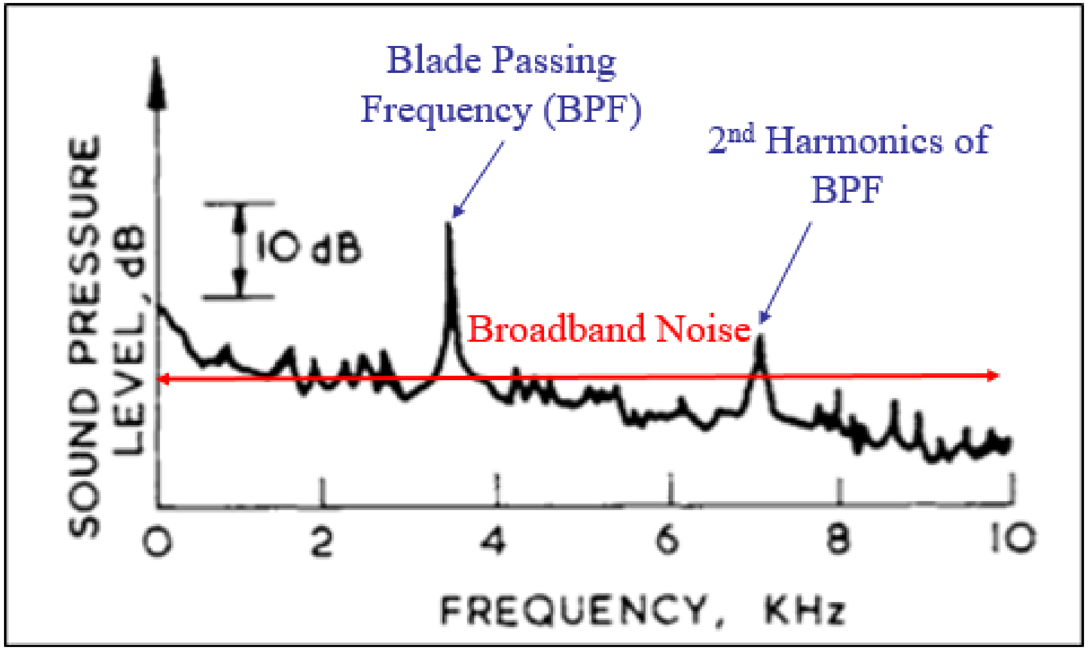
Turbomachinery Noise Types

Tonal (Discrete) Noise

- Only at certain frequencies
- Blade passing frequency, shaft rotating frequency etc.

Broadband Noise

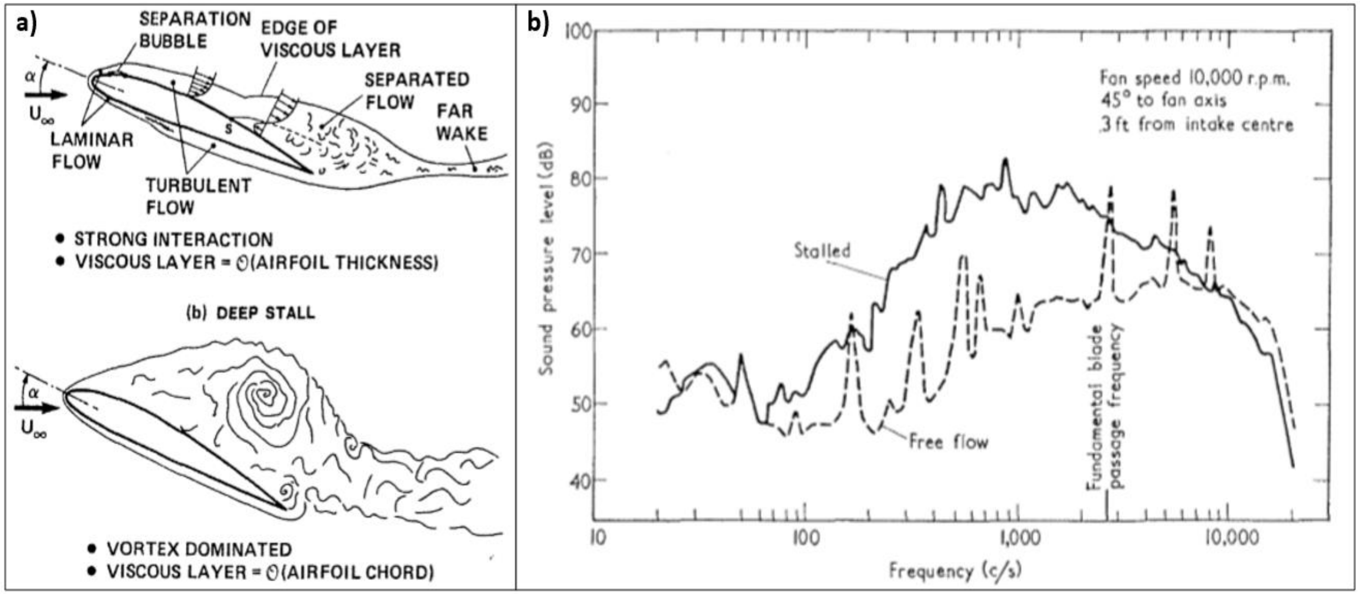
- Over a wide range of frequency.
- Range of turbulent eddy frequencies.



TURBOMACHINERY BROADBAND NOISE GENERATION MECHANISMS

- **Generated by random disturbances and characterized by continuous noise spectrum.**

- Turbulent boundary layer.
- Incident turbulence.
- Vortex shedding.
- Flow separation.
- Tip vortex.
- Quadrupole.

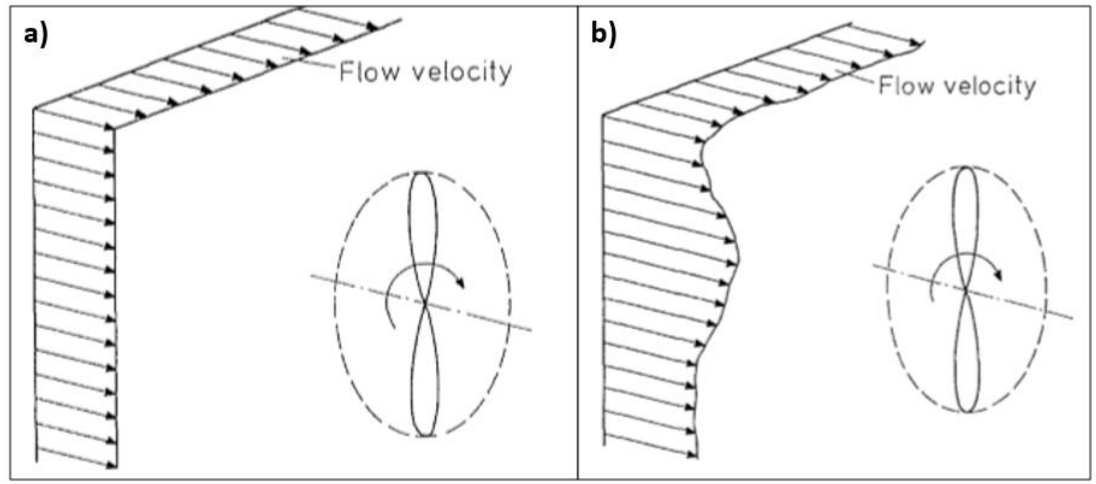


Flow Separation Noise

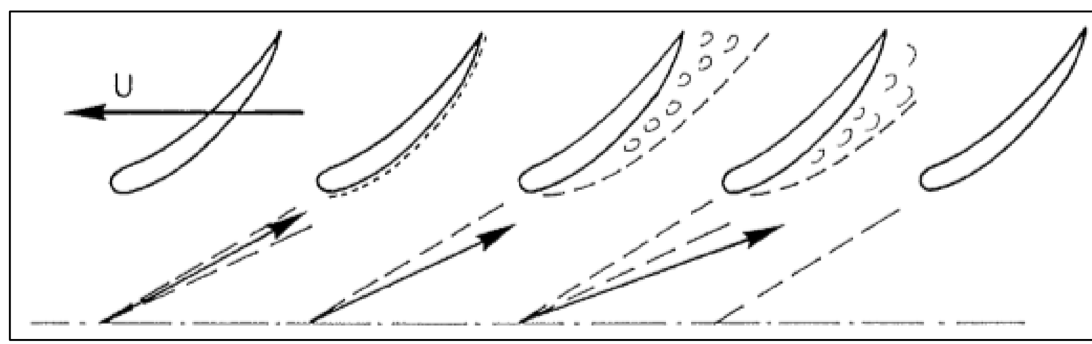
INTRODUCTION

TURBOMACHINERY TONAL NOISE GENERATION MECHANISMS

- **Radiated at discrete frequencies.**
  - Uniform & steady blade loading.
  - Non-uniform & steady blade loading.
  - Rotor-stator interactions.
  - Rotating stall.
  - Buzz-saw.



Uniform & Non-uniform flow

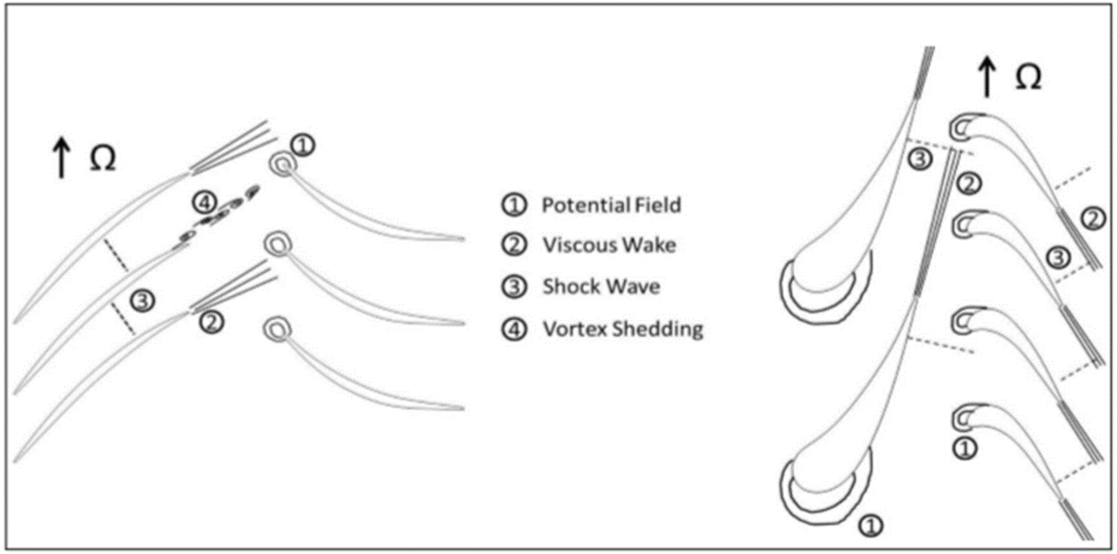


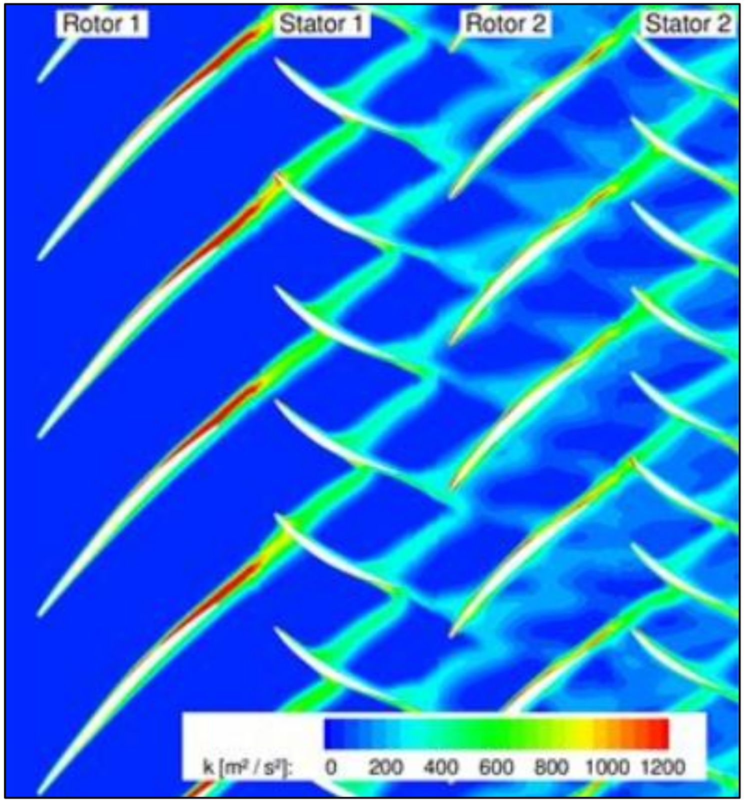
Rotating Stall

ROTOR-STATOR INTERACTION NOISE

- Multistage turbomachinary applications.
- Interaction between rotating blades (rotor) and stationary vanes (stator).
- Interaction mechanisms :

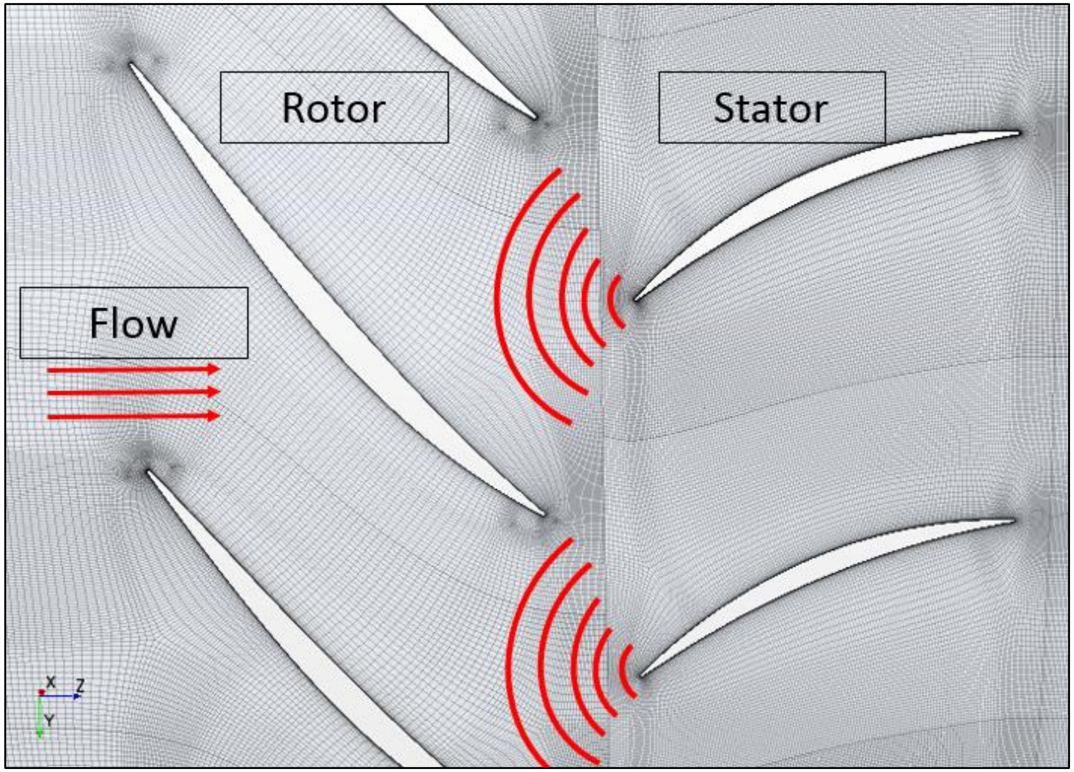
Potential Field	Viscous Wake
Shock Wave	Vortex Shedding





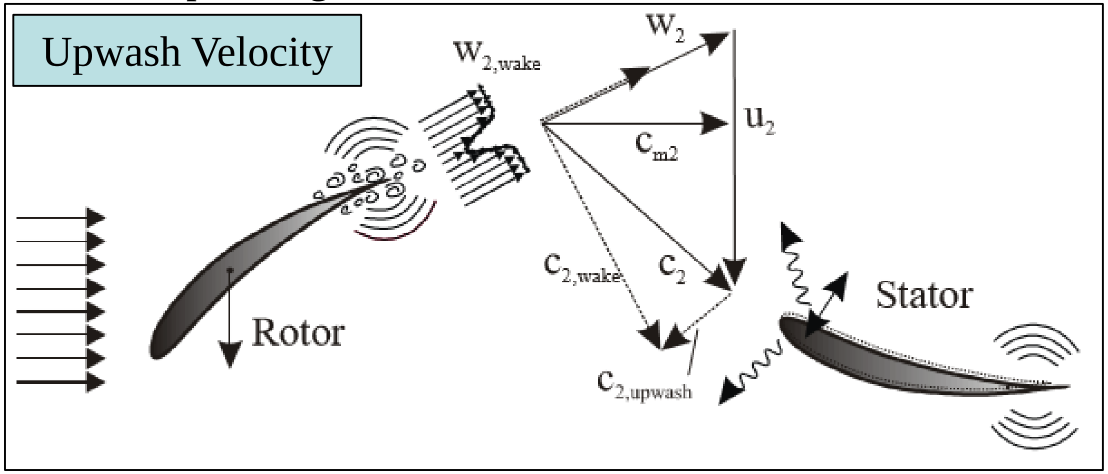
POTENTIAL FIELD

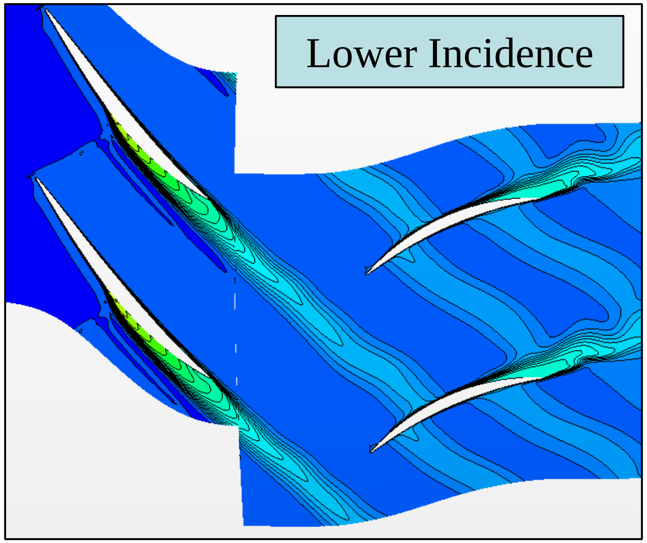
- Adjacent blade rows.
- Presence of stator in the downstream of the rotor.
- Fluctuating static pressure field.
- Highly transient.
- Axial spacing.
- Sensed on rotor blade.
- Second major tonal noise source.

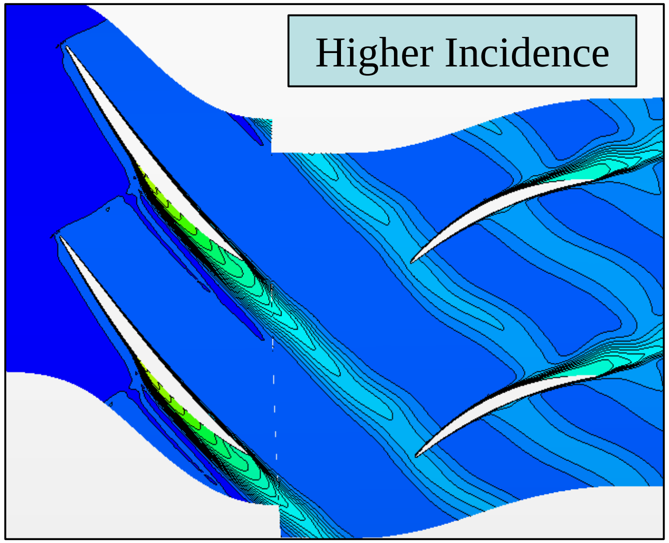


VORTICAL EFFECTS

- Composed of ; Vortex shedding, viscous wake, tip leakage, horseshoe vortices.
- Axial velocity deficit.
- Increase in tangential velocity.
- Higher incidence angle.
- Pressure fluctuation at BPF.
- Major tonal noise source.
- Upwash velocity.



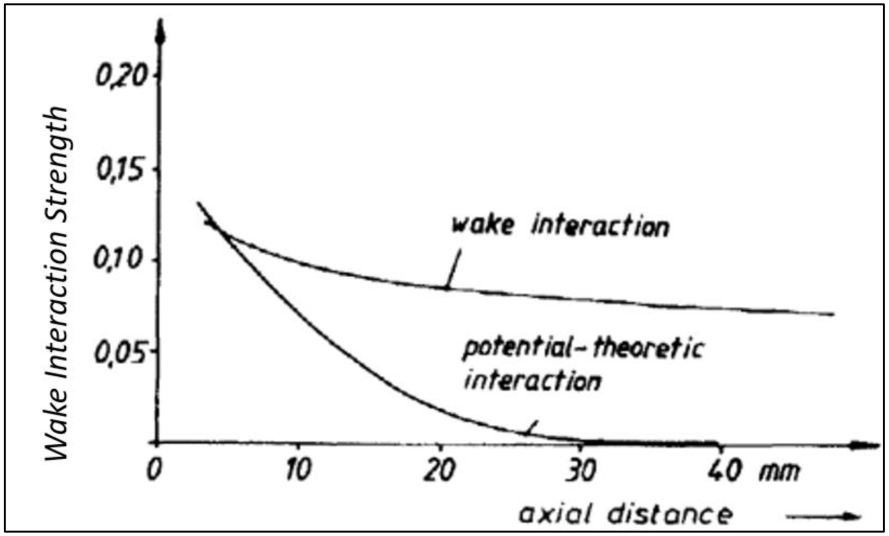


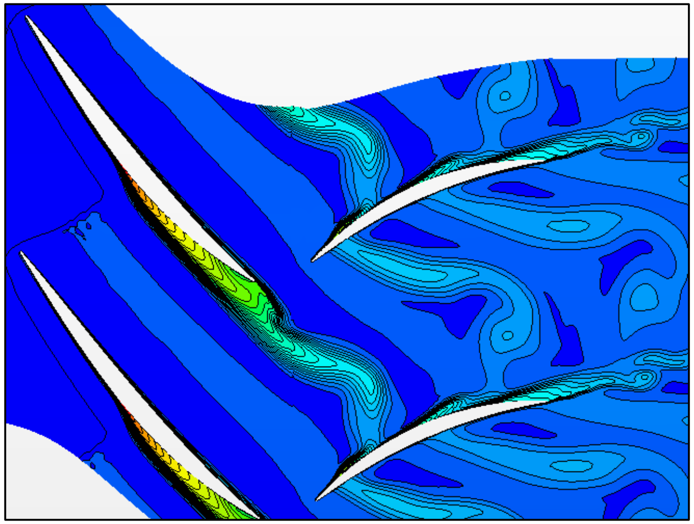


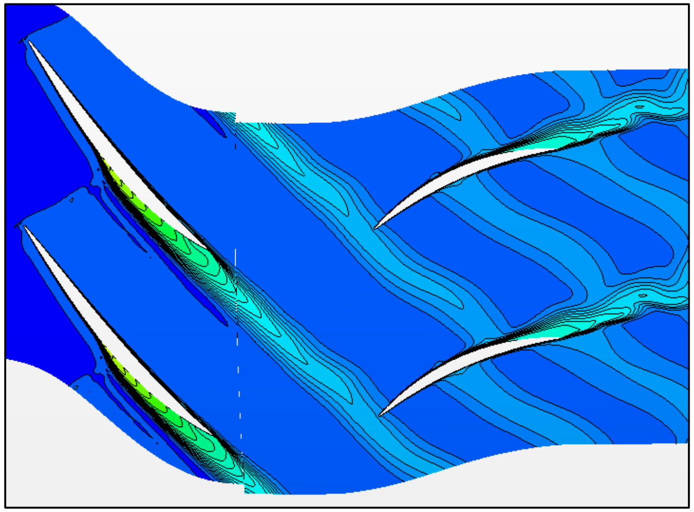
2. ROTOR-STATOR INTERACTION NOISE REDUCTION METHODS

INCREASING ROTOR-STATOR AXIAL GAP

- Effect of potential field decreases strongly.
- Wake effect does not decay rapidly as potential field.
- Tonal noise reduction between 2-6 dB.
- Decrease in aerodynamic efficiency.
- Most effective way for reduction.

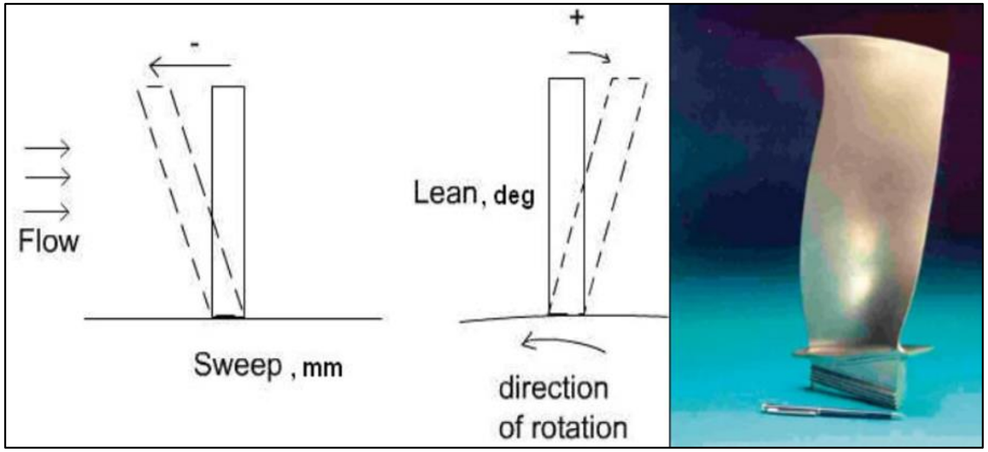




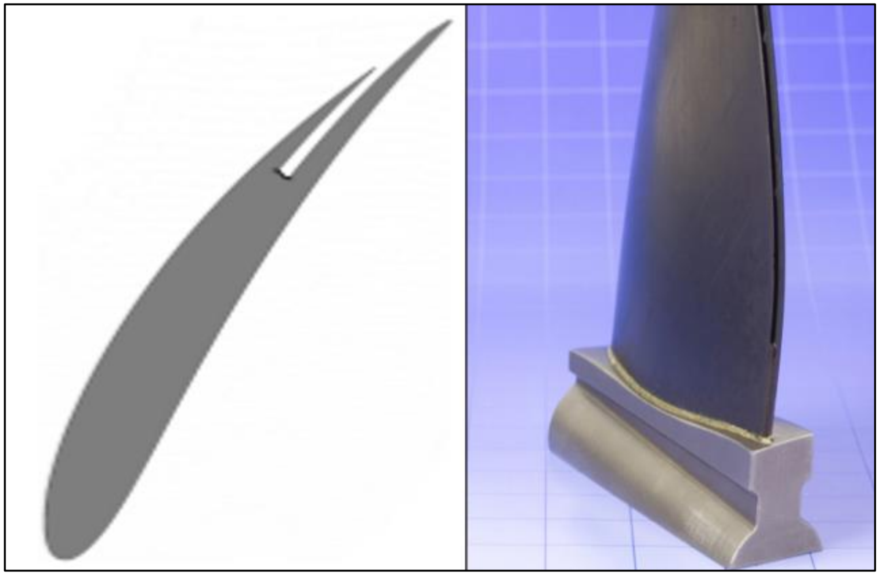


OTHER METHODS

- **Leaned & swept stator and rotor blades**
  - Sweep in axial, lean in azimuthal direction.
  - Cancellation of pressure fluctuations.
  - Reduction between 1.5-3.5 dB.

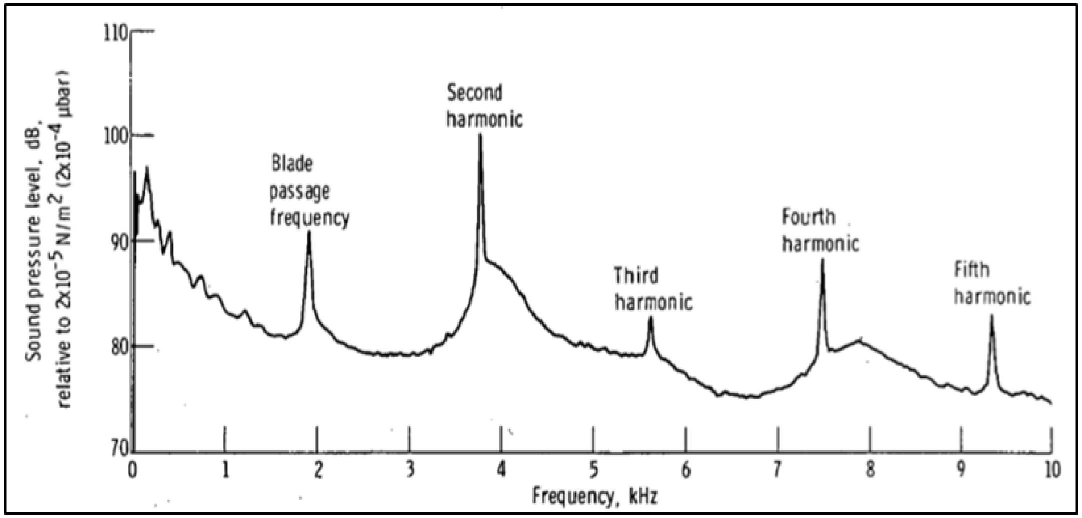


- **Wake-filling method**
  - Fluid is sprayed from rotor trailing edge.
  - Energize the momentum deficit in the wake.
  - Reduce the upwash velocity.
  - Effective for first tones.

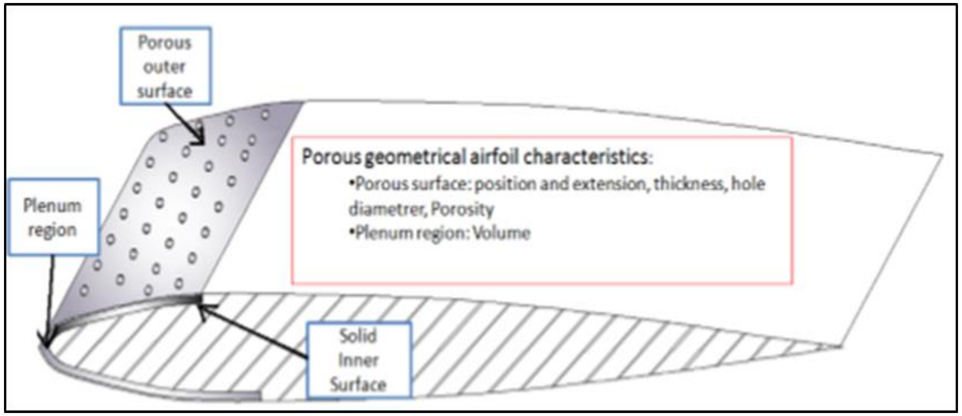


OTHER METHODS

- **Number of rotor and stator**
  - ➢ Appropriate blade / vane number ratio.
  - ➢ Cut-off for first tone.
  - ➢ Degradation of first tone radiation.



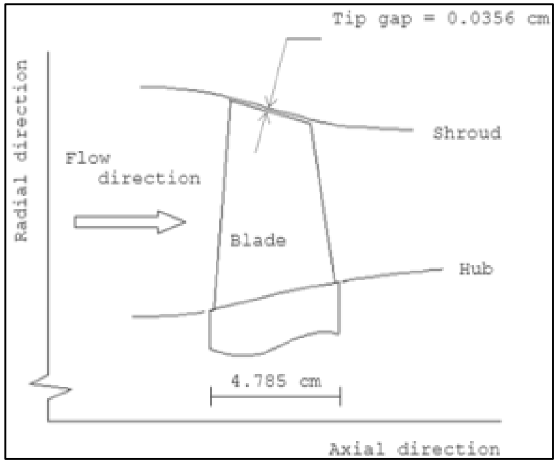
- **Porous skin on stator surface**
  - ➢ Porous skin coating on stator surface.
  - ➢ Smoother pressure distribution.
  - ➢ Unsteady pressure is attenuated.
  - ➢ Reduction up to 1-2 dB.
  - ➢ May reduce the lift force.

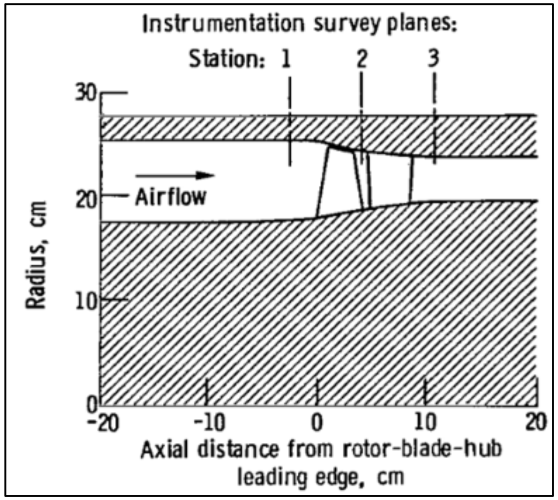


3. STEADY STATE CFD ANALYSES OF NASA ROTOR 37 & STAGE 37

NASA ROTOR 37 & STAGE 37 DESIGN

- Transonic compressor stage test case of NASA Lewis Research Center.



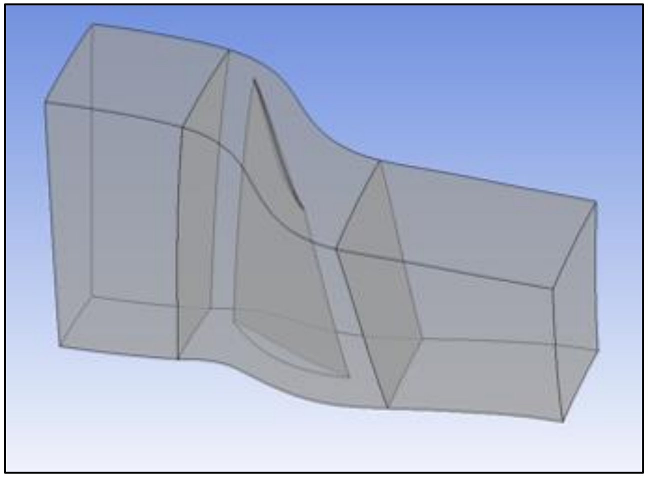


Rotor 37 Design Specifications	
Number of Blades	36
Leading Edge Tip Diameter	0.5074 m
Leading Edge Hub Diameter	0.3576 m
Rotational Speed (corrected)	17188.7 rpm
Tip Solidity	1.288
Tip Clearance	0.356 mm
Tip Speed	454.14 m/s
Total Pressure Ratio	2.106
Mass Flow Rate (corrected)	20.19 kg/s
Blading	Multiple Circular Arcs

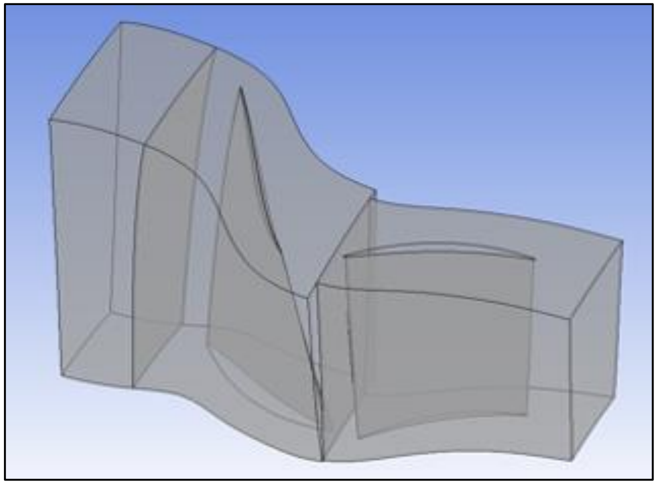
Stator 37 Design Specifications	
Number of Blades	46
Leading Edge Tip Diameter	0.4848 m
Leading Edge Hub Diameter	0.3752 m
Tip Solidity	1.3
Tip Aspect Ratio	1.26
Blading	Multiple Circular Arcs

CFD MODEL OF ROTOR 37 & STAGE 37

- CFD model constructed in ANSYS environment.
- Meshing in Turbo-Grid.
- Solving in CFX.
- Mesh dependency and turbulence model study performed.
- CFD model validated comparing the experiment.



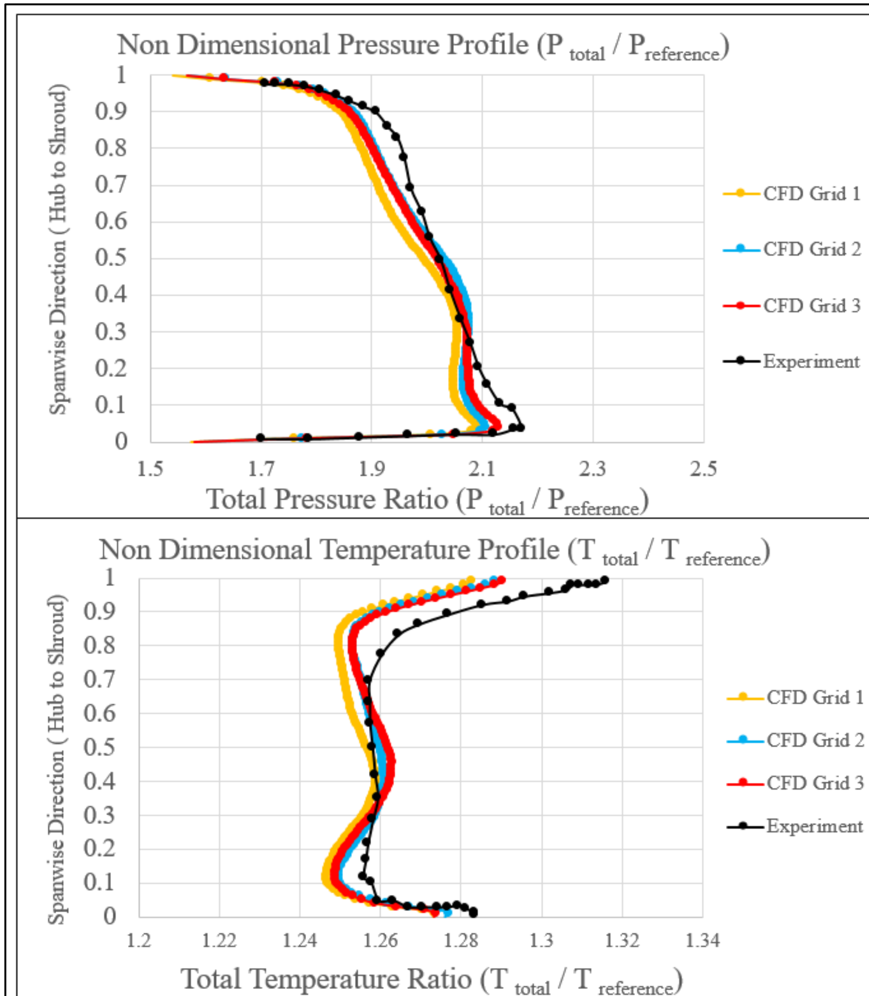
Rotor 37 Flow Domain



Stage 37 Flow Domain

MESH DEPENDENCY STUDY

- Grid structures for mesh dependency study of Rotor 37 model.
  - Grid 1 = 450,000 elements
  - Grid 2 = 750,000 elements
  - Grid 3 = 1,100,000 elements



- Boundary conditions ;
  - Inlet Absolute Total Pressure = 101325 Pa
  - Inlet Total Temperature = 288.15 K
  - Outlet Mass Flow Rate = 20.51 kg/s
  - Rotational Speed = 17188 rpm

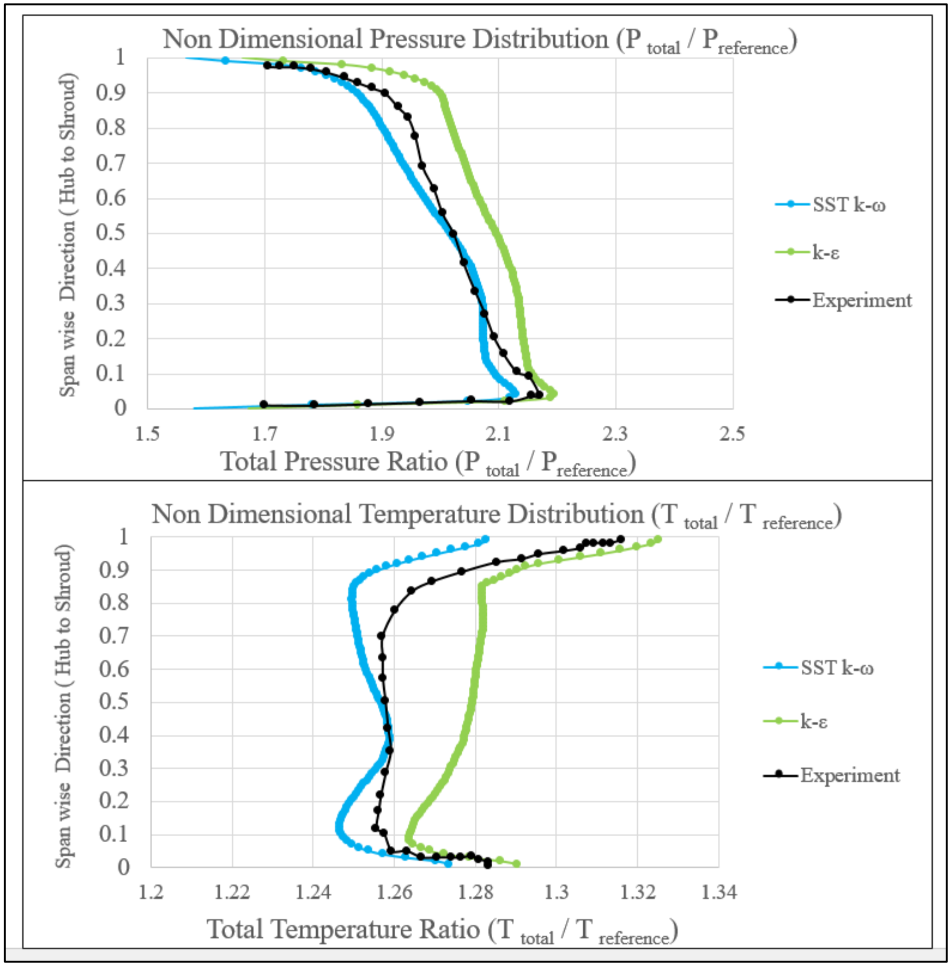
Grid 2 selected for validation analyses.

1,400,000 element used for Stage 37 simulations.

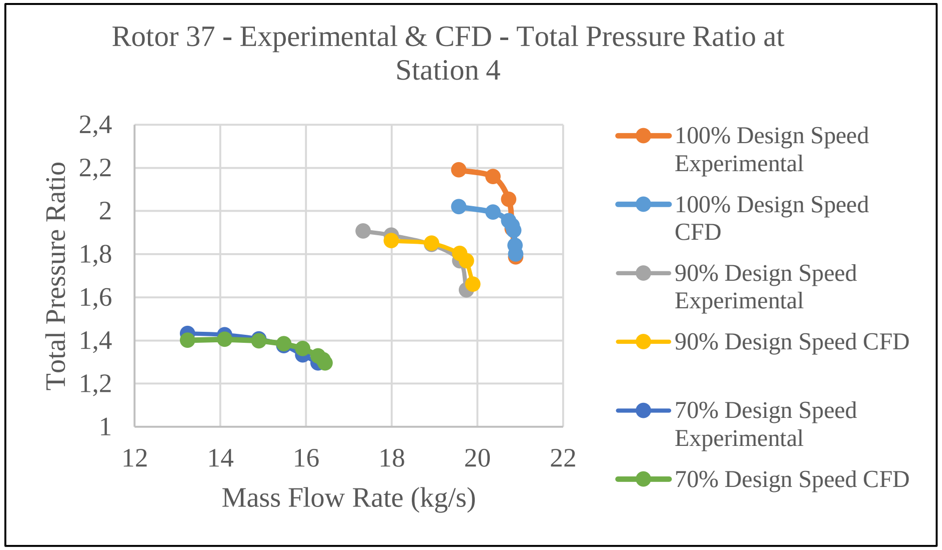
TURBULENCE MODEL STUDY

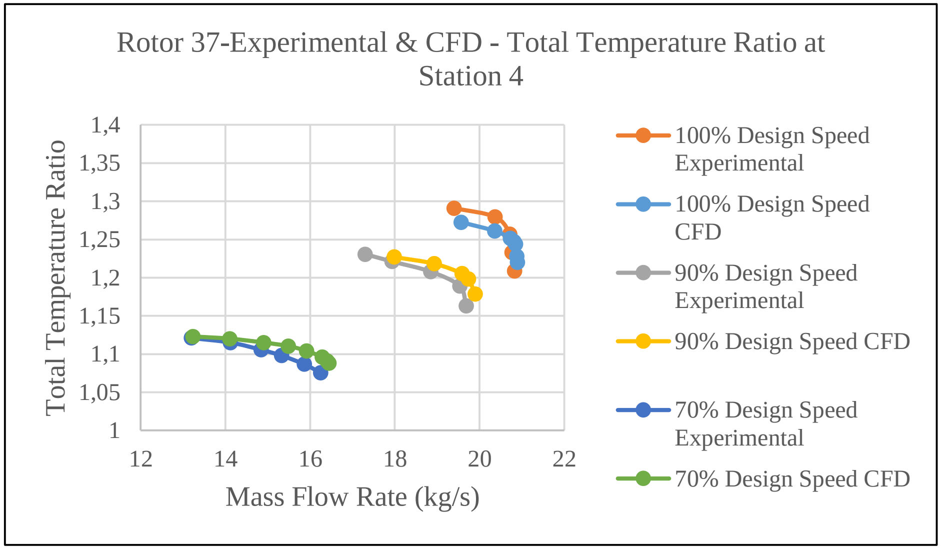
- Turbulence models for turbulence study of Rotor 37 model.
  - K-ε
  - SST K-ω
- Boundary conditions ;
  - Inlet Absolute Total Pressure = 101325 Pa
  - Inlet Total Temperature = 288.15 K
  - Outlet Mass Flow Rate = 20.51 kg/s
  - Rotational Speed = 17188 rpm
- Grid 2 mesh structure.

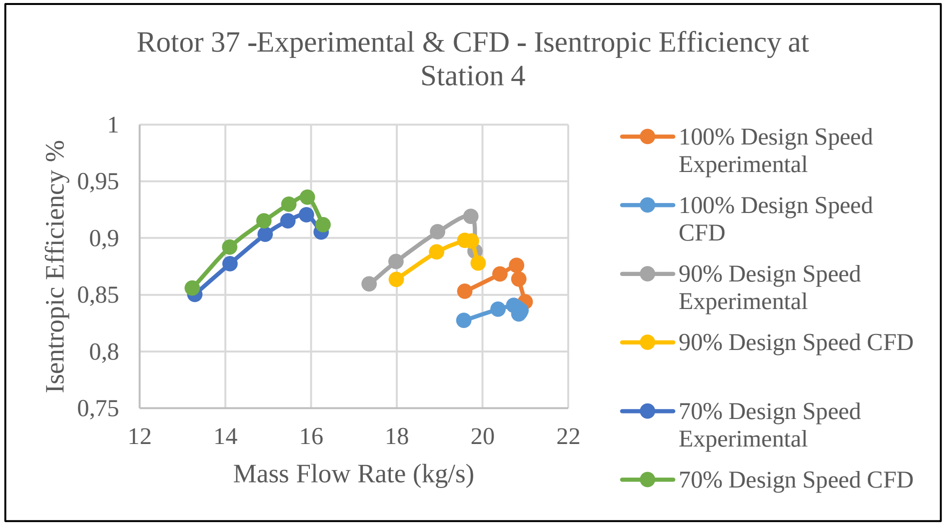
SST K-ω selected for validation analyses.



ROTOR 37 CFD MODEL VALIDATION STUDY

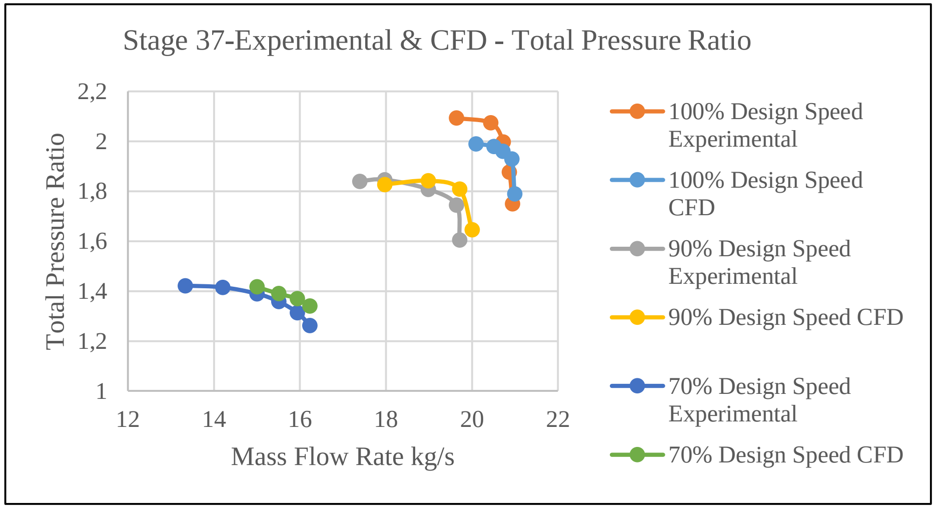


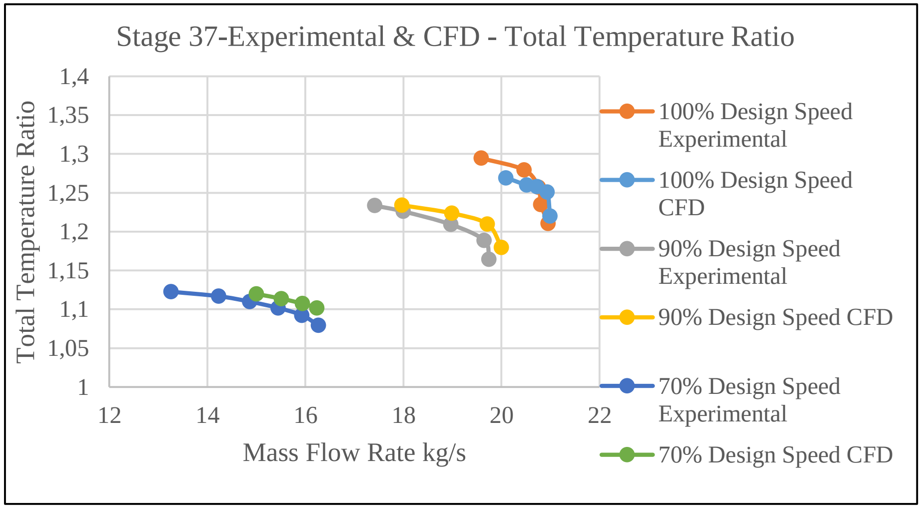


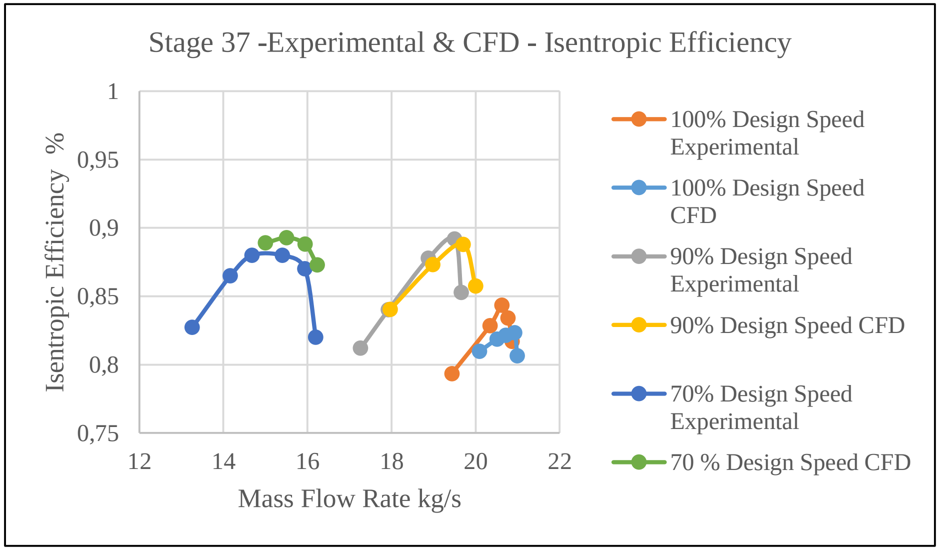


STEADY STATE CFD ANALYSES OF NASA ROTOR 37 & STAGE 37

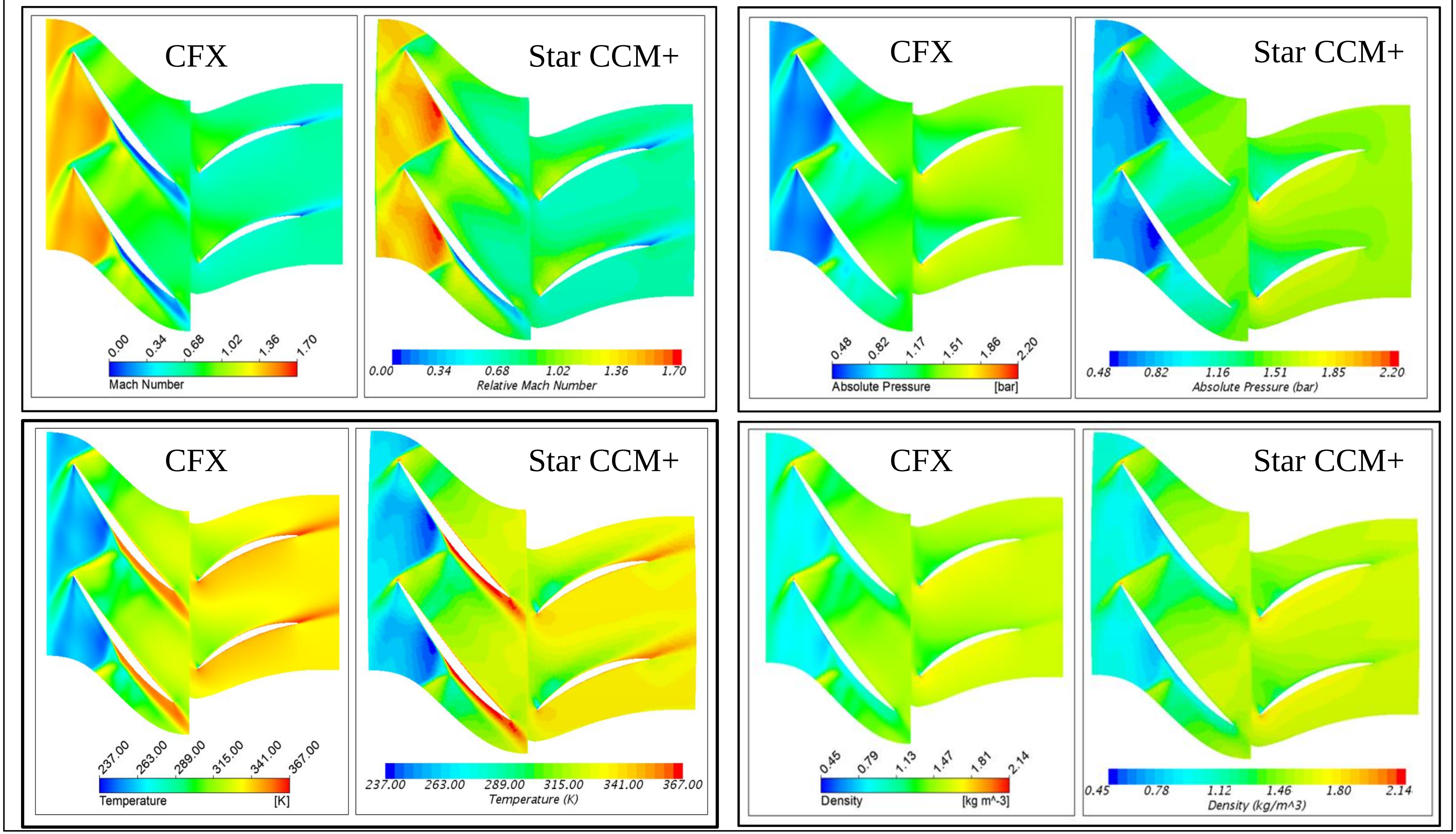
STAGE 37 CFD MODEL VALIDATION STUDY







STAGE 37 CFD SIMULATION CFX & STAR CCM+ COMPARISON



4.AEROACOUSTICS

KEY FEATURES OF AEROACOUSTICS

- Aeroacoustics is the study of noise source generation and sound propagation due to unsteady fluid motion.
- Magnitude of acoustic waves is very small compared to aerodynamic pressure.
- Frequency range is quite large : 20 Hz – 20 kHz

Example Scenerio 1

Turbulent Flow Field

Mach Number = 0.3

Sound = 60 dB

U_{mean} = 100 m/s

$P_{atmosphere}$ = 101325 Pa

Pressure Fluctuation

p' = 0.02 Pa

Velocity Fluctuation

u' = $5\text{x}10^{-5}$ Pa

$p'/P_{atmosphere} = 2\text{x}10^{-7}$

$u'/U_{mean} = 5\text{x}10^{-7}$

Example Scenerio 2

U_{mean} = 102.2693842736423 m/s

- First two digit (100) by mean convective flow.
- Next five digits (2.2693) by turbulence
- The remaining digits (0.0000842736423) by sound

COMPUTATIONAL AEROACOUSTICS

Computational Aeroacoustics

Direct Noise Calculation

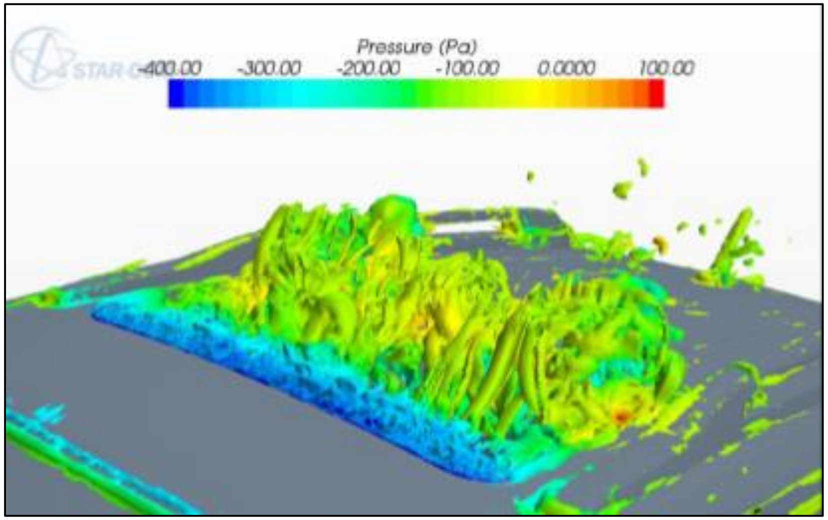
- Simulates all flow and acoustics within one single simulation

Hybrid Methods

- Divide the simulation into several steps
- CFD is carried out to capture sound sources
- Additional simulation steps propagates the sources to an observer location

DIRECT NOISE CALCULATIONS

- All aeroacoustics aspects are considered within single simulation.
- Solve both noise sources and sound propagation
- Unsteady, compressible CFD.
- LES & DES based turbulence models.
- URANS only for tonal noise.
- Recording time-varying pressure at probes.



BENEFITS

- Few modeling assumptions
- Less work to set up

CHALLANGES

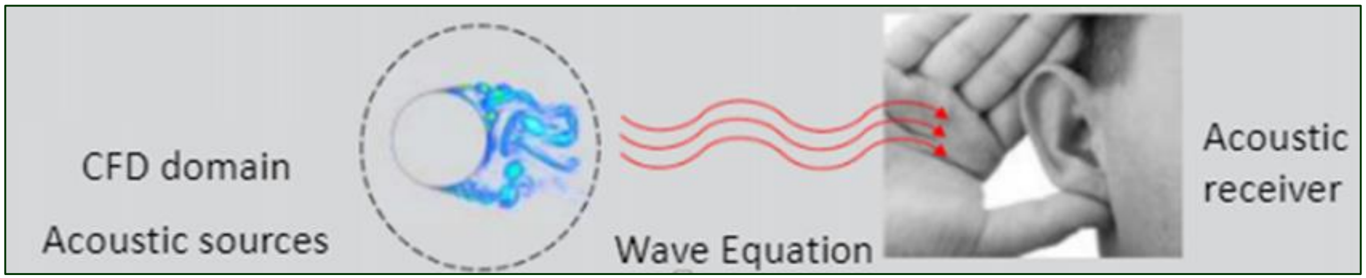
- High requirements on numerical accuracy
- Non-reflecting boundary treatments
- Long computational time
- Large mesh size

HYBRID METHODS

- Based on two steps :

1. Simulate transient flow field using CFD (DNS, LES, DES, URANS) to obtain noise sources.

2. Propagate the acoustic waves from noise to the receiver by using an acoustic solver.



- Acoustic analogy methods are used as acoustic solver :

Lighthill's Analogy
- Primitive analogy
- Only quadrupole noise

Curle's Analogy
- Extension of Lighthill
- Effect of stationary solid bodies
- Dipole and quadrupole noise

Ffowcs-Williams Hawkings Analogy (FWH)
- Most advanced
- Motion of solid bodies
- Monopole, dipole and quadrupole noise

AEROACOUSTICS SIMULATION PLAN

Aeroacoustics Calculation

Near-Field Acoustics

- Direct noise calculation
- URANS simulation
- Resolving sources and acoustic waves
- Only tonal noise

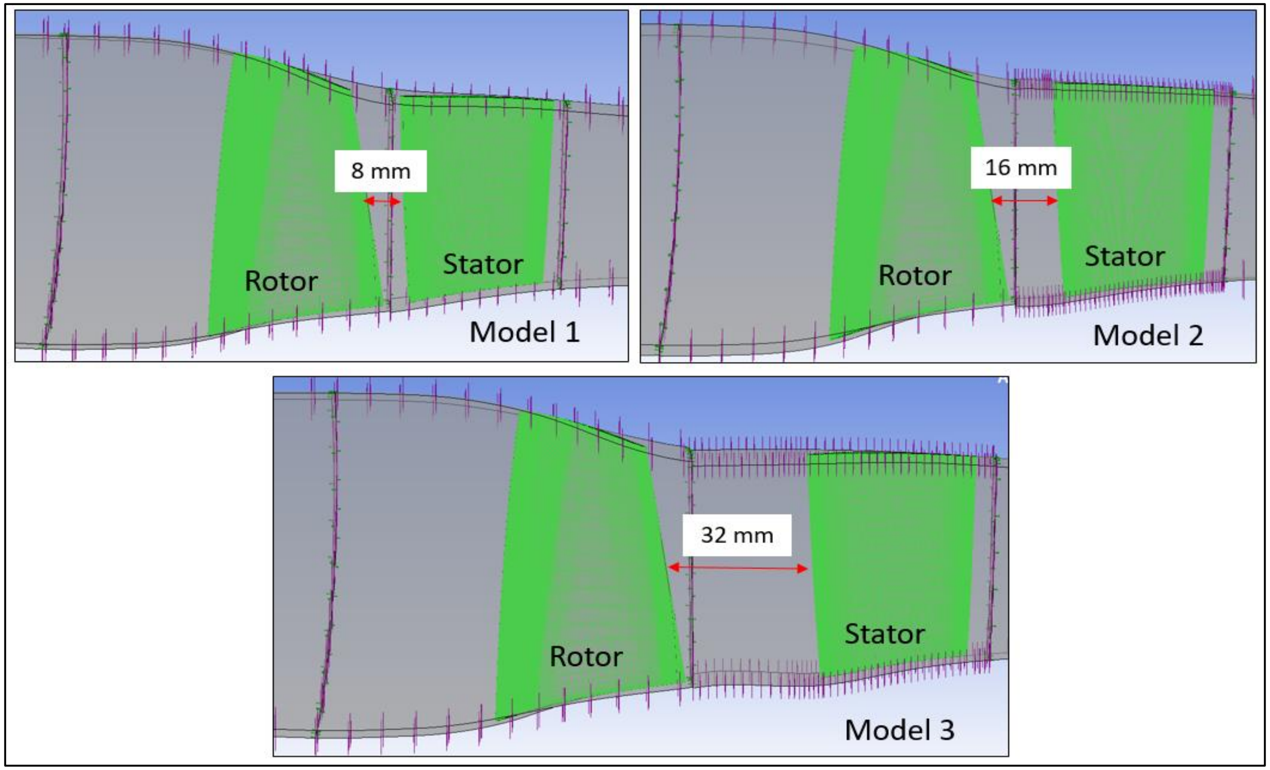
Far-Field Acoustics

- FW-H Acoustic Analogy
- Processing transient pressure data from CFD
- Sources on rotor and stator blades
- Only monopole and dipole sources

5.AEROACOUSTICS SIMULATIONS

SIMULATION MODEL

- Rotor-stator interaction.
- Axial gap effect on noise.
- NASA Stage 37.
- 3 axial gap configurations.
- Star CCM+.



Model Number	Axial Gap
Model 1	8 mm
Model 2	16 mm
Model 3	32 mm

SIMULATION MODEL

- Modeling assumptions:

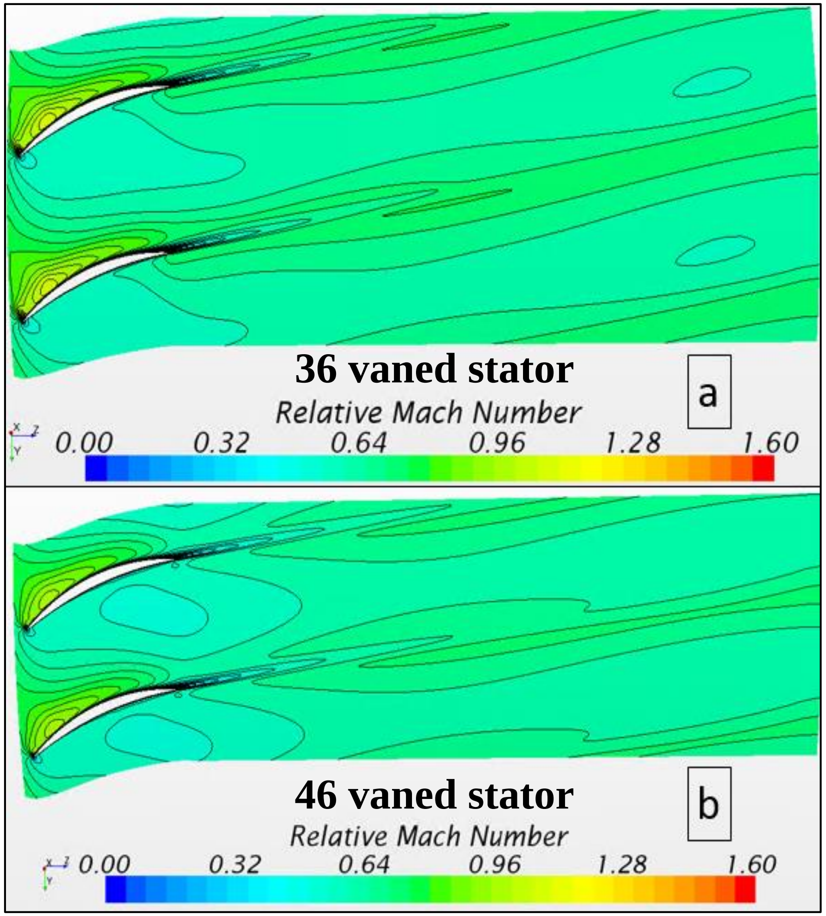
1. Number of Stator Vanes : 46 → 36

Former Rotor-Stator Pitch Ratio: $\frac{10°}{7.82°} = 1.27$

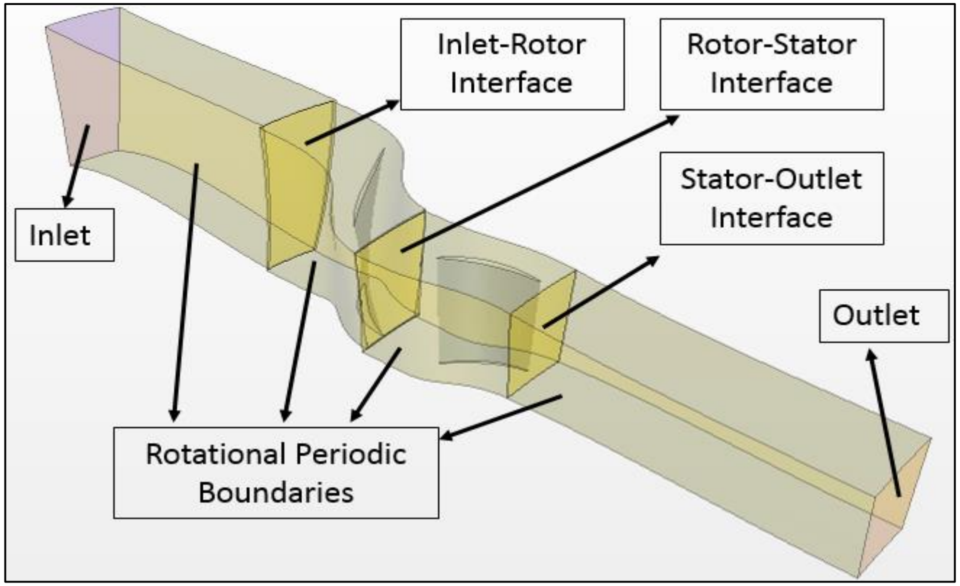
Current Rotor-Stator Pitch Ratio: $\frac{10°}{10°} = 1$

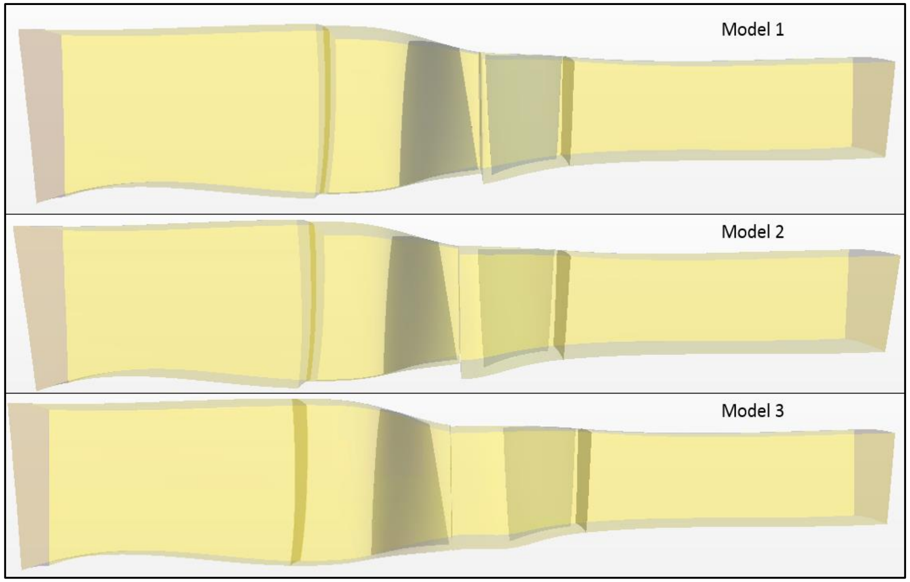
2. No tip clearance of rotor blade.

Model 1	Total Pressure Ratio	Total Temperature Ratio	Rotor Blade Torque [N*m]	Mass Flow Rate [kg/s]	Isentropic Efficiency [%]
36 Vaned Stator	1.956	1.259	24.29	20.75	82.04
46 Vaned Stator	1.941	1.251	23.46	20.73	83.16



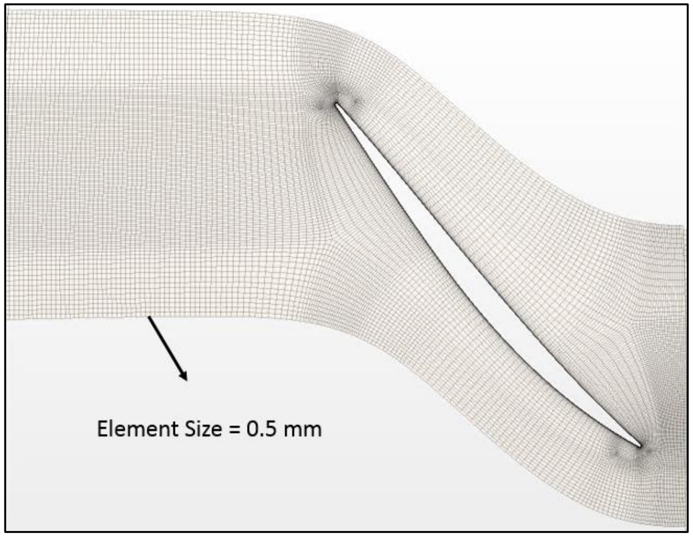
SIMULATION MODEL

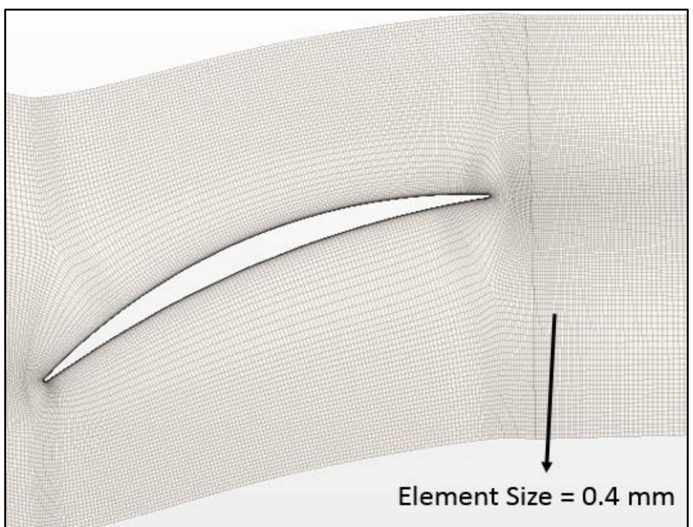


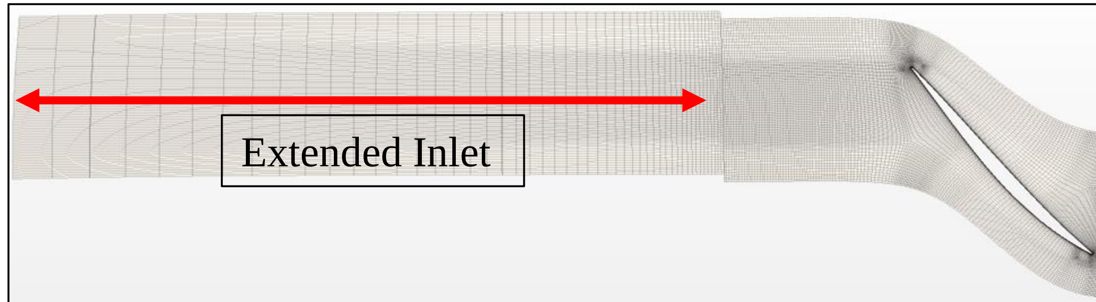


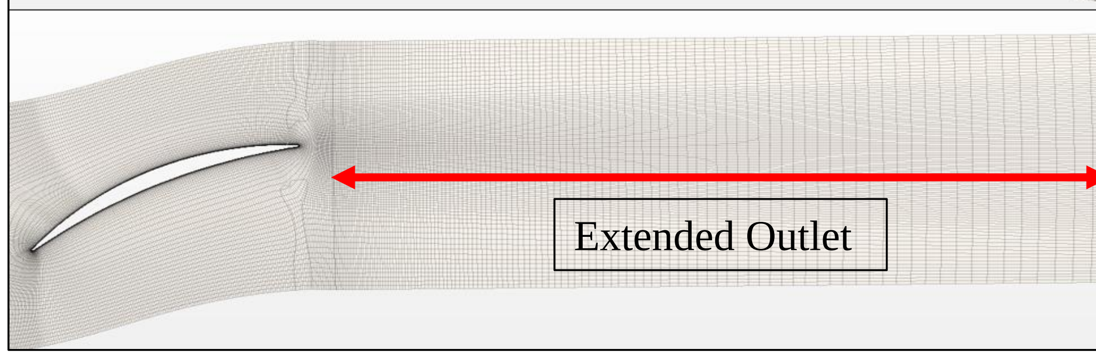
URANS Simulation Numerical Model Details	
Solver	Unsteady Implicit Coupled Solver
Rotation Modeling	Rigid Body Motion
Material	Air Ideal Gas
Time Step Size	9.696×10^{-7} s
Rotational Speed	17188.7 rpm
Inlet Absolute Total Pressure	101325 Pa
Inlet Total Temperature	288.15 K
Outlet Absolute Static Pressure	145000 Pa
Turbulence Model	SST k-ω

SIMULATION MODEL









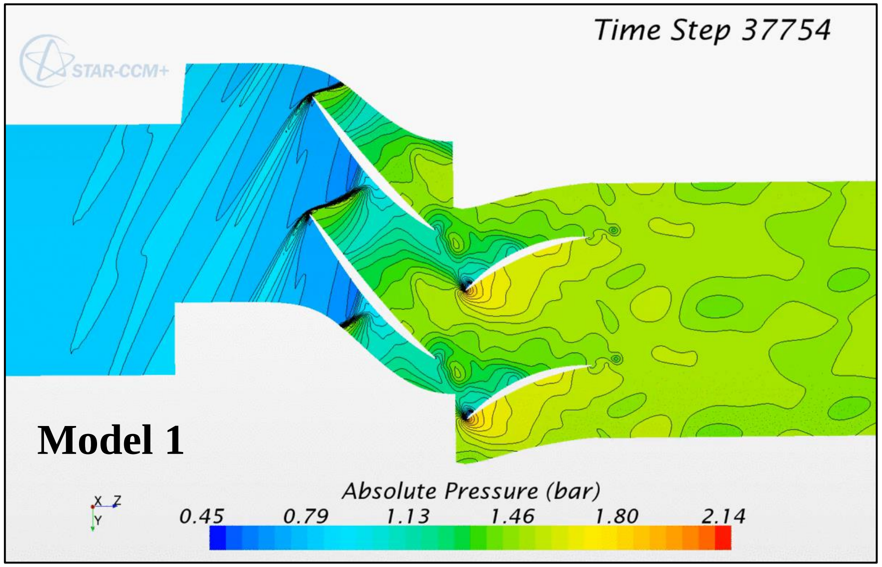
Model	Inlet Region	Rotor Region	Stator Region	Outlet Region	Total
Model 1	265,000	1,216,562	1,434,328	903,000	3,818,890
Model 2	265,000	1,216,562	1,519,677	839,040	3,840,279
Model 3	265,000	1,216,562	1,888,621	804,224	4,174,407

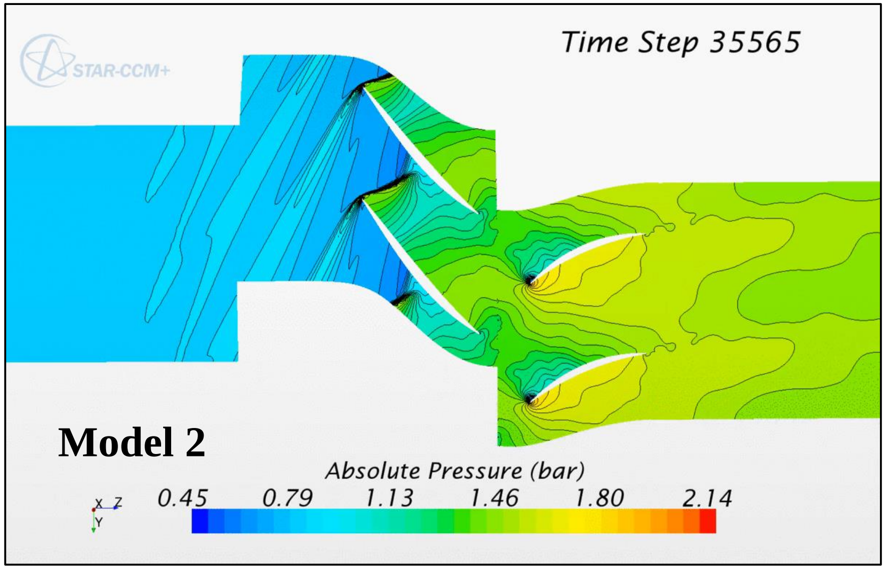
AERODYNAMIC PERFORMANCE

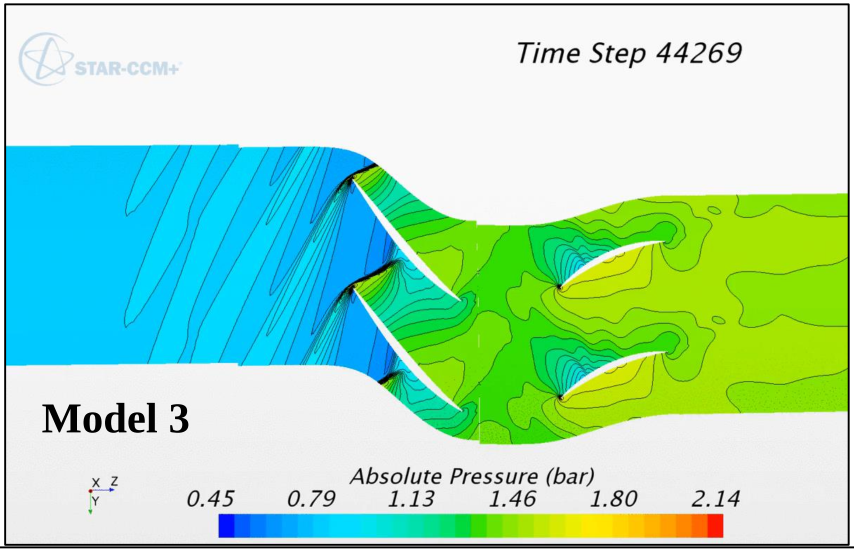
- Aerodynamic performance degrades with the increasing gap.
- 1-2% efficiency loss per doubling
- Trade-off between efficiency loss and noise reduction.

Model	Total Pressure Ratio	Total Temperature Ratio	Isentropic Efficiency
Model 1	1.953	1.257	0.832
Model 2	1.939	1.254	0.820
Model 3	1.915	1.245	0.800

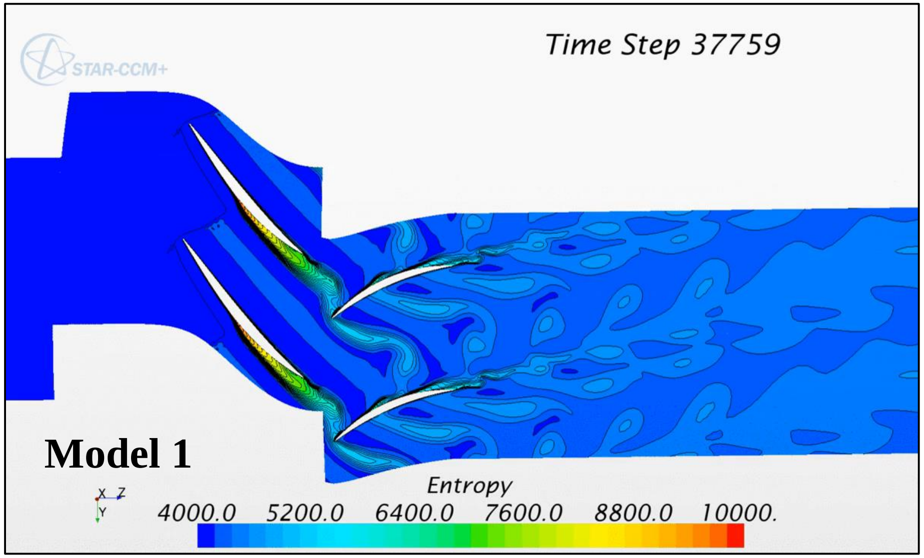
FLOW FIELD IN COMPRESSOR STAGE

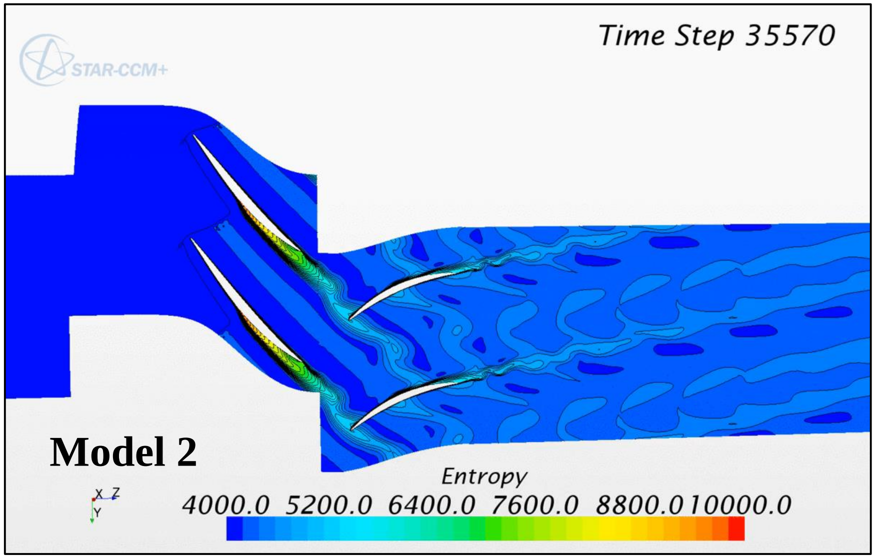


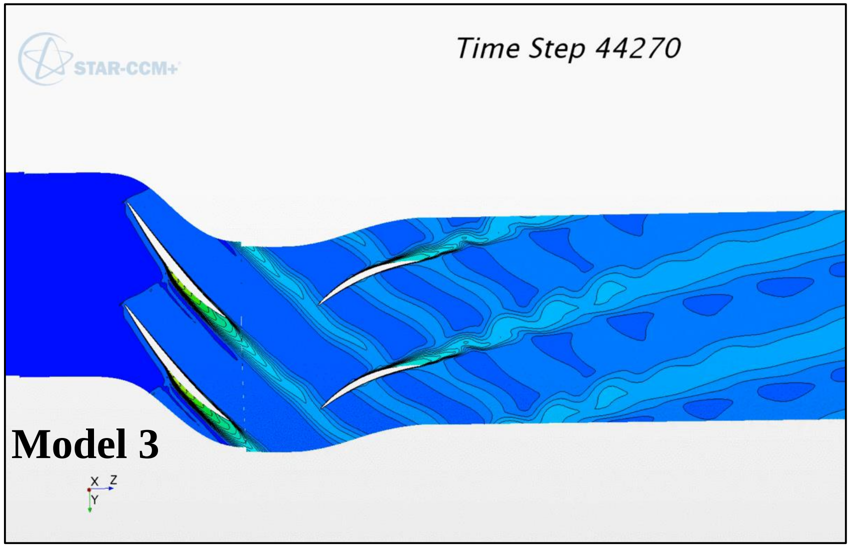




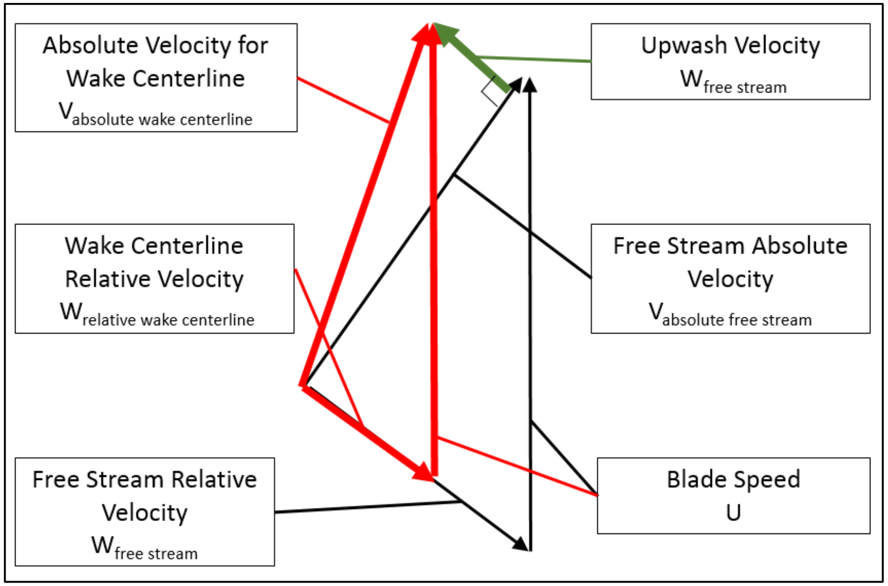
FLOW FIELD IN COMPRESSOR STAGE

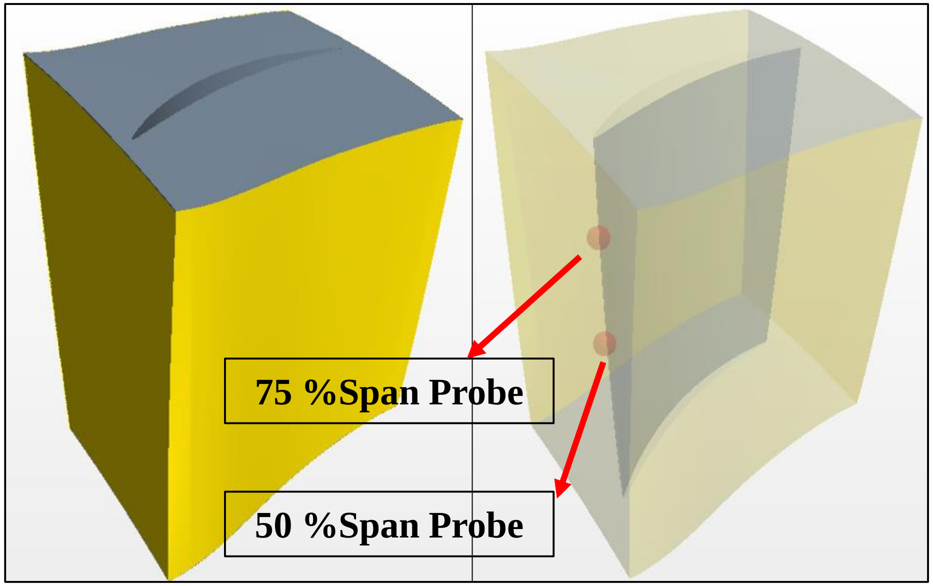






UPWASH VELOCITY

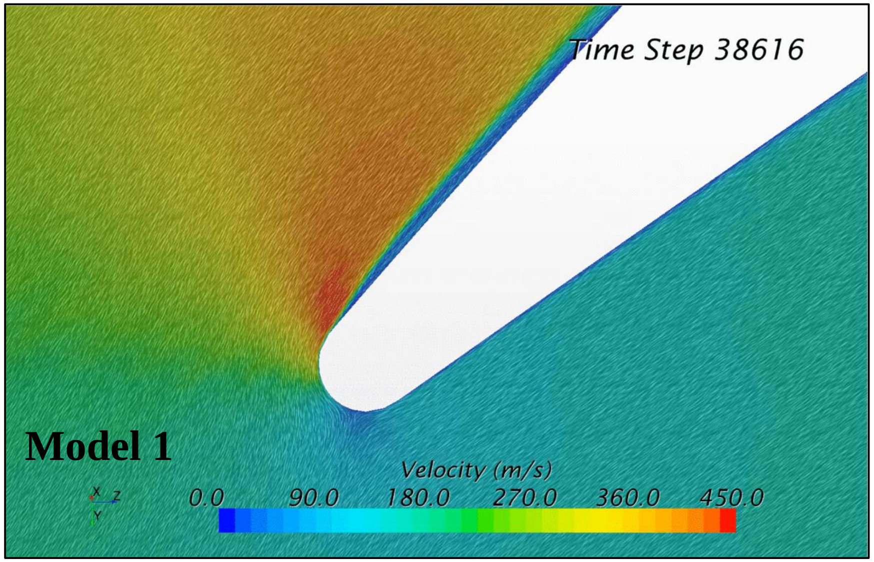


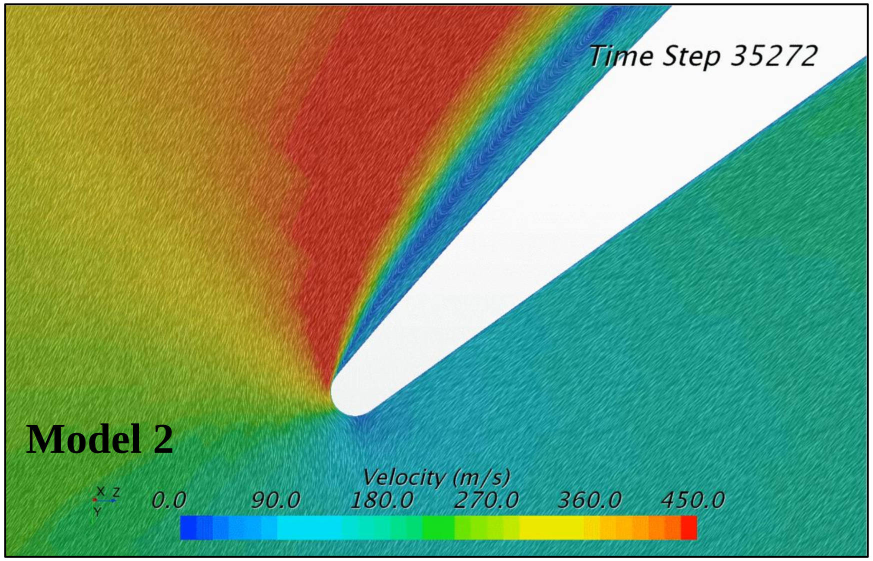


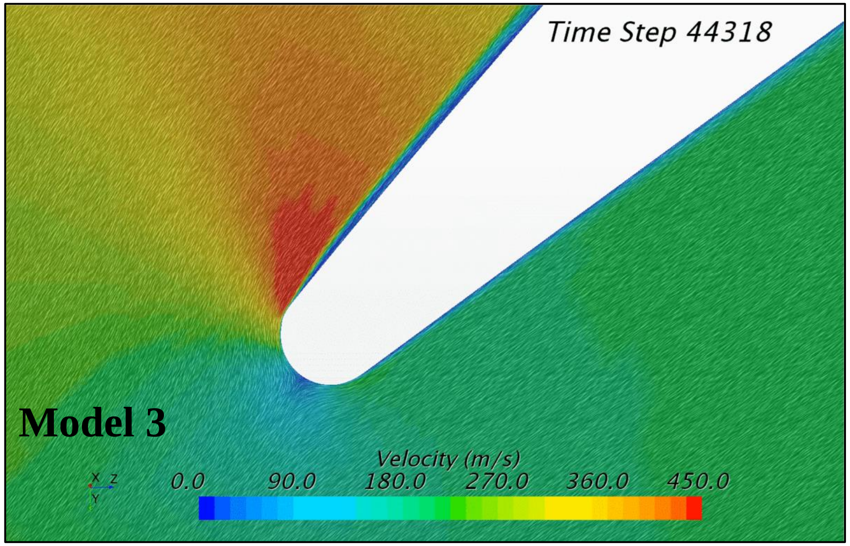
Model	Blade Speed [m/s]	Free Stream Absolute Velocity [m/s]	Free Stream Relative Velocity [m/s]	Absolute Velocity for Wake Centerline [m/s]	Wake Centerline Relative Velocity [m/s]	Upwash Velocity [m/s]
Model 1	387	195	247	213	177	147.9
Model 2	387	195	250	201	194	119.7
Model 3	387	213	262	212	230	49.4

Model	Blade Speed [m/s]	Free Stream Absolute Velocity [m/s]	Free Stream Relative Velocity [m/s]	Absolute Velocity for Wake Centerline [m/s]	Wake Centerline Relative Velocity [m/s]	Upwash Velocity [m/s]
Model 1	414	167	301	200	210	146.2
Model 2	414	201	272	233	191	128.6
Model 3	414	245	290	247	225	92

FLOW FIELD IN COMPRESSOR STAGE

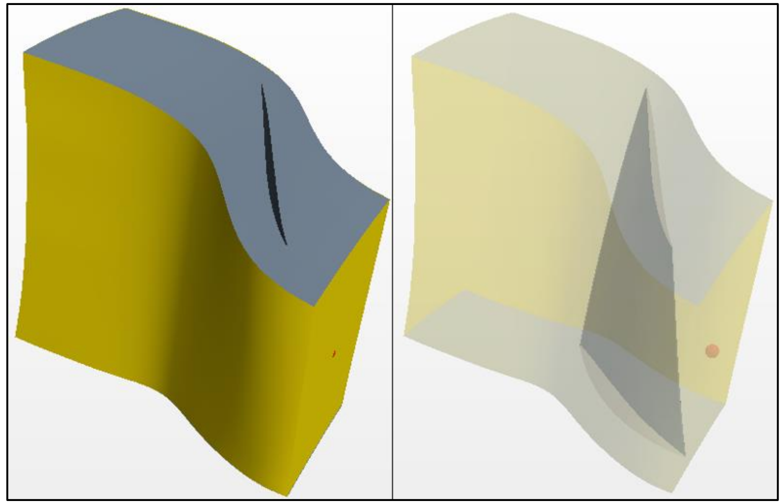


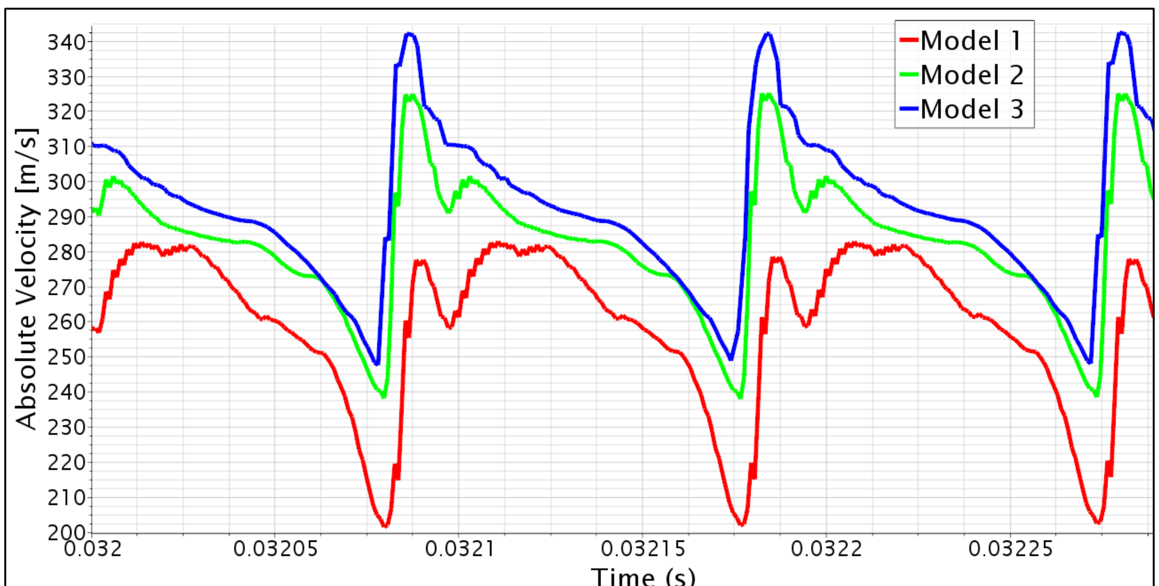




FLOW FIELD IN COMPRESSOR STAGE

- Probe at downstream of rotor.
- Stator potential field.
- Decrease in velocity.

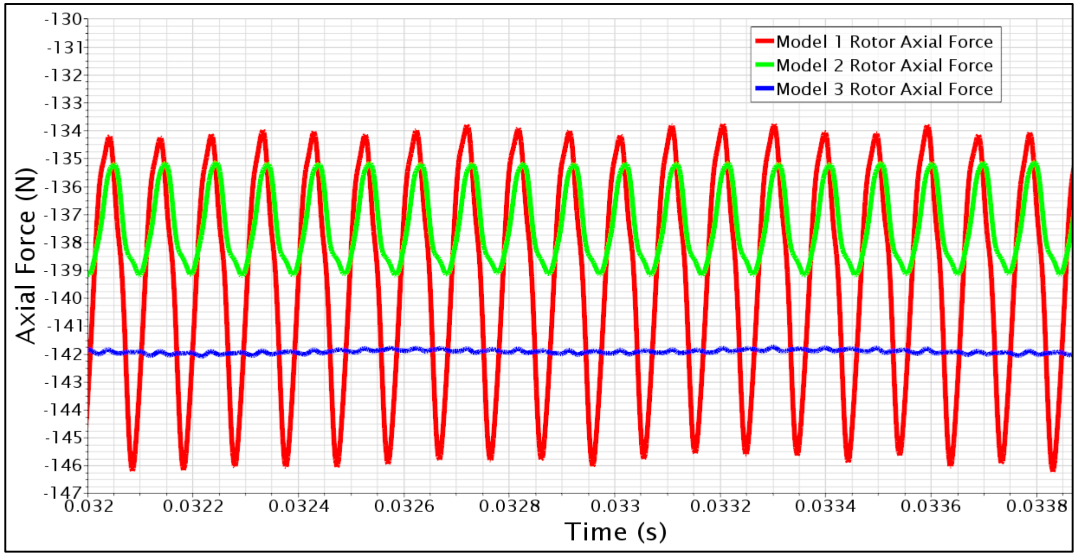




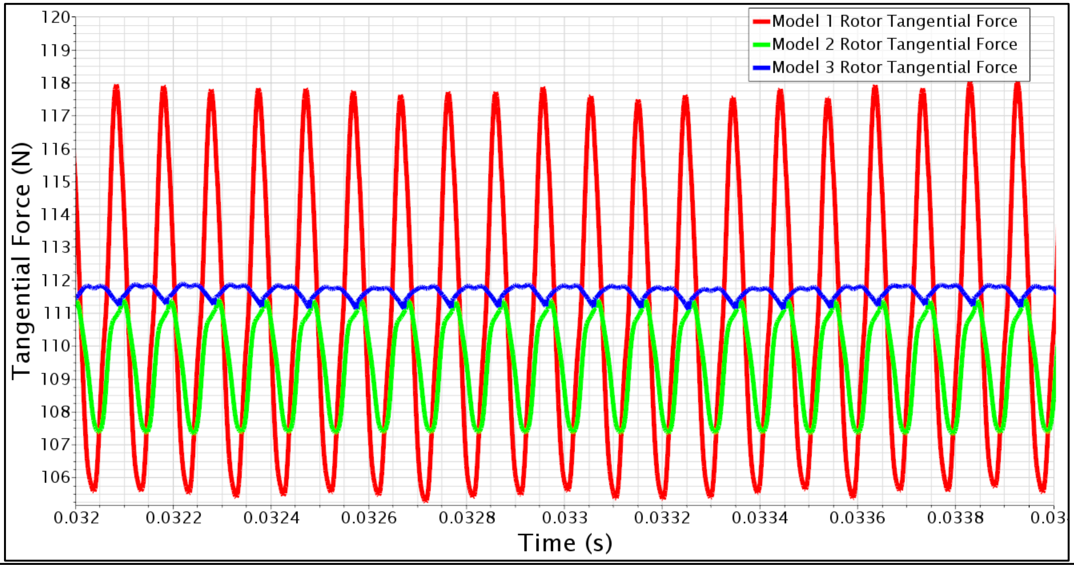
UNSTEADINESS ON ROTOR BLADE

- **Unsteady forces on rotor blade**

Axial Force on Rotor Blade



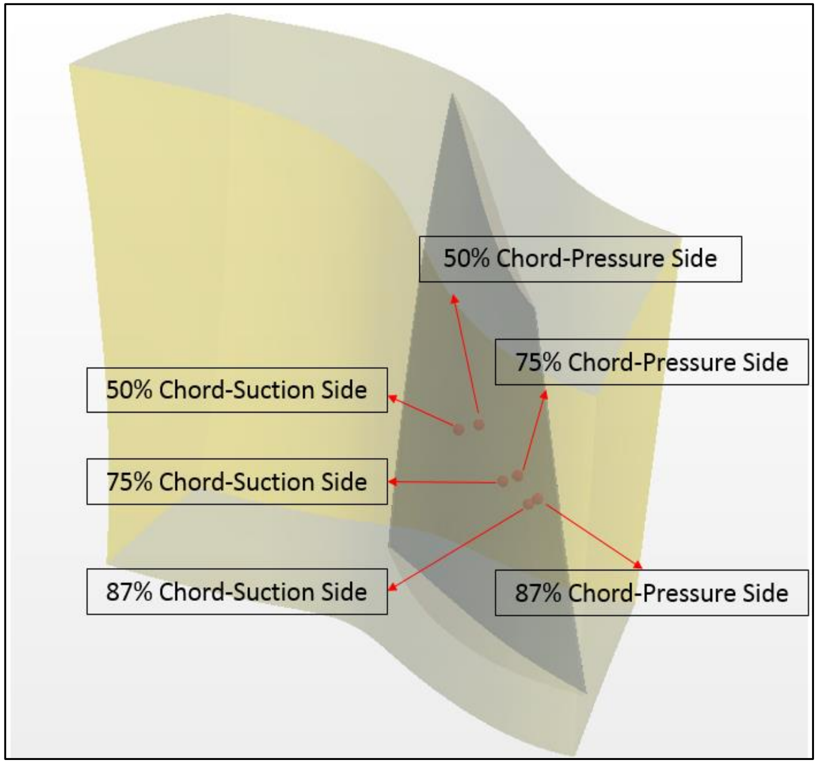
Tangential Force on Rotor Blade

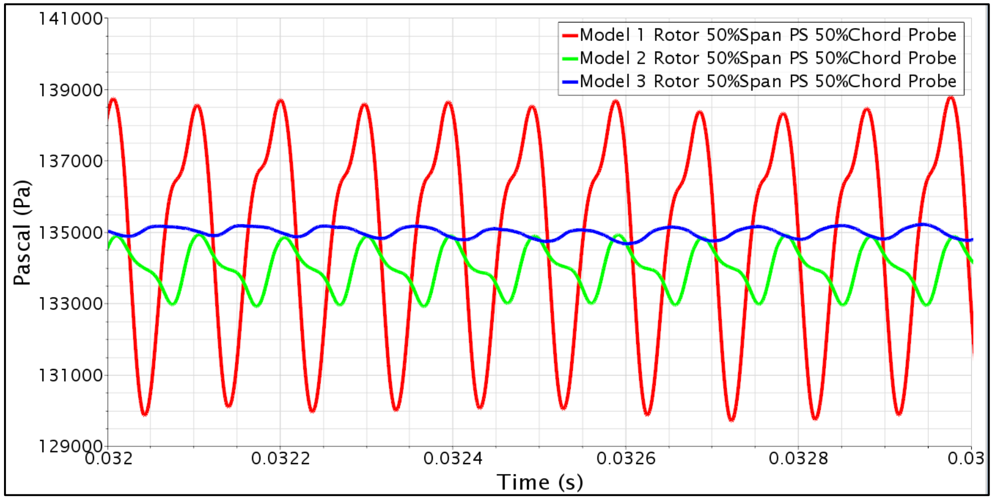


UNSTEADINESS ON ROTOR BLADE

- **Averaged Normalized Unsteady Pressure**

$$\bar{p}_{normalized} = \frac{\sum_{i=1}^{i=n} \frac{p(t)_i - \bar{p}}{p_{0,ref}}}{n}$$





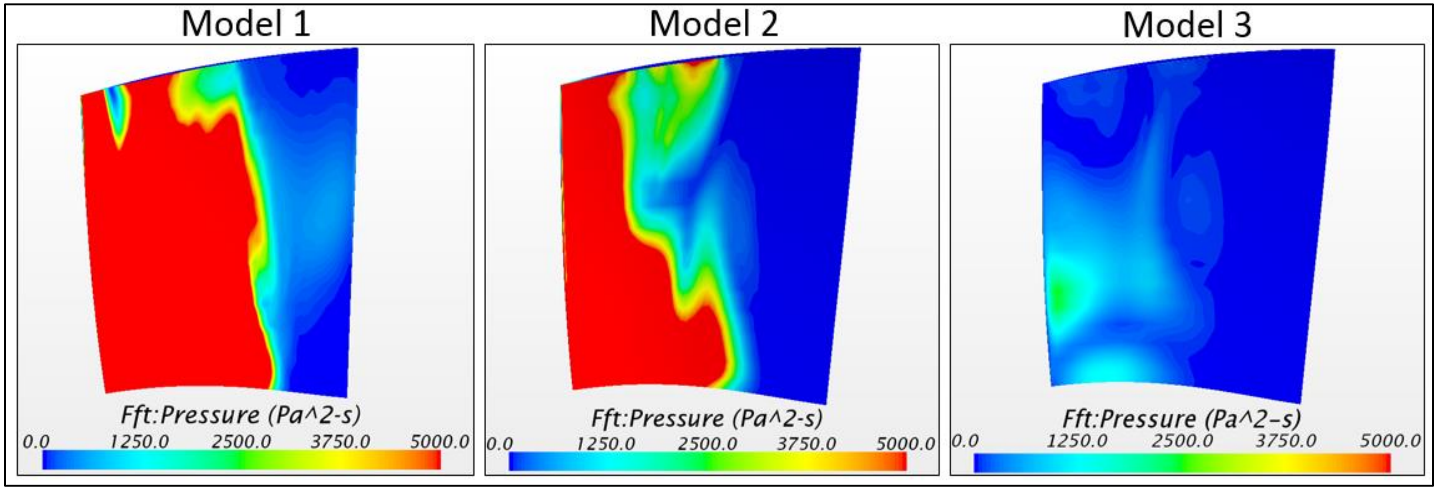
Pressure Side Probes			
Model	**50% Chord**	**75% Chord**	**87% Chord**
Model 1	0.0244	0.0477	0.0393
Model 2	0.0048	0.0159	0.0246
Model 3	0.0011	0.0050	0.0051

Suction Side Probes			
Model	**50% Chord**	**75% Chord**	**87% Chord**
Model 1	0.0060	0.0282	0.0166
Model 2	0.0015	0.0066	0.0037
Model 3	0.0005	0.0037	0.0021

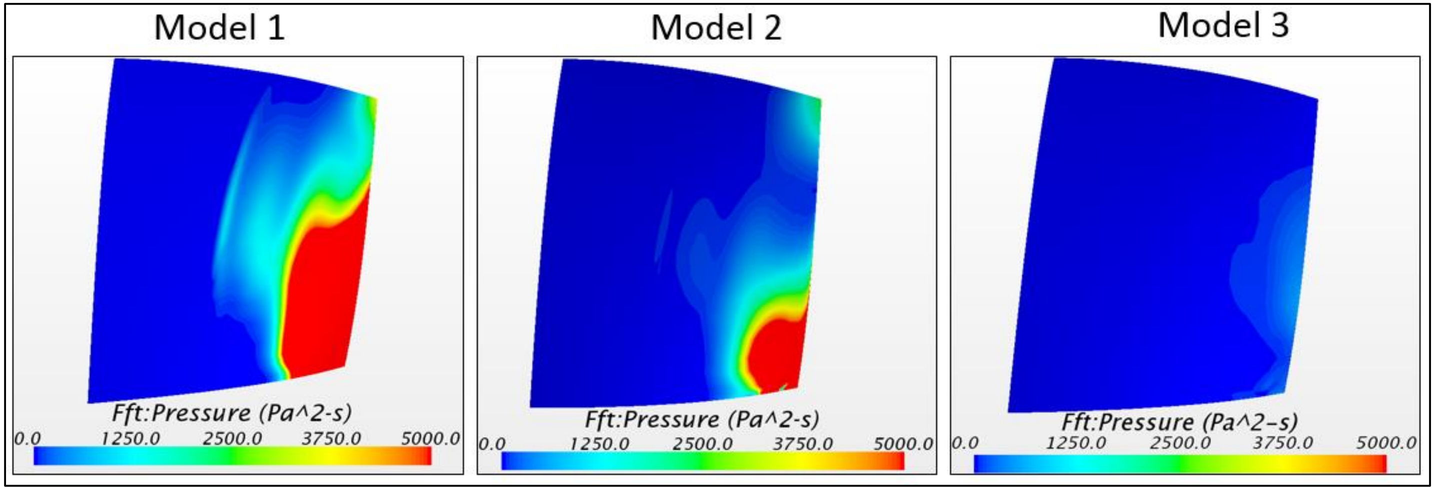
UNSTEADINESS ON ROTOR BLADE

- **Power Spectral Density :** Energy of the pressure fluctuations.

Pressure Side 1st BPF



Suction Side 1st BPF

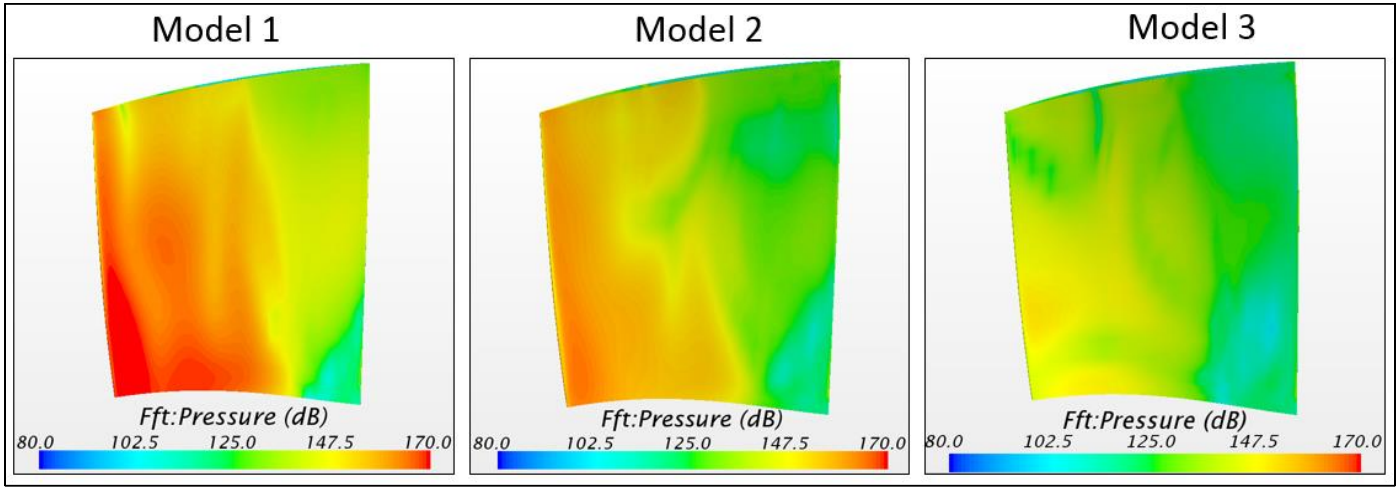


UNSTEADINESS ON ROTOR BLADE

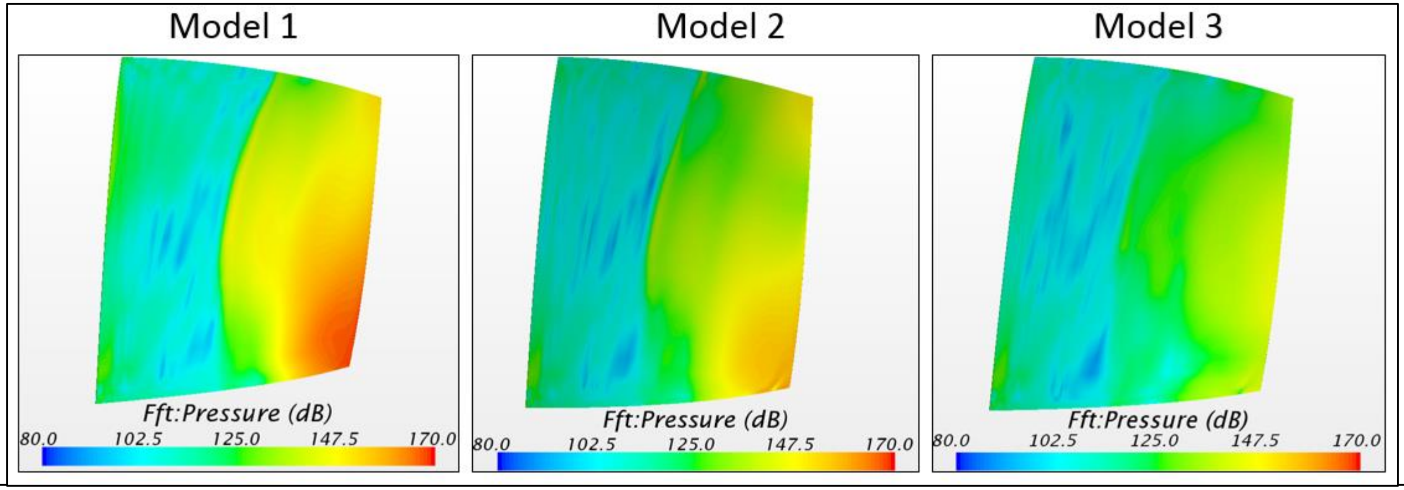
- **Sound Pressure Level:** Magnitude of the radiated acoustic waves.

$$SPL = 10\, log\left(\frac{P_{rms}^2}{P_{ref}^2}\right)$$

Pressure Side
1^{st} BPF



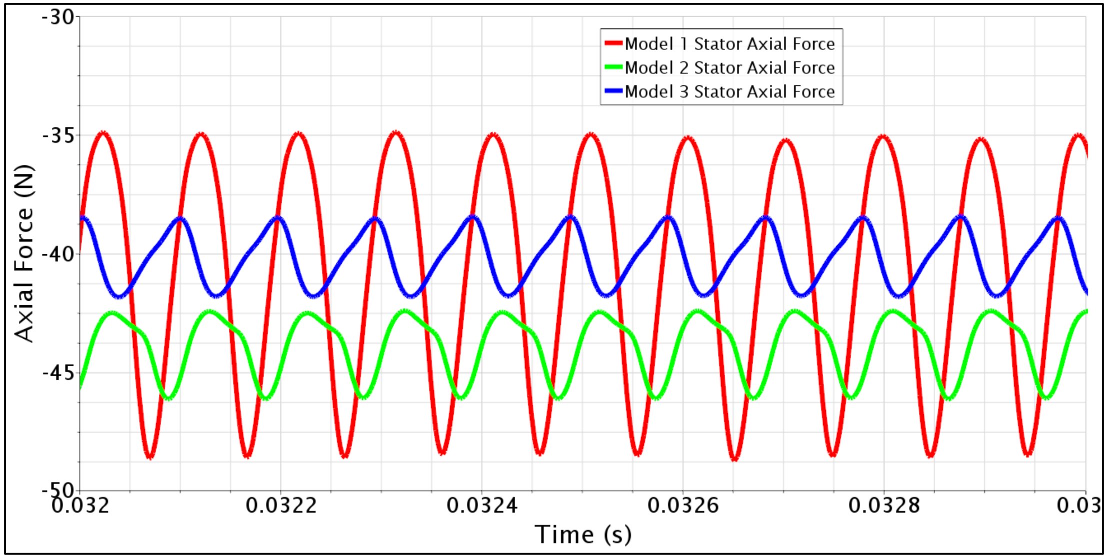
Suction Side
1^{st} BPF



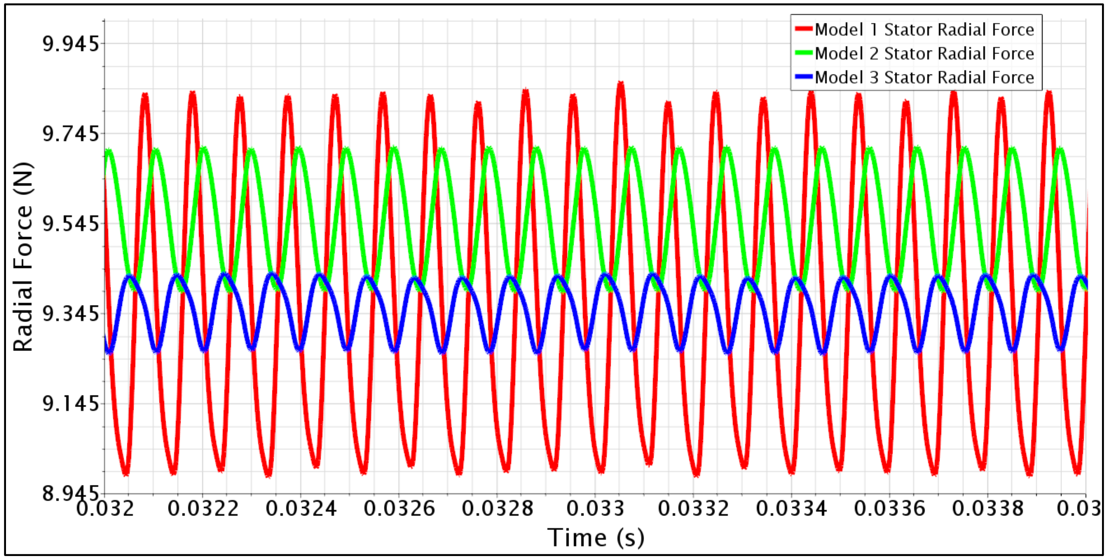
UNSTEADINESS ON STATOR VANE

- **Unsteady forces on stator vane**

Axial Force on Stator Vane



Radial Force on Stator Vane



UNSTEADINESS ON STATOR VANE

- **Space-Time Plots**

- Normalized Unsteady Presure:

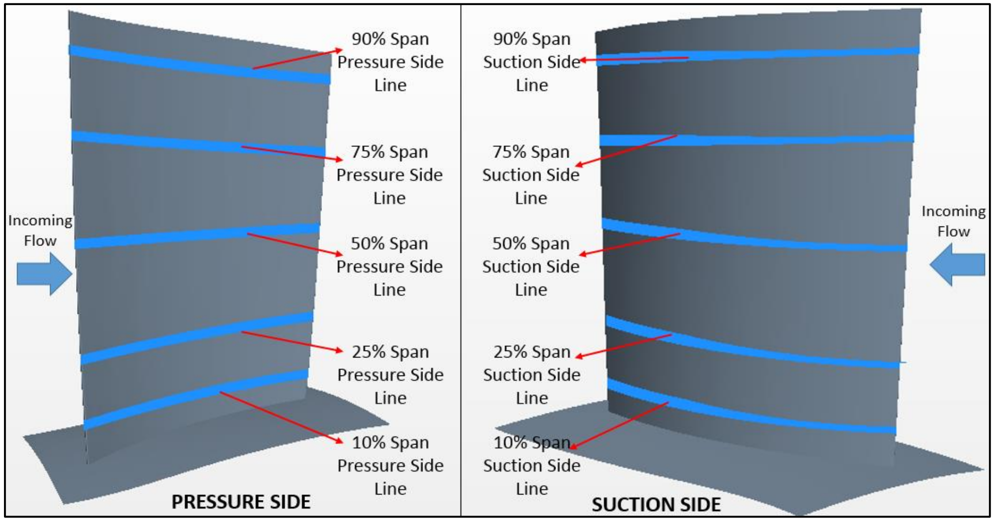
$$p_{normalized} = \frac{p(t) - \bar{p}}{p_{0,ref}}$$

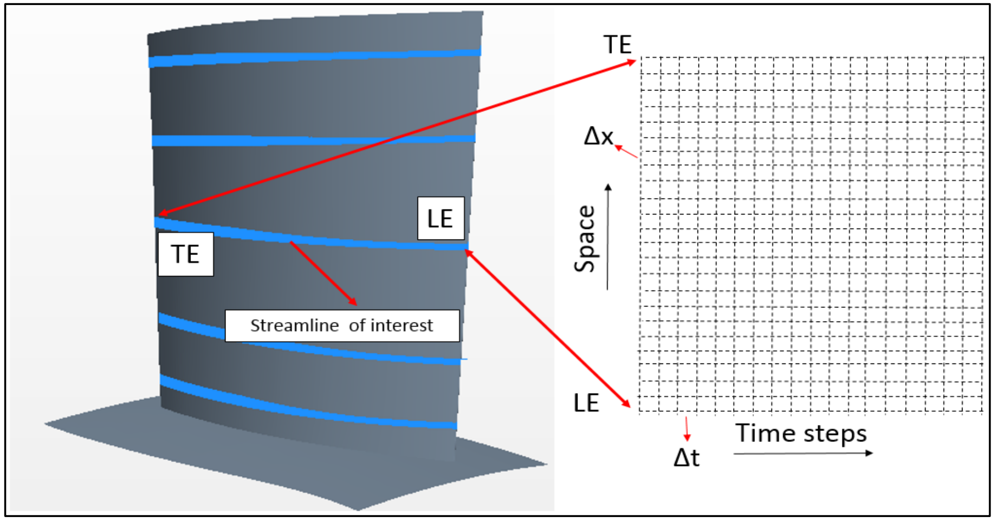
- Line probes on pressure and suction sides.

- Each line at least 200 probes.

- Horizontal axis is time (5 blade passing)

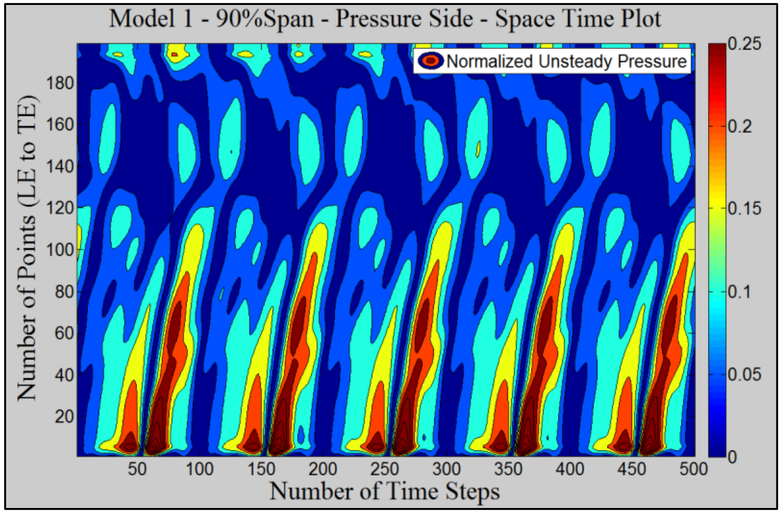
- Vertical axis is space (from LE to TE)

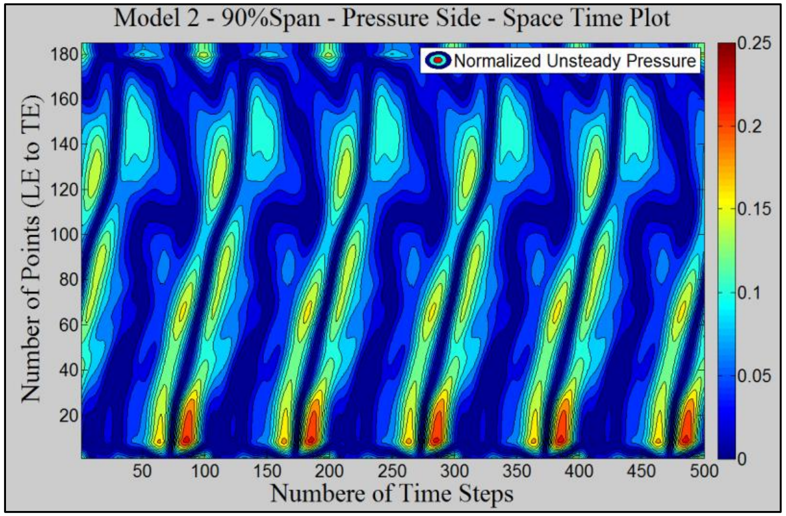


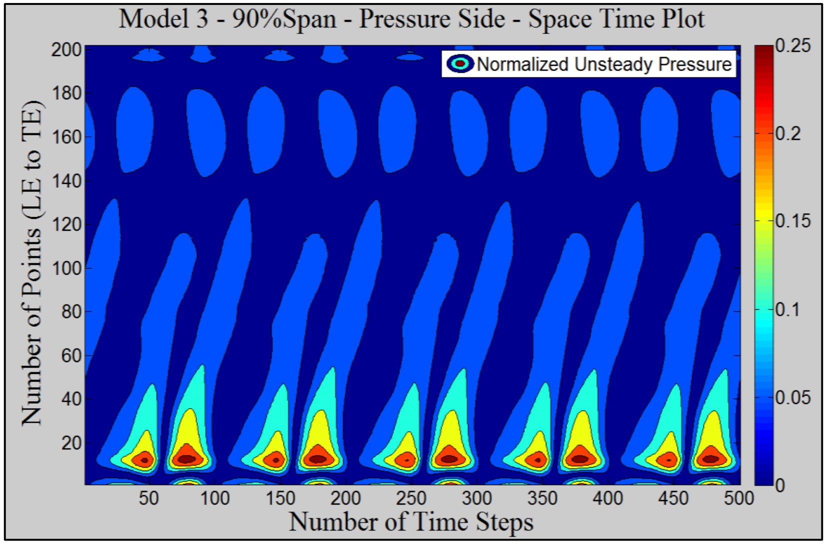


UNSTEADINESS ON STATOR VANE

- **Space-Time Plots**



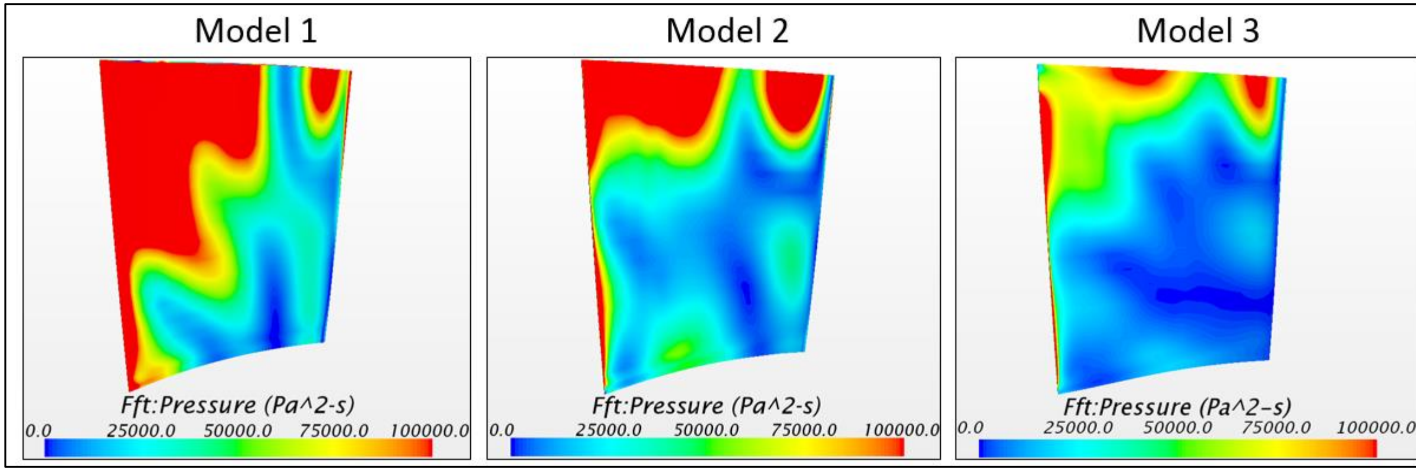




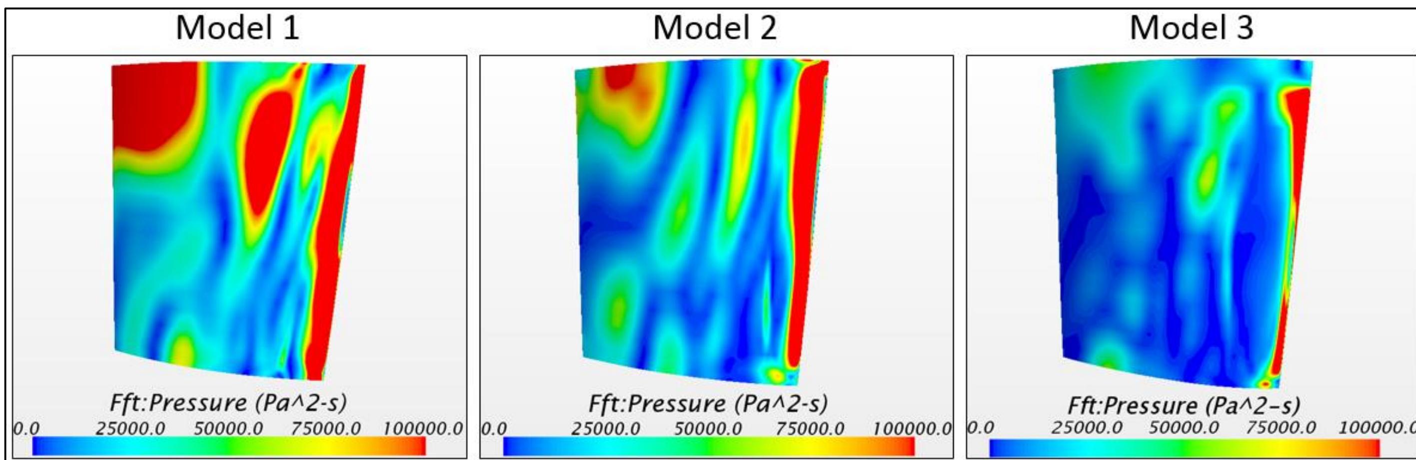
UNSTEADINESS ON STATOR VANE

- **Power Spectral Density**

Pressure Side
1st BPF



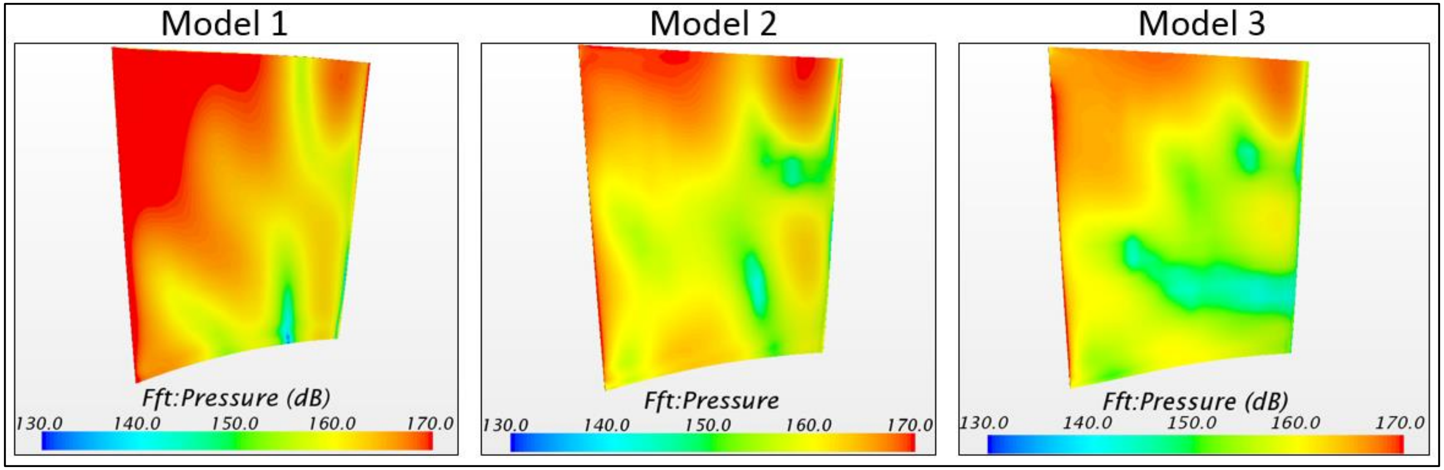
Suction Side
1st BPF



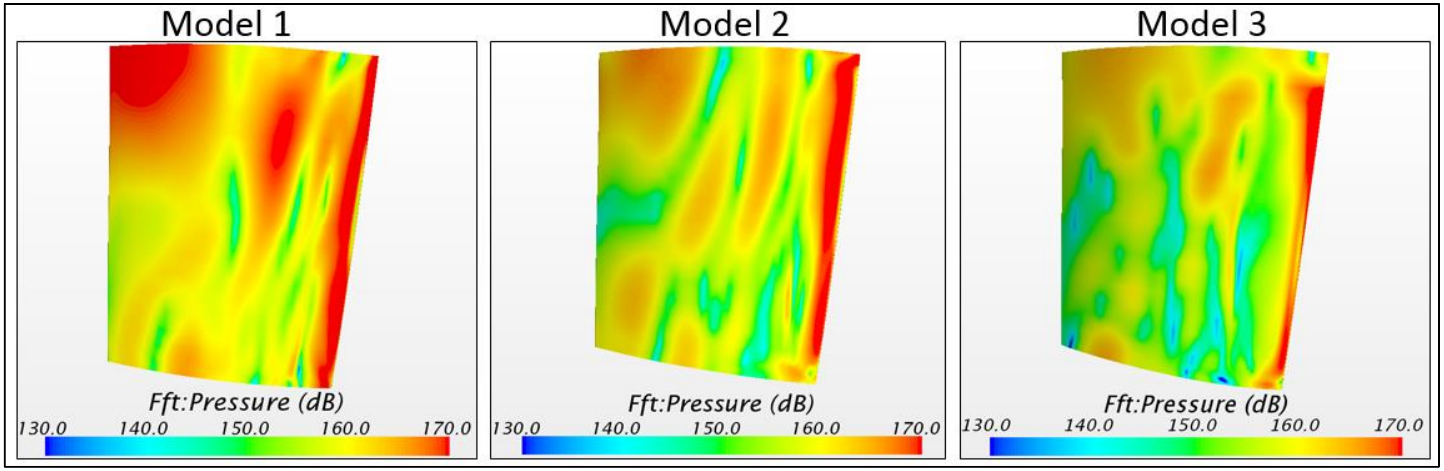
UNSTEADINESS ON STATOR VANE

- **Sound Pressure Level**

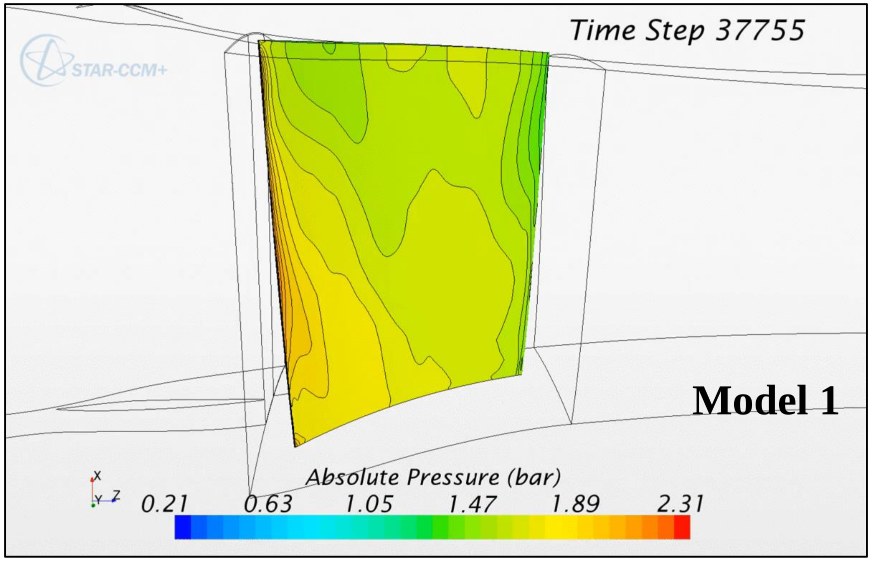
Pressure Side
1st BPF

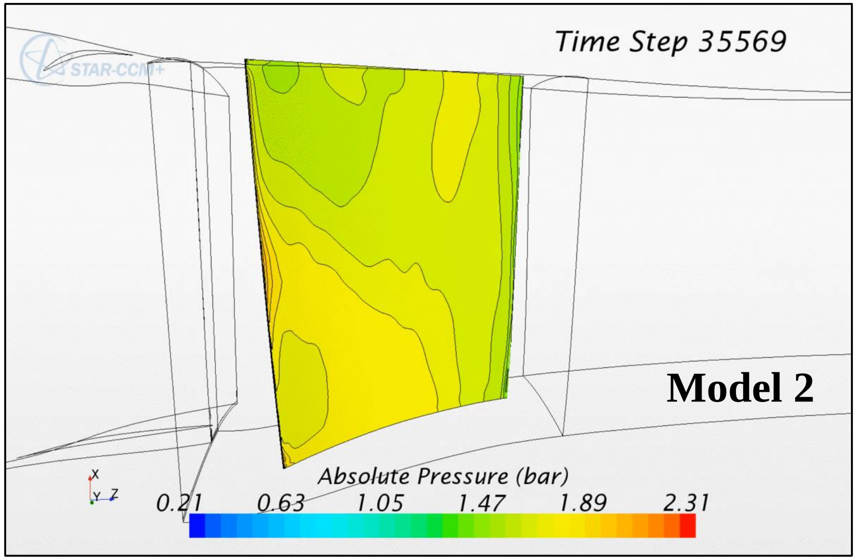


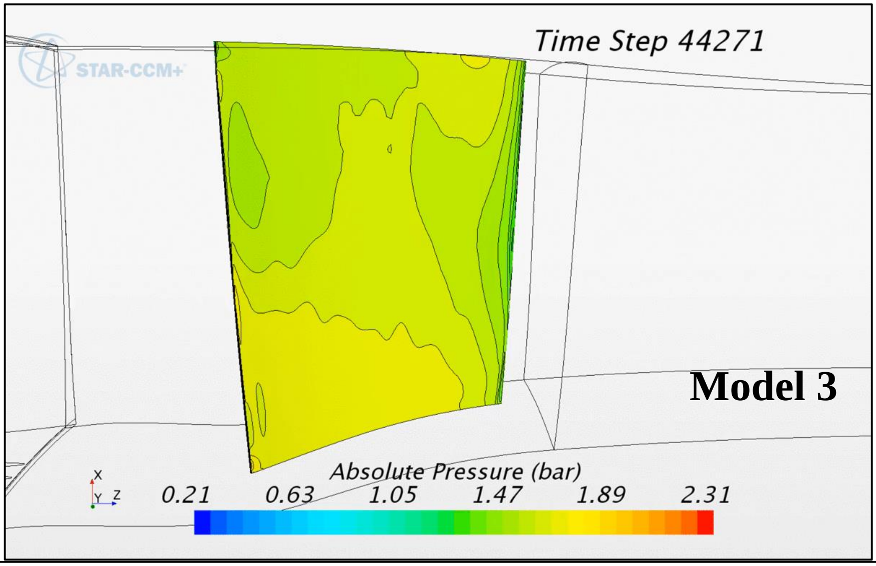
Suction Side
1st BPF



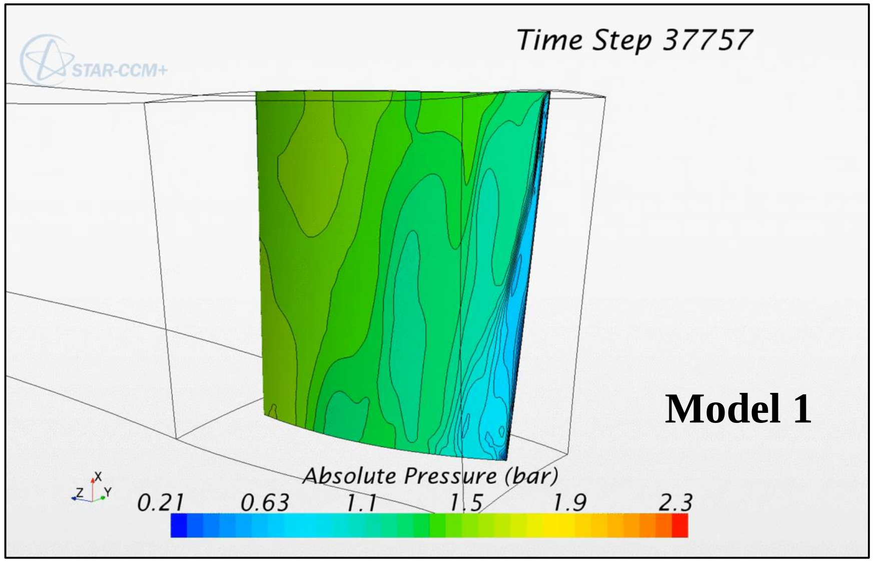
UNSTEADINESS ON STATOR VANE

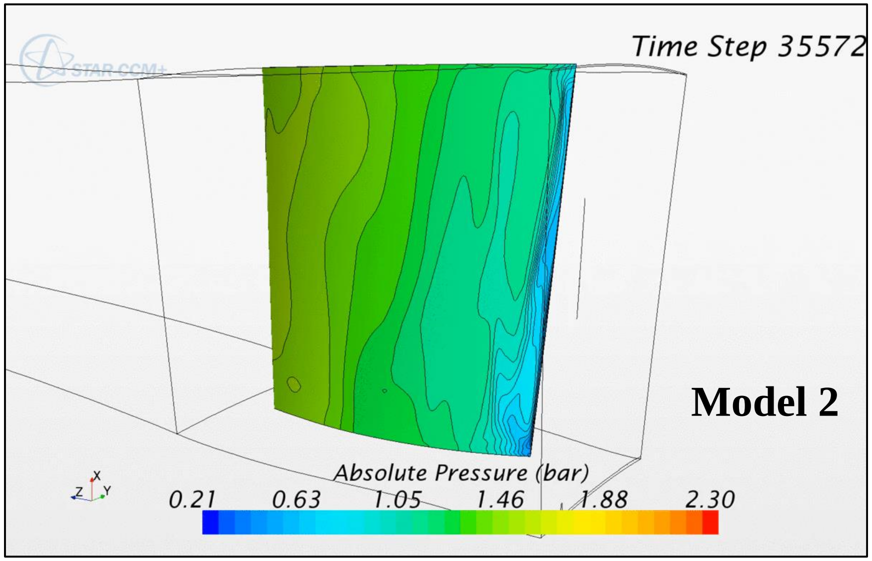


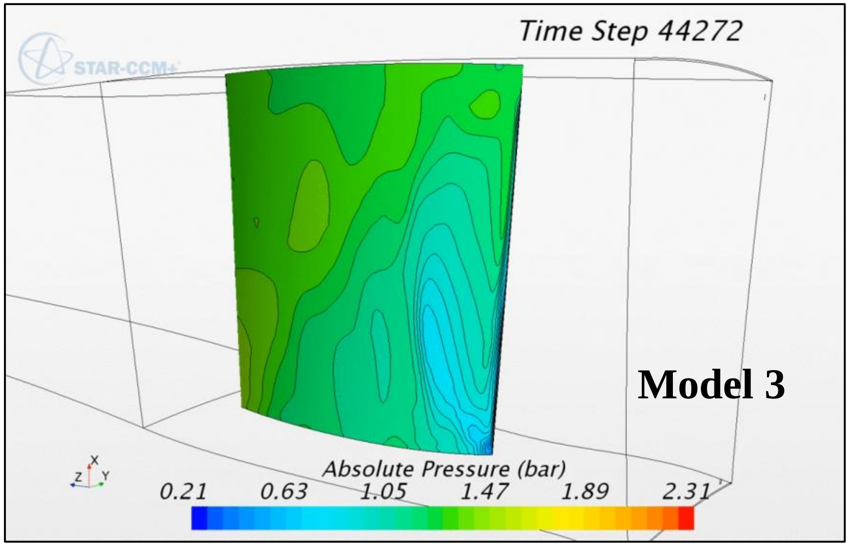




UNSTEADINESS ON STATOR VANE

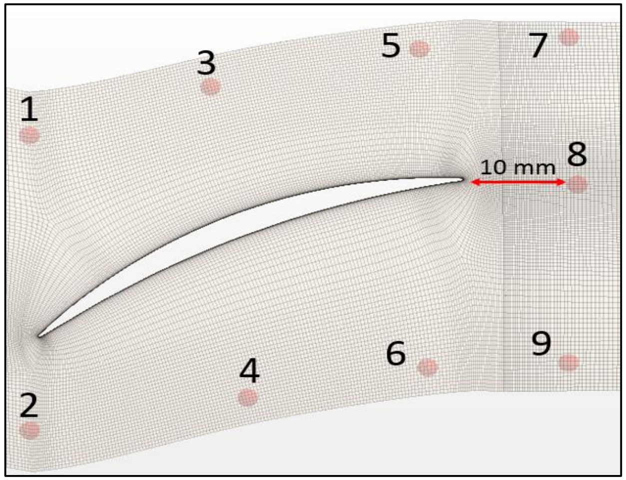






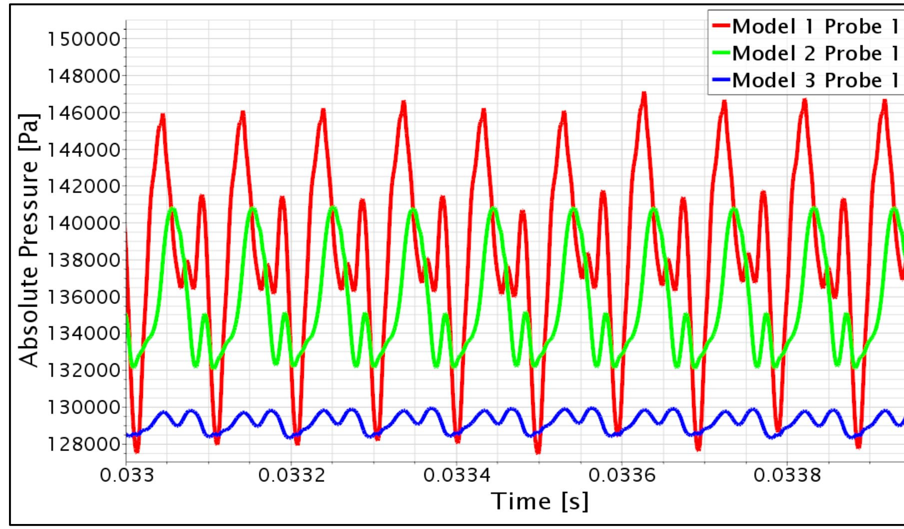
NEAR-FIELD ACOUSTICS

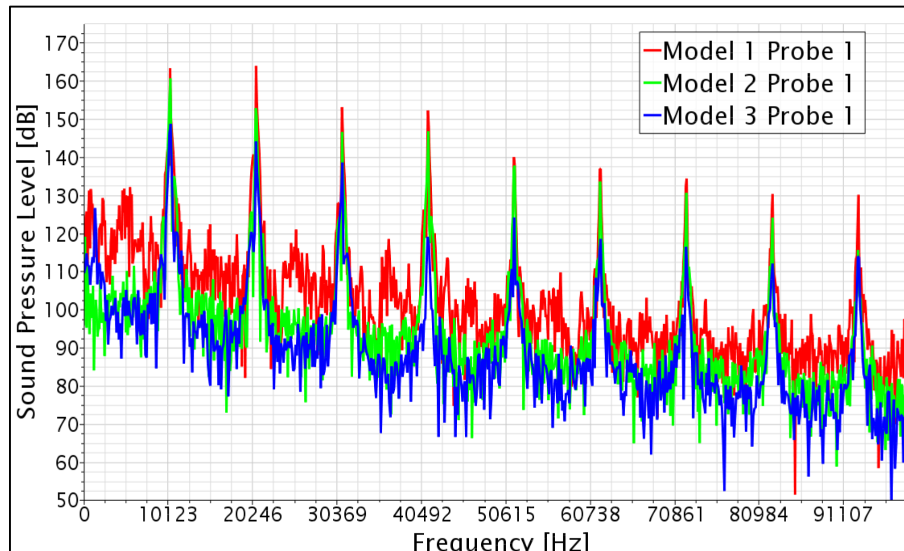
- Direct noise calculation.
- 9 pressure probes near the noise sources.
- SPL of the recorded pressure.



Probe	Model	1^{st} BPF	2^{nd} BPF	3^{rd} BPF
Probe 1	Model 1	163.3	163.8	153.0
	Model 2	160.6	152.8	146.6
	Model 3	148.7	144.0	138.5

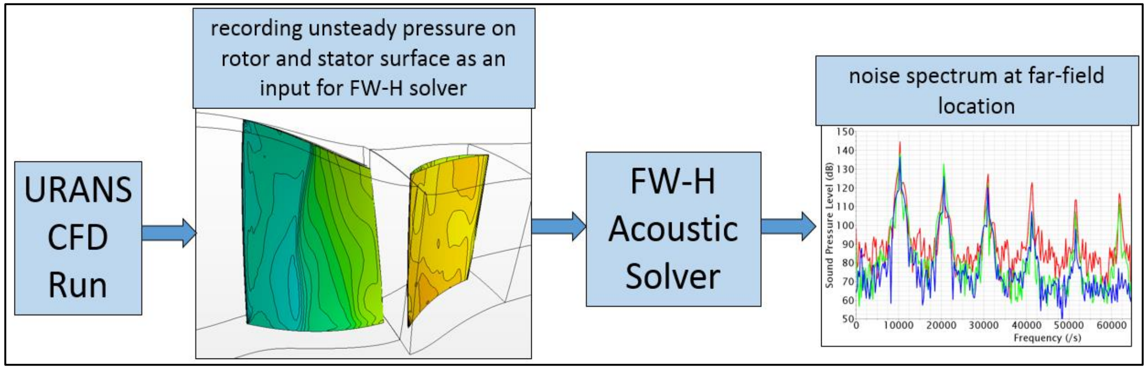
Tonal noise values of first three BPF at Probe 1

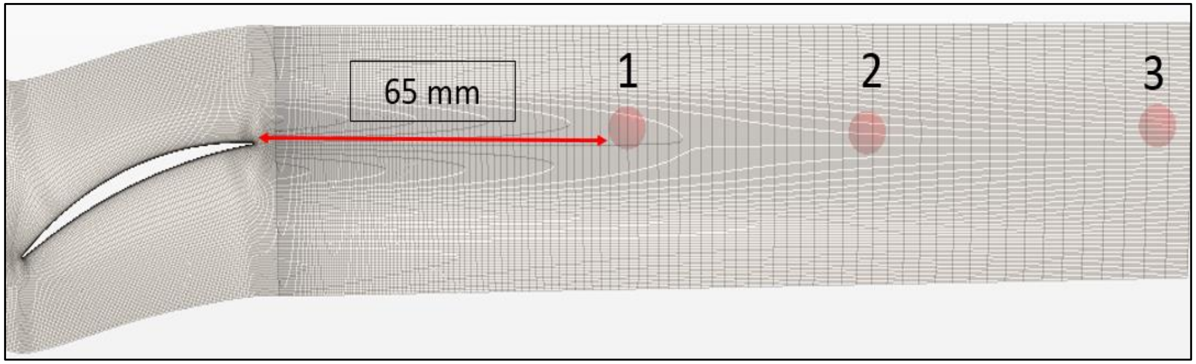




FAR-FIELD ACOUSTICS

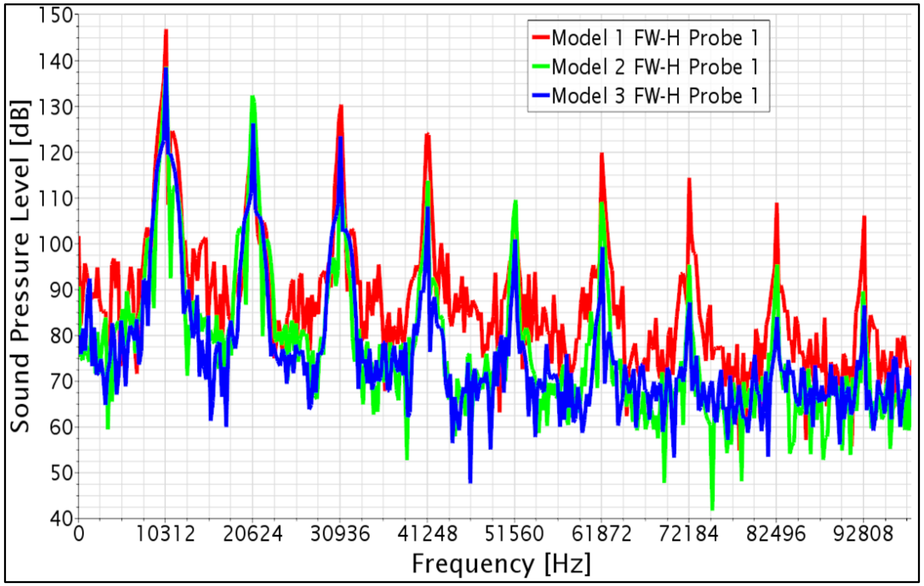
- Hybrid methods.
- First step : Direct noise calculation.
- Second Step: FW-H acoustic analogy.
- 6 far-field probes.
- Noise sources → rotor and stator surface.

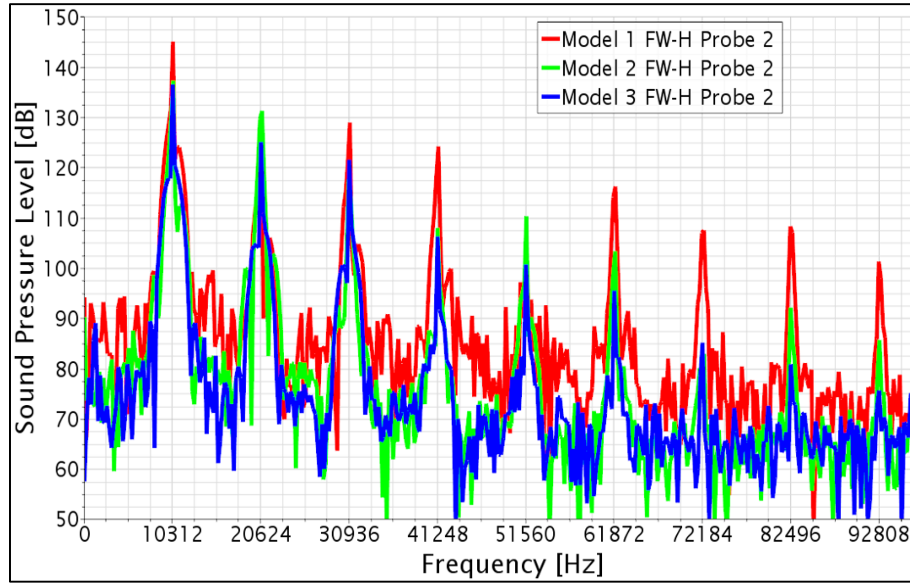




Probe	Distance [mm]
Probe 1	65
Probe 2	105
Probe 3	155
Probe 4	270
Probe 5	420
Probe 6	670

FAR-FIELD ACOUSTICS





FW-H Probe	Model	1st BPF	2nd BPF	3rd BPF	4th BPF
Probe 1	Model 1	146.7	130.6	130.3	124.0
	Model 2	138.5	132.3	118.6	113.7
	Model 3	138.4	126.2	123.4	108.1

Tonal noise values of first four BPF at Probe 1

FW-H Probe	Model	1st BPF	2nd BPF	3rd BPF	4th BPF
Probe 2	Model 1	145.0	129.9	129.0	124.3
	Model 2	137.3	131.3	117.6	108.0
	Model 3	136.5	125.0	121.5	106.3

Tonal noise values of first four BPF at Probe 2

6. CONCLUSION

CONCLUSION

- Aerodynamic noise of turbomachines.
- Physics of rotor-stator interaction.
- Flow in transonic axial compressors.
- Computational aeroacoustics.
- Developing CFD methodology for turbomachinery aeroacostics.
- Considerable decrease in tonal noise.
- Slight decrease in broadband noise.

THANK YOU