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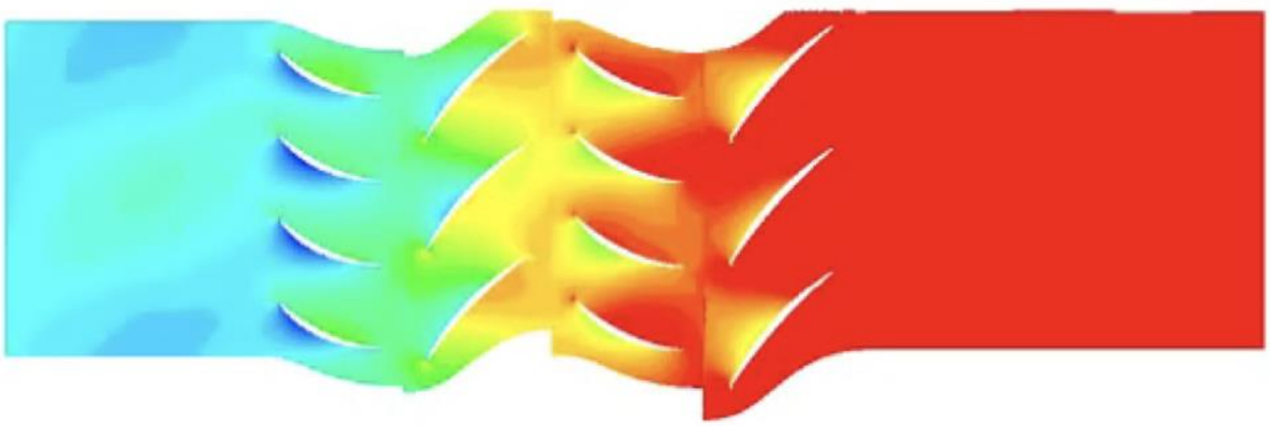
GUIde 5 Consortium

Forced Response Study of an Embedded Compressor Rotor



Mech Aero 2018

6th International Conference and Exhibition on Mechanical & Aerospace Engineering

Robert Kielb

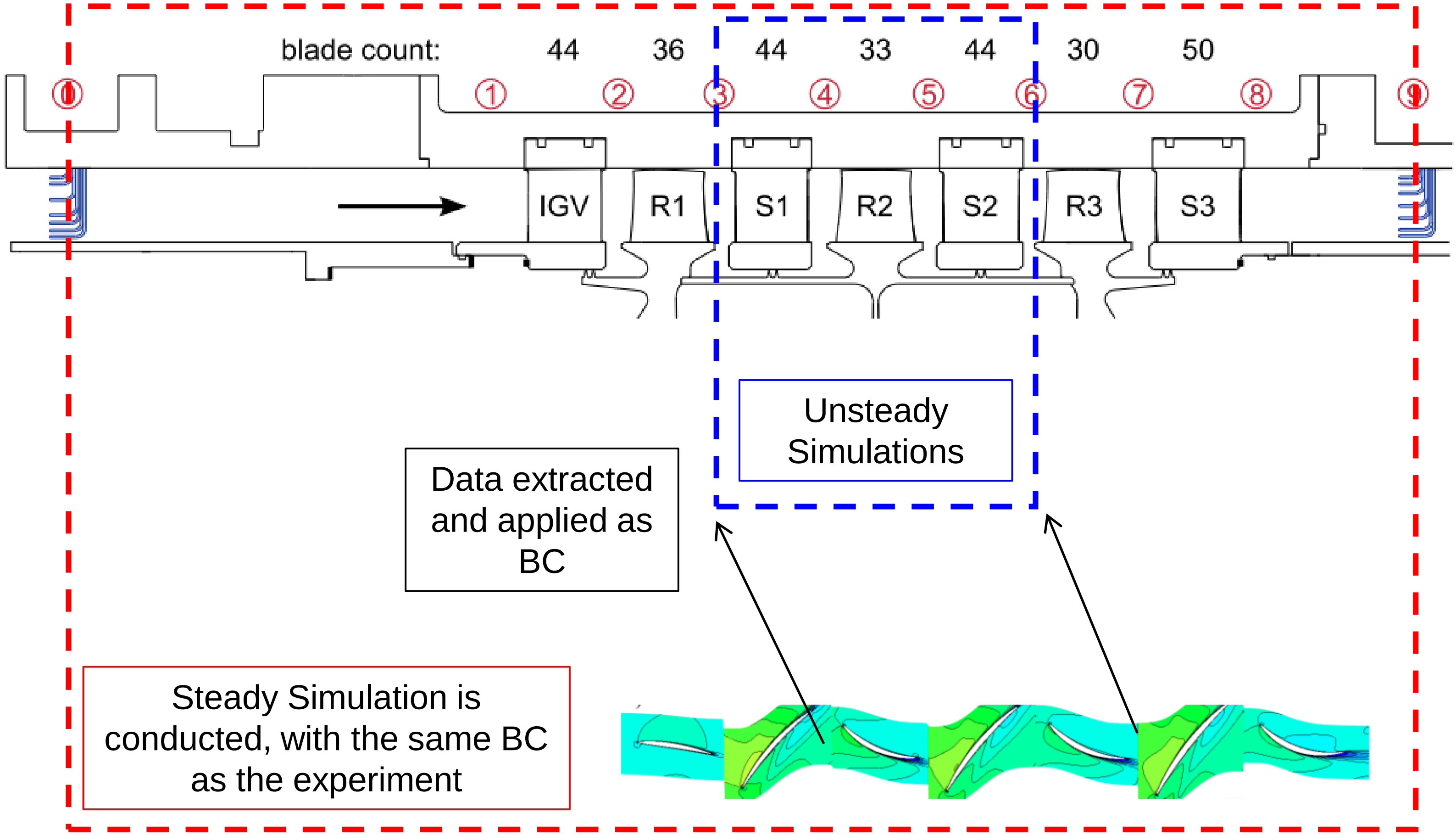
November 2018

Outline

- Forcing Function (Modal Force)
- Damping Study
  - Aerodynamic (Mistuned Eigenvalues)
  - Hysteretic
- Mistuned Response

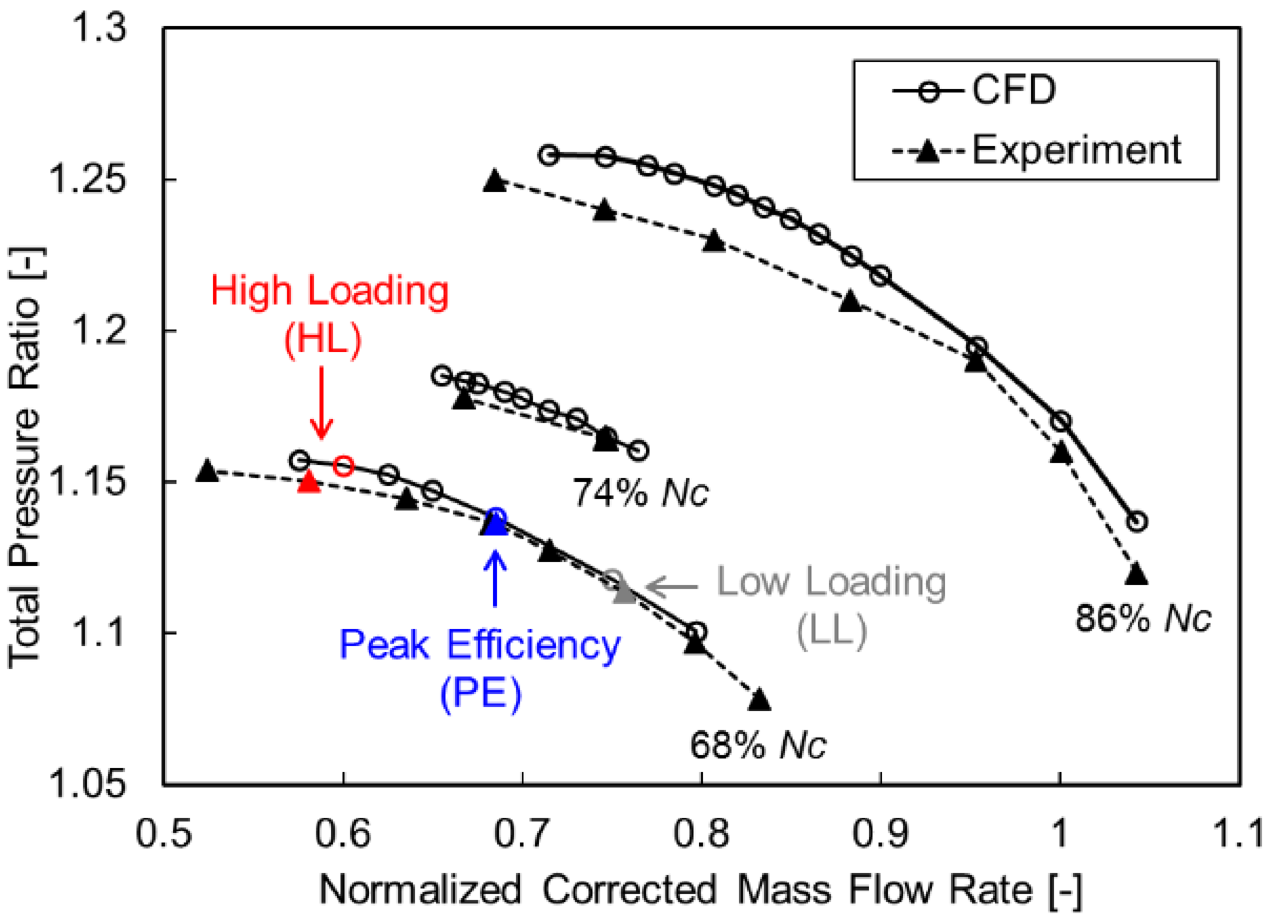
Why do we care? SAFETY

Kegworth Disaster



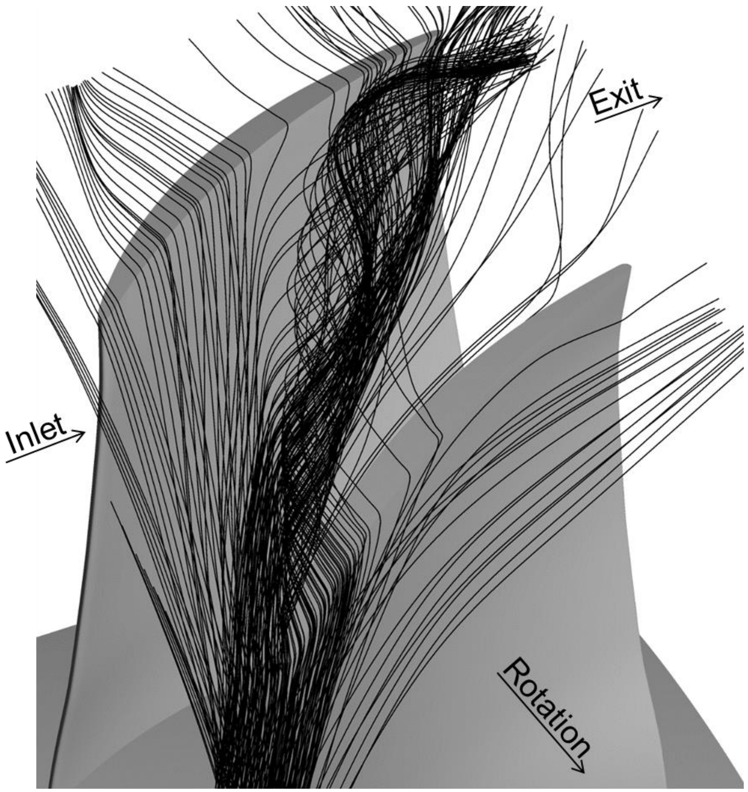
- The foundation of a good unsteady solution is a good time averaged solution.
- Full compressor time averaged simulation is conducted to determine the boundary conditions for the unsteady simulations.

Compressor Map

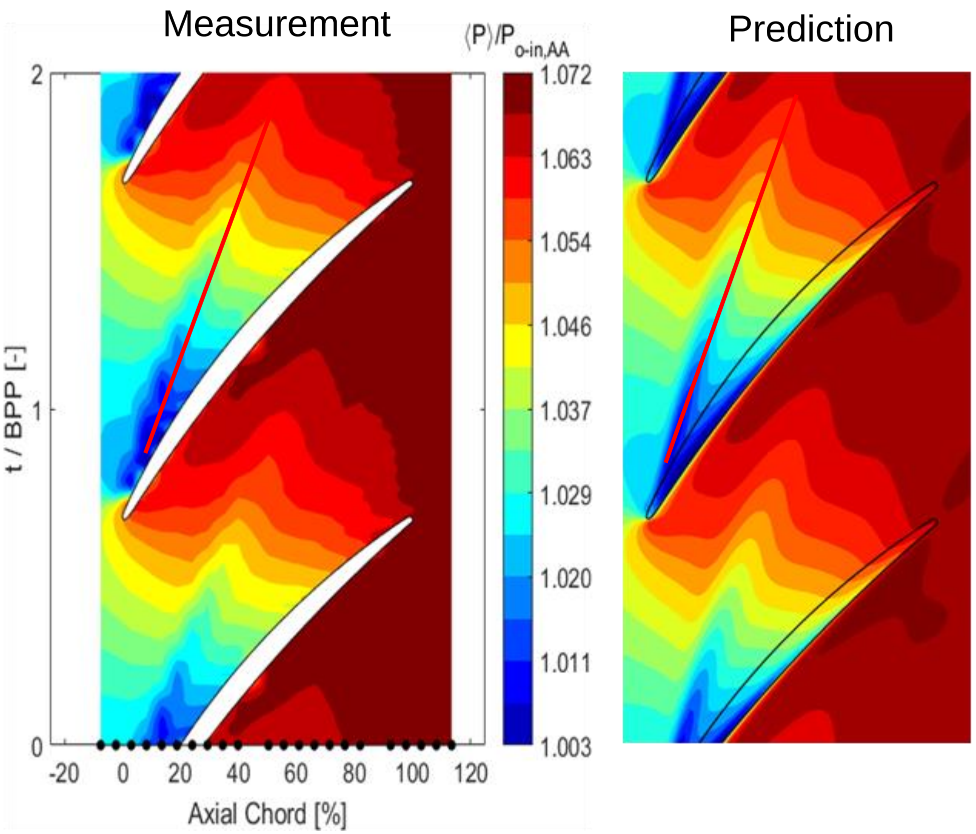


- Compressor time averaged loading is very well predicted.

Time-Averaged Aerodynamics in the Rotor



Rotor tip leakage flow

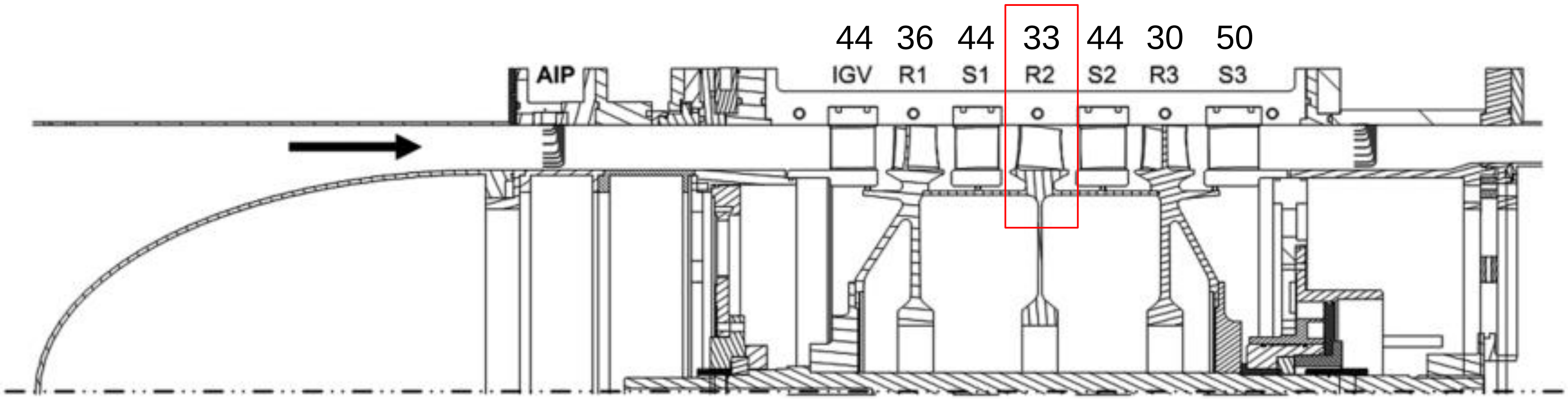


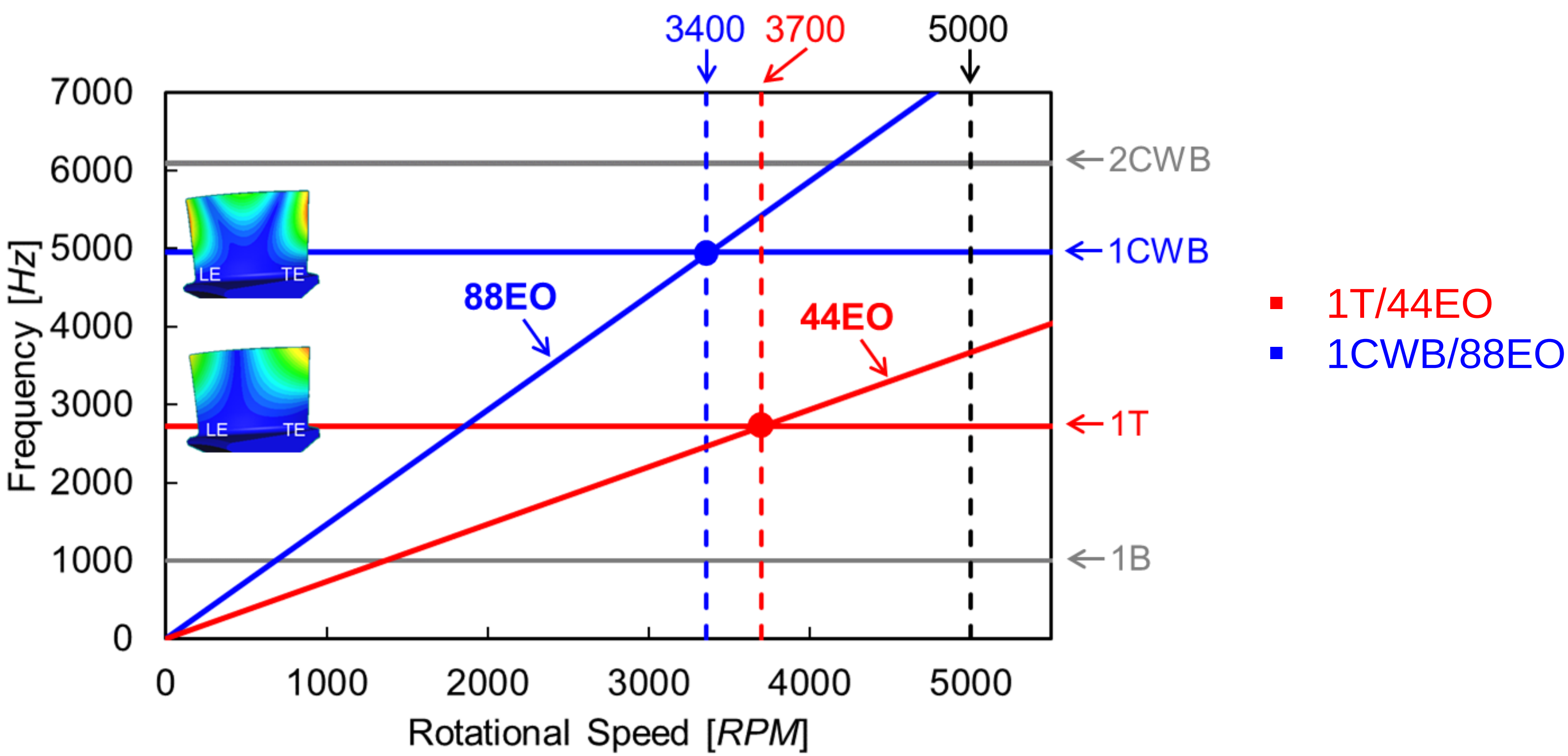
R2 casing time-averaged static pressure field (HL). Black dots show the positions of functional Kulites.

- Both value and trajectory of tip leakage flow are very well predicted.

*Purdue GUIde 5 Report, 2016 Q2

Purdue 3-Stage Research Compressor, Old S1





Roadmap of Simulations

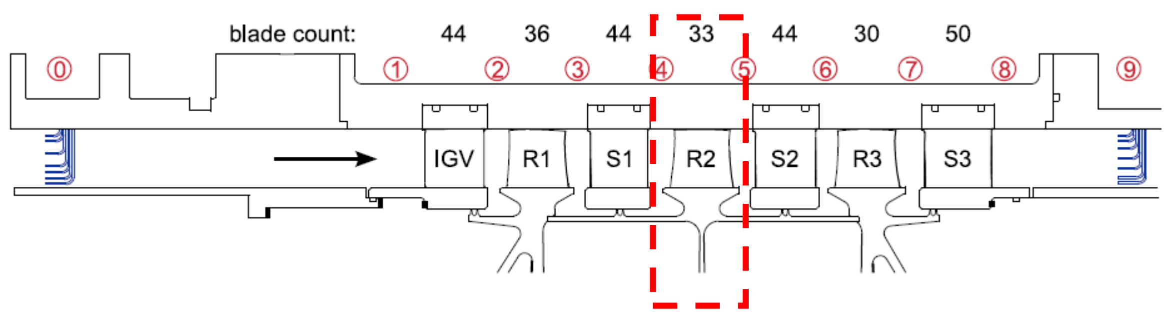
1990's

	Simulation Roadmap	Comments/Purposes
1)	Stator Frozen Gust / Rotor	Industrial standard
2)	Stator / Rotor	Ignore downstream stator
3)	Stator / Rotor + Rotor / Stator	Poor approximation to 4) Strong S-S interaction
4)	Stator / Rotor / Stator	S-S interaction; industrial applicable
5)	Rotor / Stator / Rotor / Stator	R-R interaction
6)	Stator / Rotor / Stator / Rotor / Stator	Influence of the IGV further upstream
7)	Stator / Rotor / Stator / Rotor	Address physical wave reflections
8)	… / Rotor / Stator / Rotor / Stator / Rotor / …	Full compressor simulation

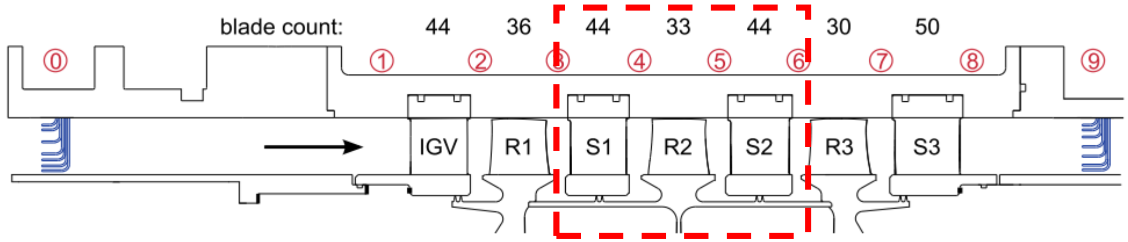
Industry ?

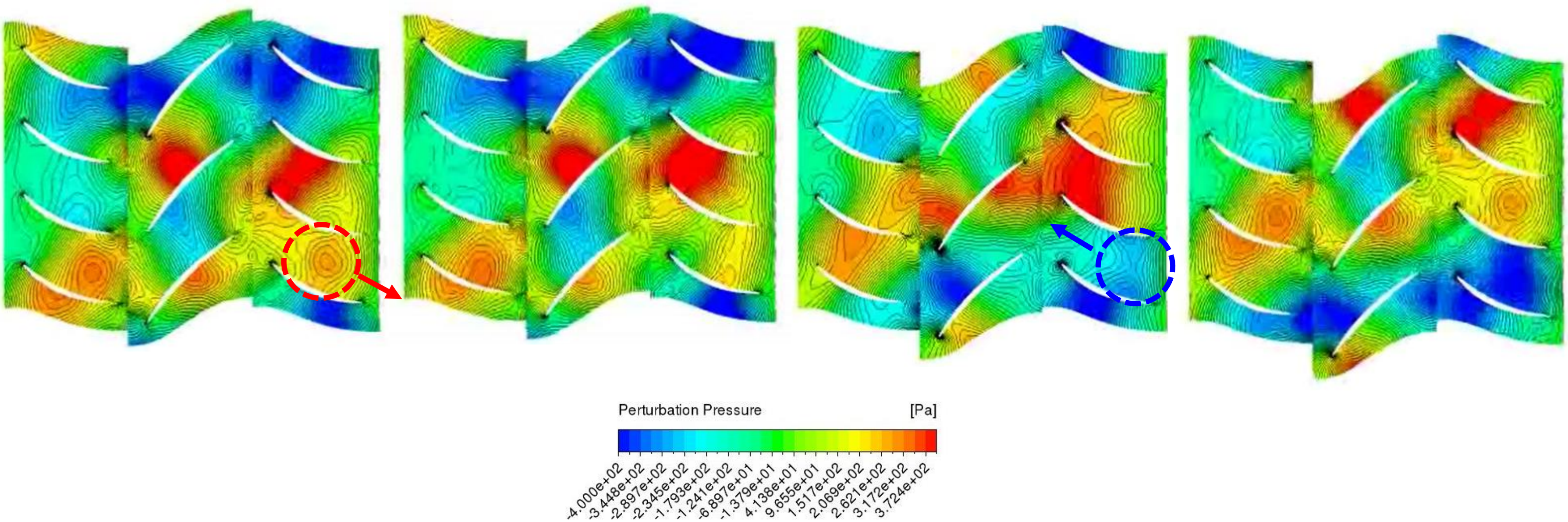
Academia

Higher computational cost



Wave Reflections from the Reflecting BCs



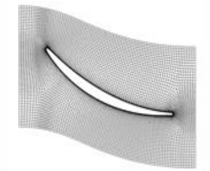


Perturbation pressure sequence of the short domain simulation. The wave marked in red is moving downstream and the one in blue is moving upstream.

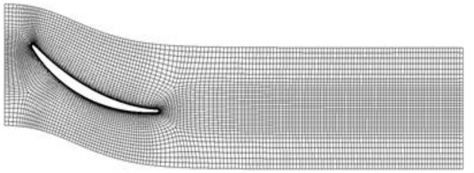
- Spurious wave reflections are seen at the exit boundary.

Extended Inlet and Exit

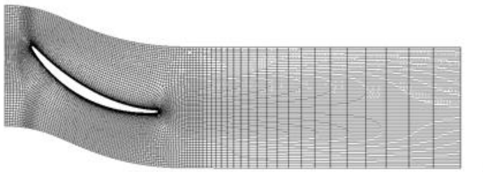
- Extend the R2 domain further downstream to reduce reflection.



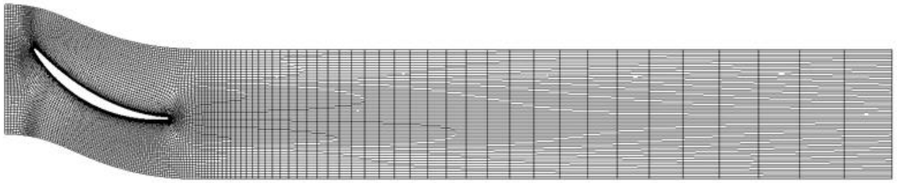
Short domain



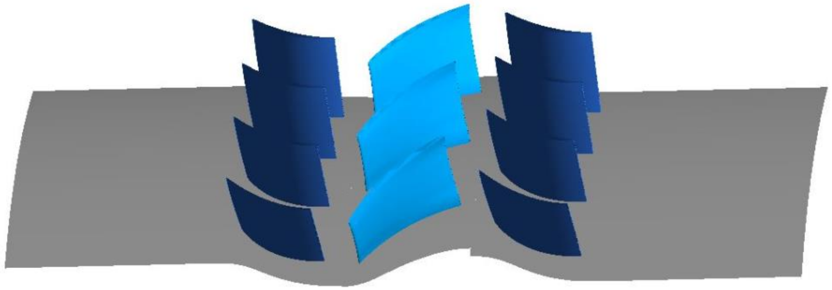
Extended domain, uniform mesh



Extended domain, inflated mesh



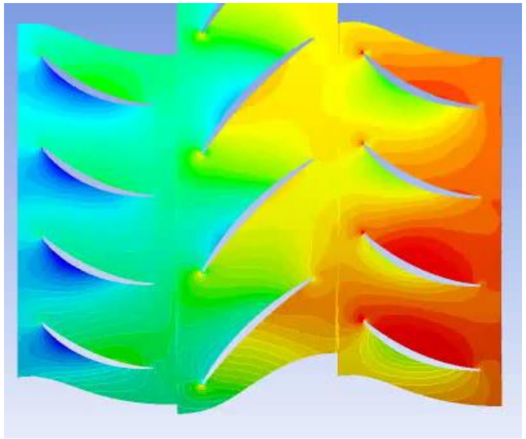
Double extended domain, inflated mesh



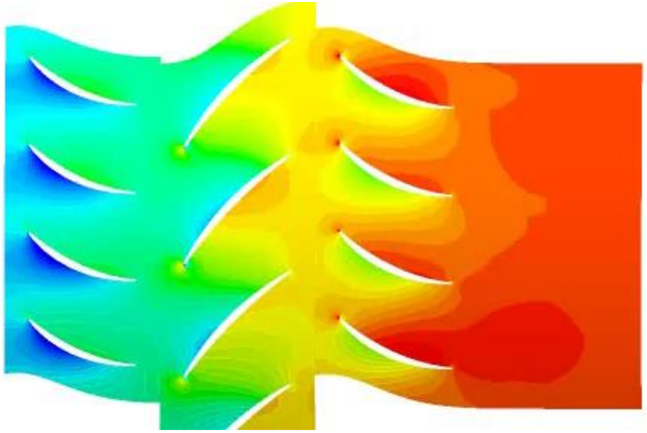
Model used for domain extension

Domain Extension Study

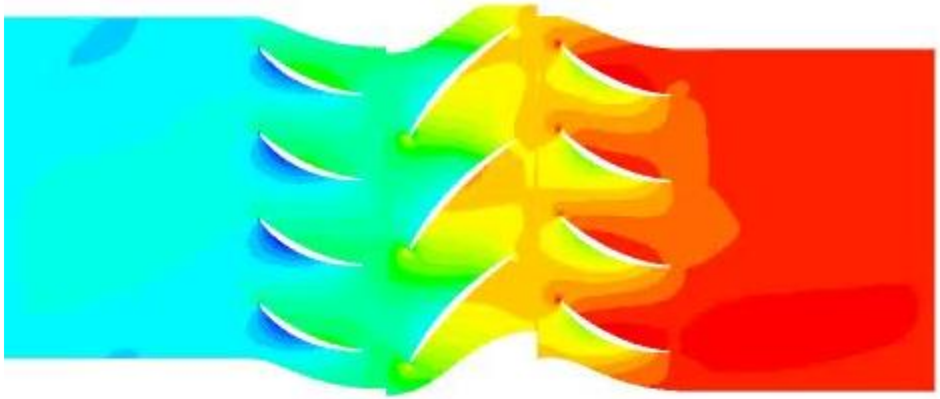
- 50% Span Pressure Animation



S1/R2/S2



S1/R2/S2 with extension (uniform mesh, S2 extended only)

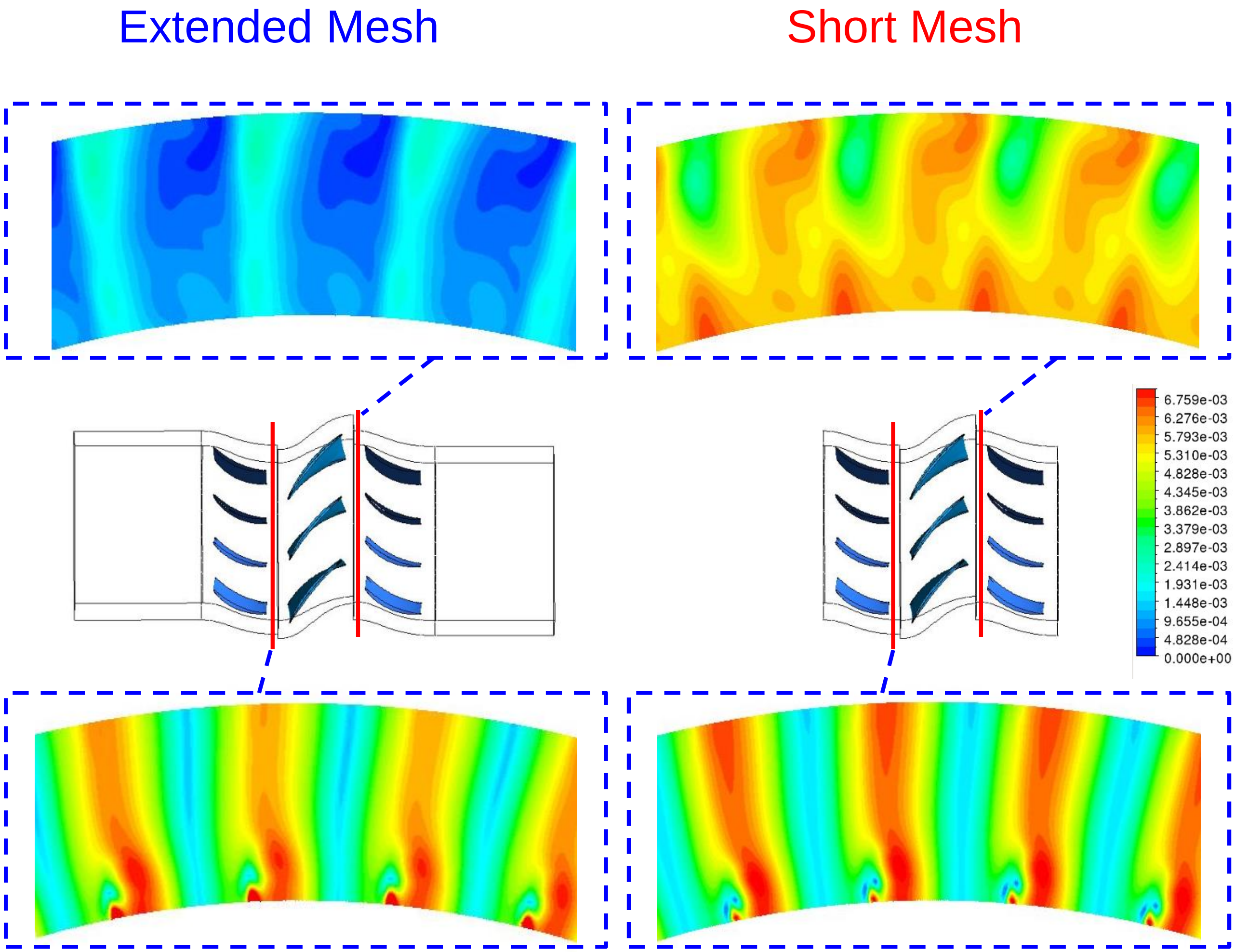


S1/R2/S2 with extension (inflated mesh)

- Reflecting wave is highly reduced by extending the domain with inflated mesh.

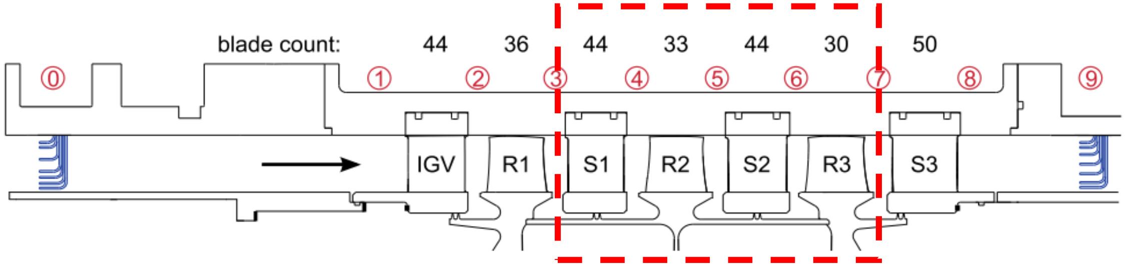
Domain Extension Study

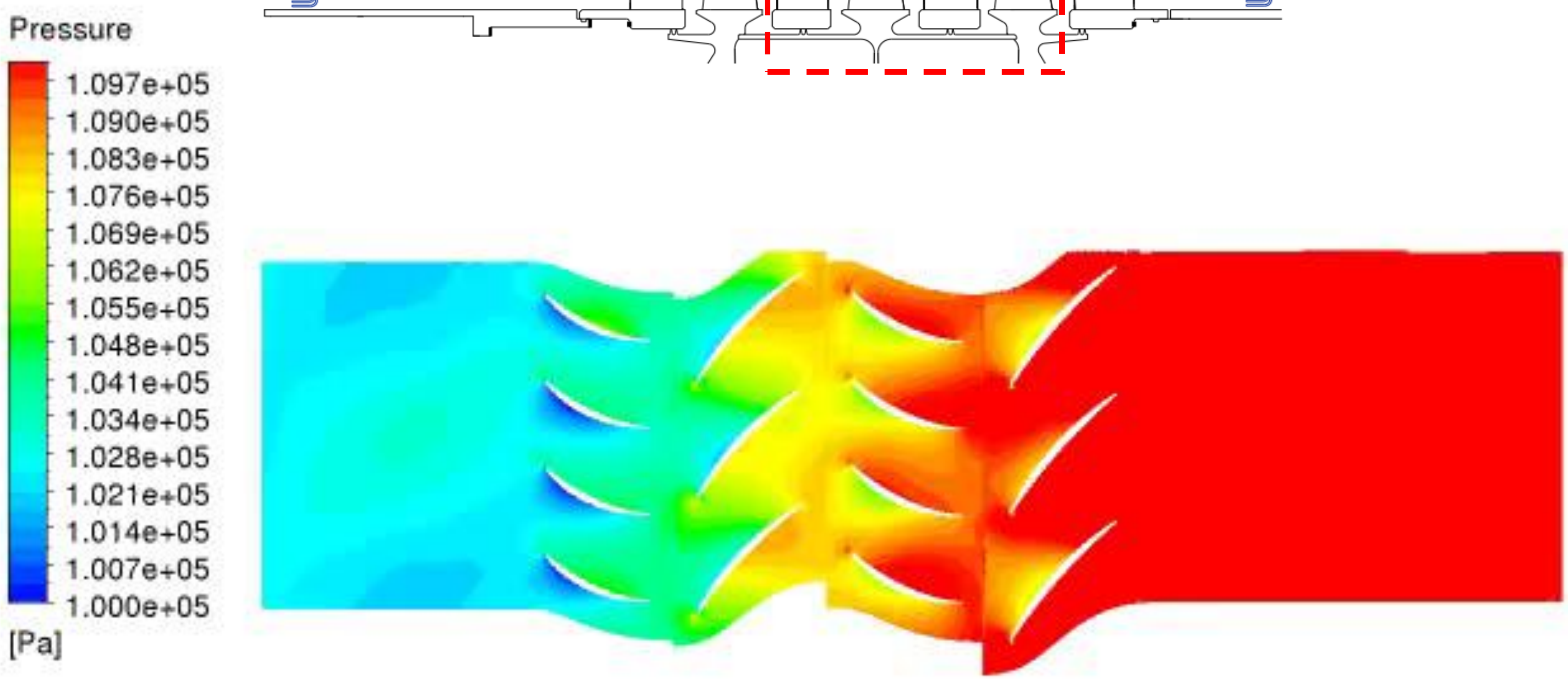
- Comparison of unsteady pressure level.



- Unsteady pressure level from downstream decreases significantly when using the extended domain.

Physical Wave Reflections from R3

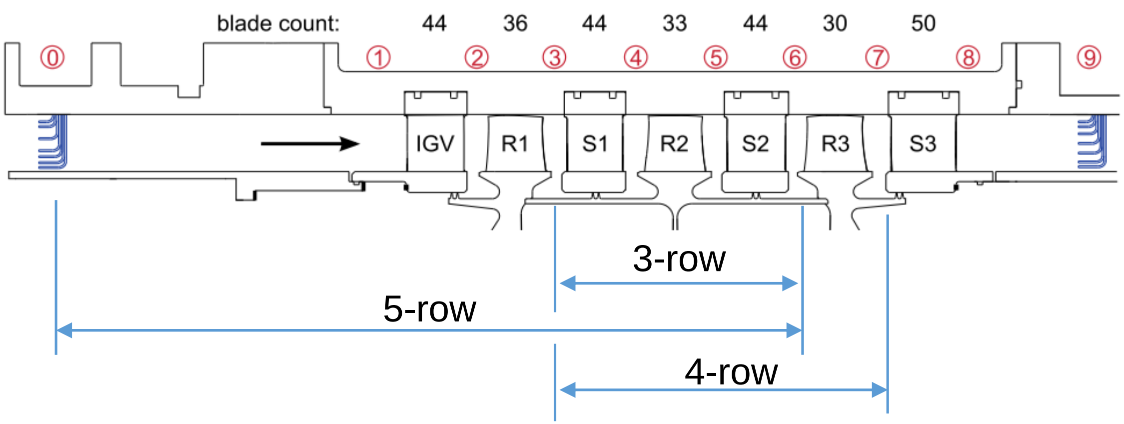




- The reflection from R3 is signification and results in a destructive interference

Resulting Modal Force, 1T-44EO

Case label	Case explanation	Resulting modal force, normalized by experimental data*
	Experiment	1
a	3-row, no extension	1.85
b	3-row, extended domain, uniform mesh	1.71
c	3-row, extended domain, inflated mesh	1.25
d	3-row, double extended domain, inflated mesh	1.24
e	5-row, extended domain, inflated mesh	1.18
f	4-row, extended domain, inflated mesh	0.90



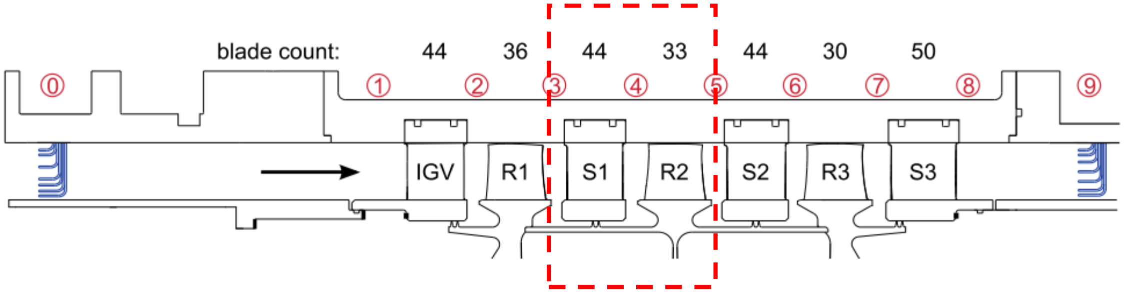
- Experiment modal force was identified from tip timing data by using system ID method.
- The modal force is 10% low, and the mistuned response is about 12-15% low.

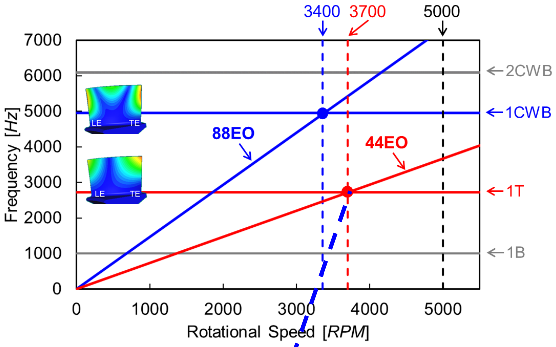
* Based on the most recent experimental data, calculated conservatively by using the peak with the most discrepancies.

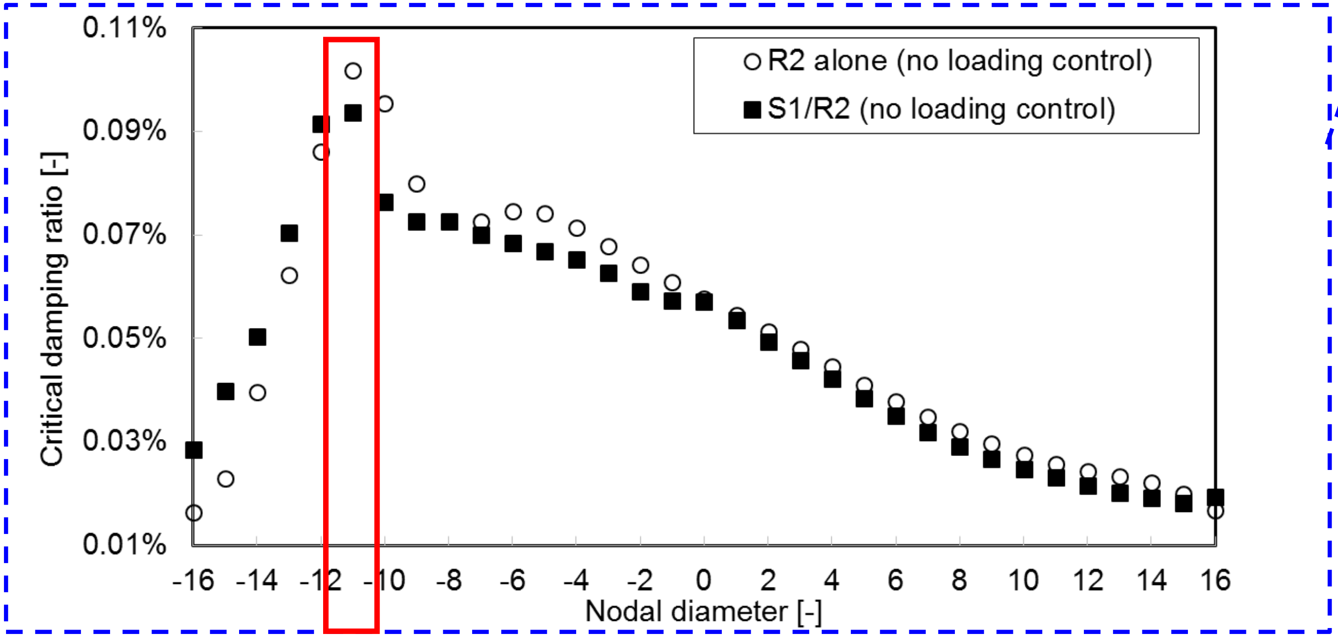
Summary, Findings in the Forcing Function Study

- Domain Extension
  - Reflection from exit plane does influence unsteady pressure and modal force.
  - Inlet and exit extension with inflated mesh can effectively reduce reflection and increase the accuracy of modal force prediction.
- Influence of IGV Wake
  - IGV wake has a week interact with S1.
  - When the IGV is included, the modal force prediction improves, but the computation cost increases drastically.
- R3 Wave Reflections
  - R3 refection interacts with S1 and S2 forcing function, and the value is significant.
  - This R3 reflection has a destructive interference and reduces the modal force.
- Linear superposition
  - Superposition does not hold (combining 2 2-row FR results linearly can not obtain a 3-row FR result).

Multi-row vs. Single-row Tuned Damping (1T)







- Limited differences in damping are observed between single-row and multi-row analysis

Damping: Mistuned Prediction and SDOF Curve Fit

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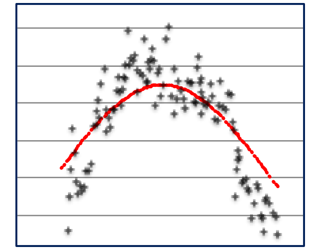
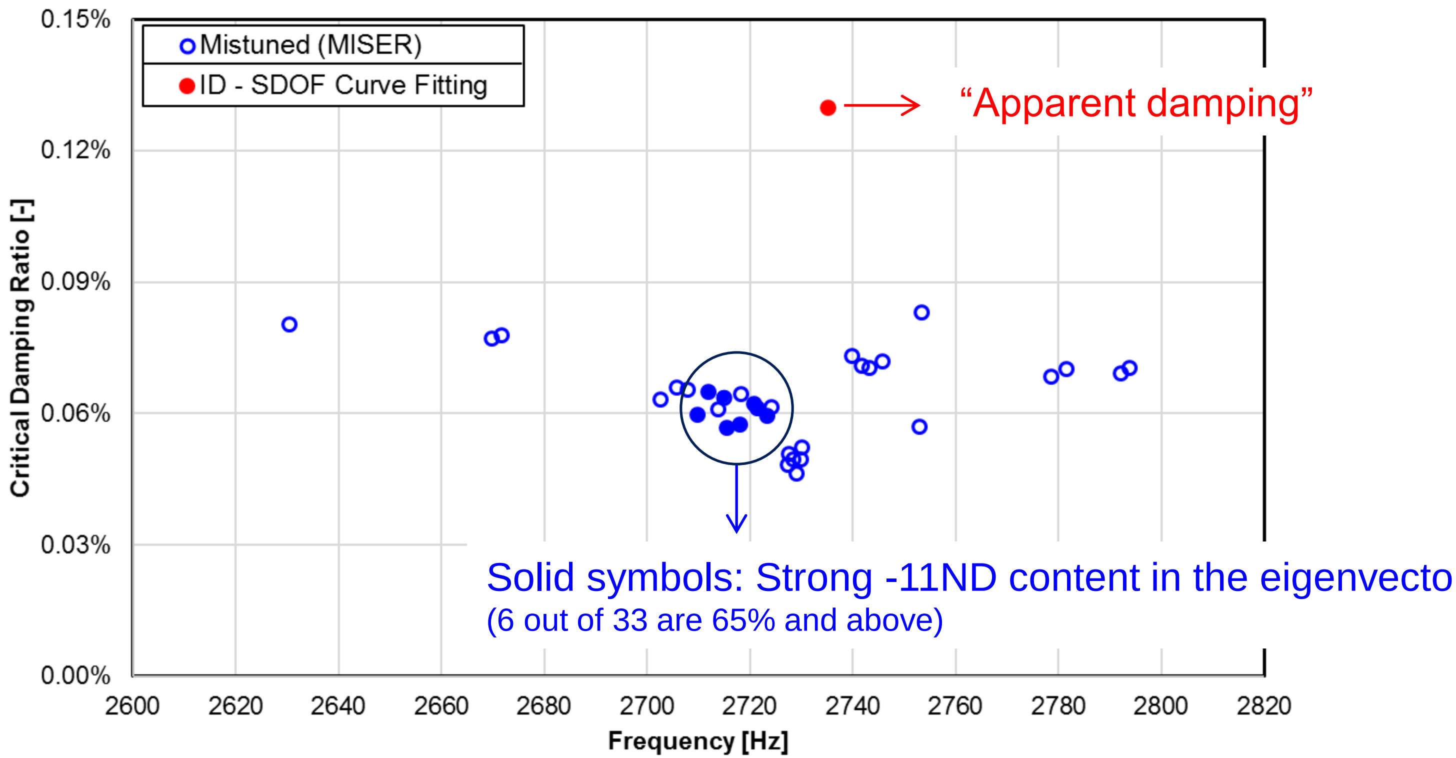
Mistuned eigenvalues prediction:

- MISER: FMM, both structural and aerodynamic coupling are considered

Identifying damping from experimental tip-timing data:

- SDOF curve fitting: Pick a clean SDOF-like peak and fit a SDOF FRF;
- The identified damping is the “apparent damping”.



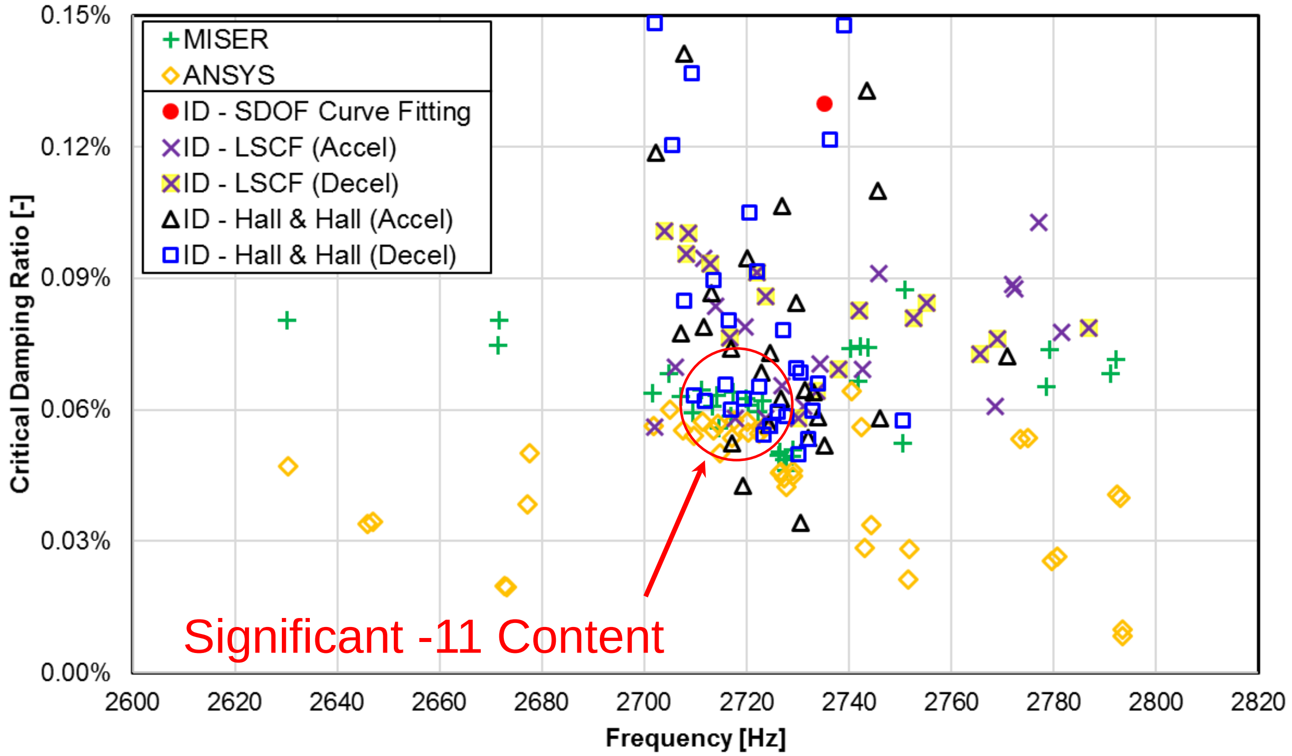


- Efforts to achieve improvement of both prediction and ID of mistuned eigenvalues.

Damping: Prediction and System ID – Summary

Mistuned eigenvalue prediction and ID:

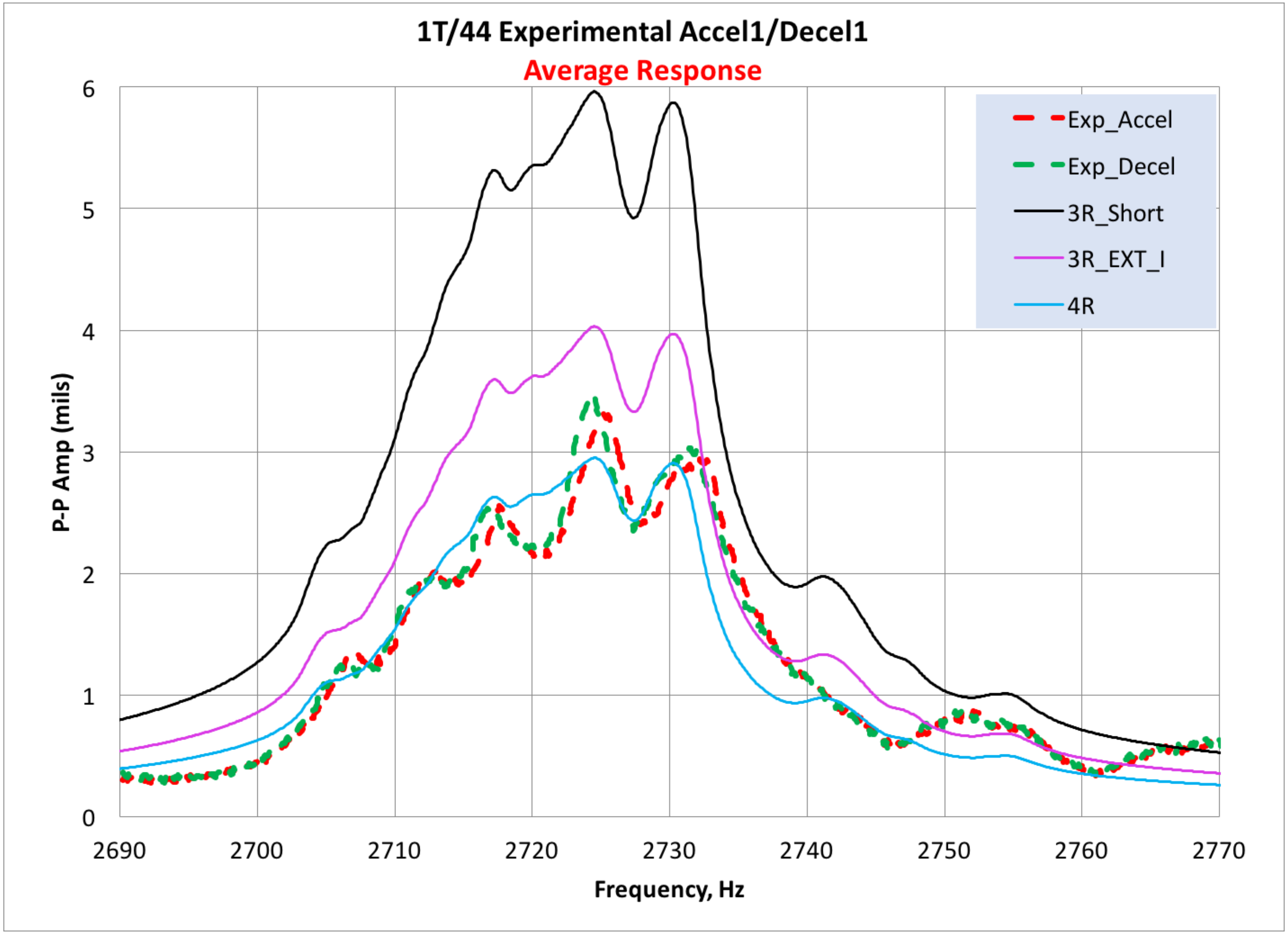
- Curve fitting does not give accurate prediction
- MISER, ANSYS, LSCF have very good agreement on the prediction of the complex eigenmodes containing significant -11ND content



Summary, Findings in the Damping Study

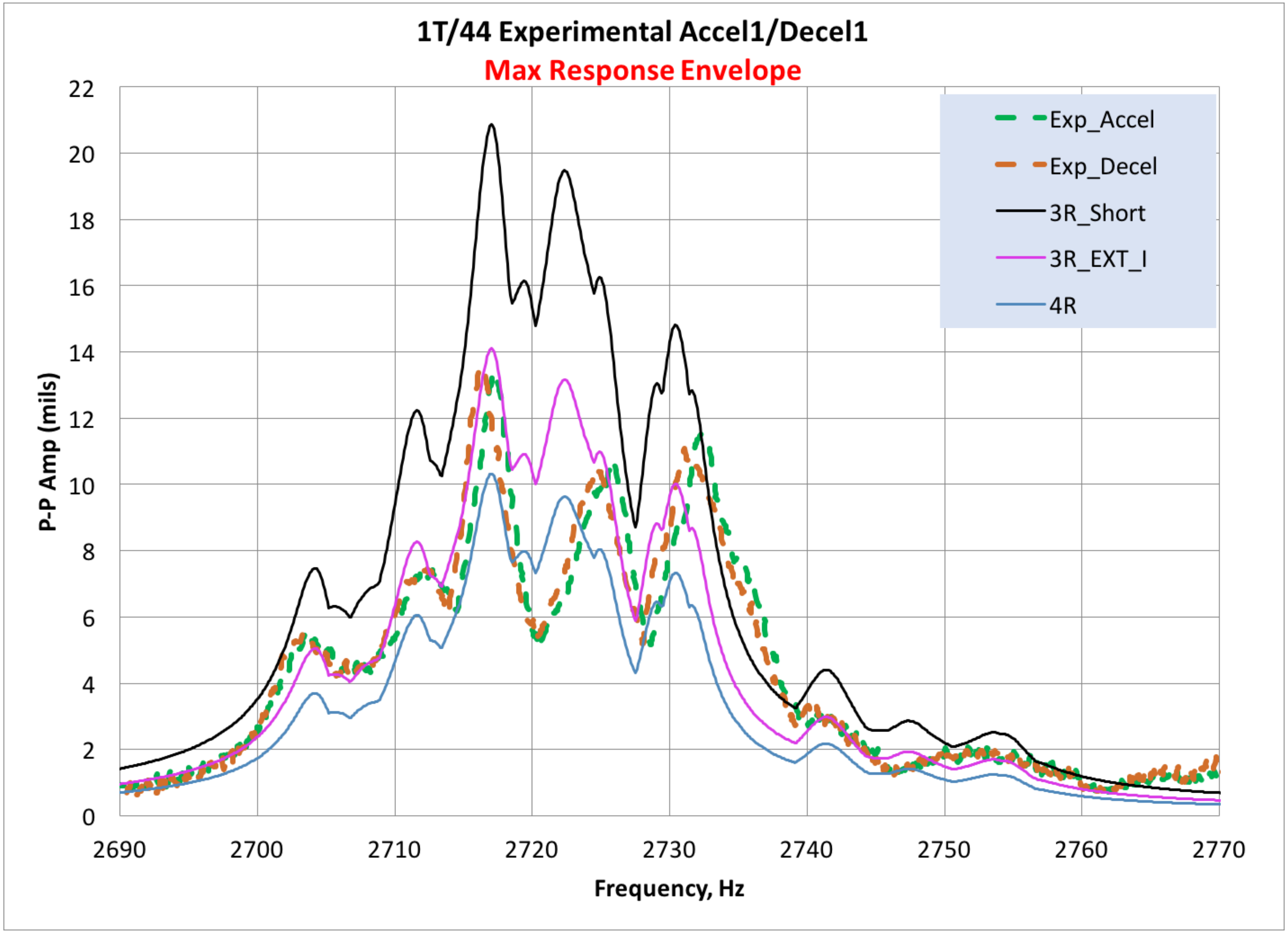
- Single-row vs. multi-row
  - Single row gives sufficient accuracy of damping prediction. There is a minor difference between the single-row and multi-row simulation for the damping prediction.
- Linearity of damping
  - the linearity between damping and vibration amplitude holds until a fairly large vibration.
- Eigenvalue prediction
  - NSMS data can be used to identify aeroelastic properties of the system.
  - The system ID tools and MISER have an good agreement on the eigenvalue prediction.
  - SDOF curve fitting results are twice that of System ID and computational values.

Mistuned Response (FRF) Average of all Blades



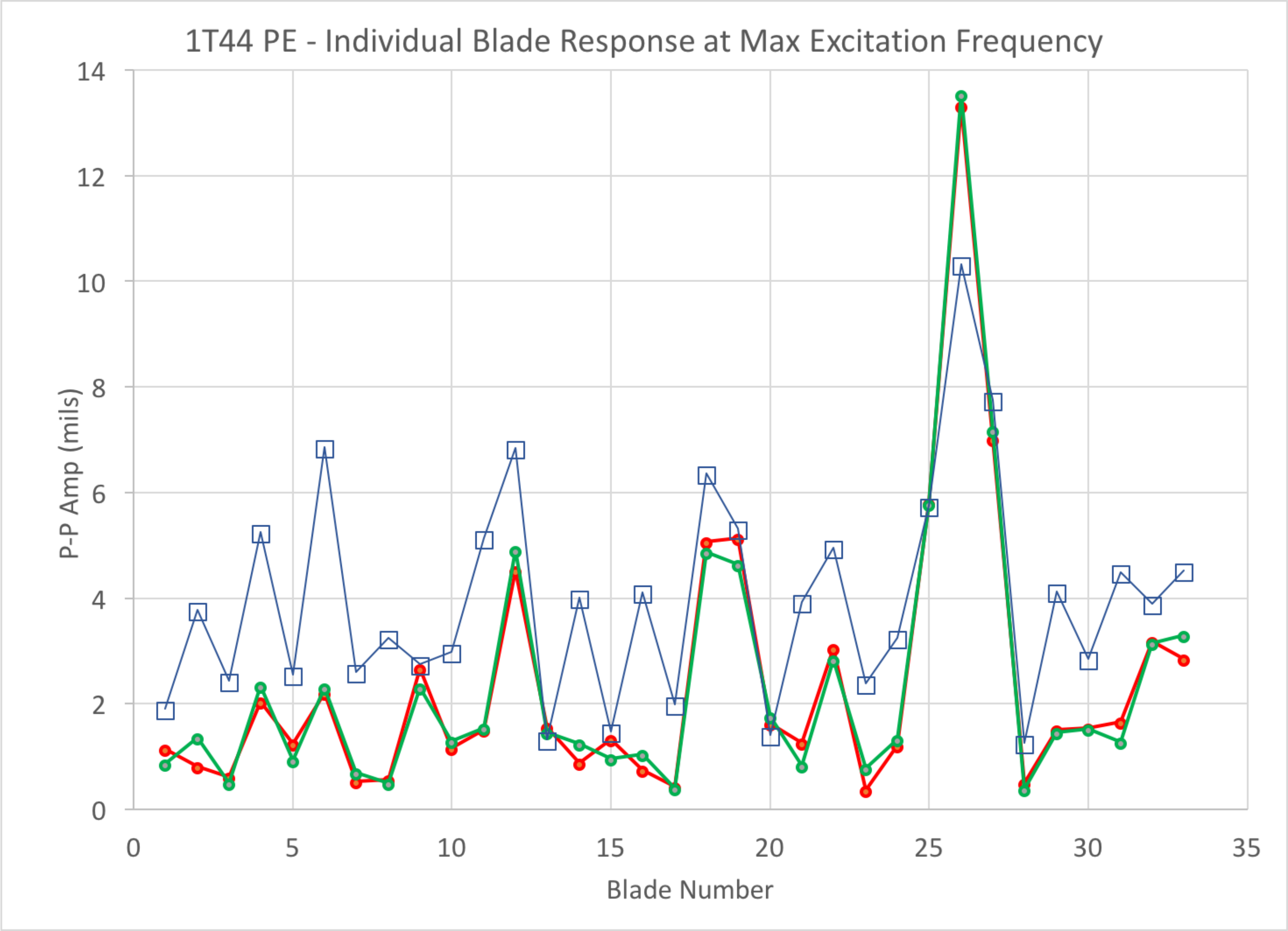
- The average response (maximum) is under predicted by 12%

Mistuned Response (FRF) Maximum of all Blades



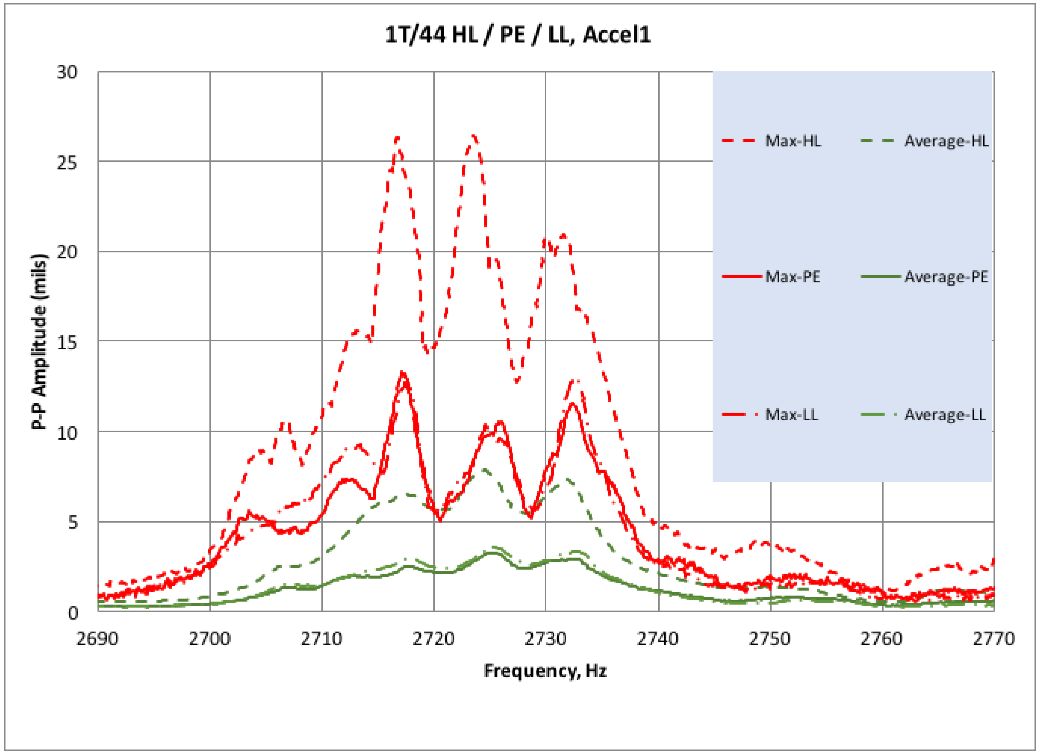
- The maximum response is under predicted by 23%

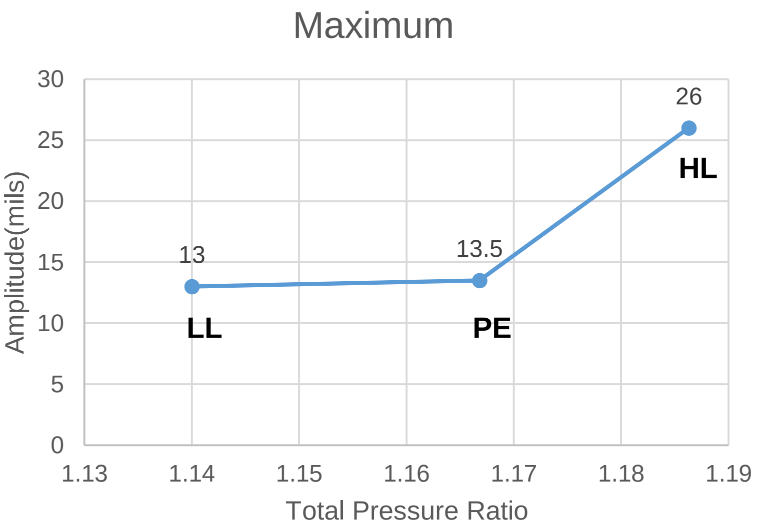
Mistuned Response of all Blades at Maximum Excitation Frequency

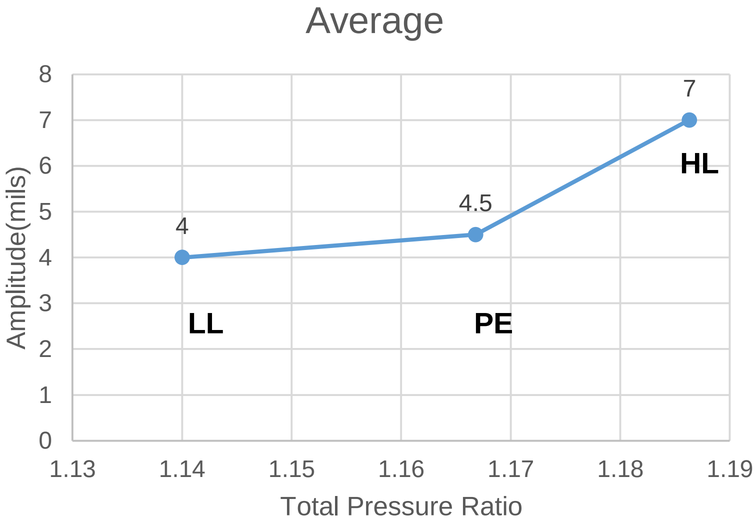


- The maximum response is under predicted by 23%
- Computational results have less mode localization

1T/44: Corrected Data, PE / HL / LL







- A non-linear pattern is observed between pressure ratio and vibration amplitude.
- Will be studied computationally in G6.

Summary, Mistuned Response

- Modal force
  - Average response is a good indicator of modal force, and there is an underprediction of 12%.
- Mistuning amplification factor
  - Underprediction of mistuning amplification factor of 11%.
  - The resulting max response is underpredicted by 23%.
- Non-linear pattern
  - A non-linear pattern is observed between loading and vibration amplitude.

Summary of Findings

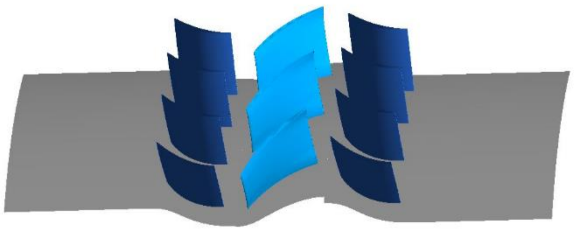
- Forcing Function Study
  - Inlet and exit extension with inflated mesh can effectively reduce spurious reflections and increase the accuracy of modal force prediction.
  - The 4-row case which includes physical wave reflections from the downstream rotor underpredicts the modal force by 12%.
  - Superposition does not hold when combining 2 2-row FR results linearly can not obtain a 3-row FR result.
- Damping Study
  - Single and 2-row simulations provide good prediction for aerodynamic damping.
  - Complex eigenvalues obtained in computations show good agreement with experimental data (system ID) .
  - Linearity between damping and vibration amplitude holds.
- Mistuning Study
  - Experimental amplification factor approaches the Whitehead Limit.
  - Mistuning amplification factor is underpredicted by 11%.
- Loading Study
  - A non-linear behavior is observed between blade loading and vibration amplitude at both 1T-44EO and 1CWT-88EO


Thank you

Extra Charts

Ansys CFX ---- Time Domain CFD, FR

Steps	Purposes
1) Steady Simulation – Mixing Plane	Obtain the BCs for the unsteady simulation
2) Unsteady Simulations	TT method for Fourier coefficients Obtain converged results for MF calculation
3) Add Modeshapes and User Defined Functions	Modal force calculation UDFs for post processing
4) Post Process Data	Data visualization and extraction



Key Experiences:

- Domain extensions and inflated mesh needed to reduce spurious wave reflections.
- Down stream rows needed to address physical wave reflections.
- Maximum 2 times of TT can be used.

MISER ---- Mistuning Analysis

Input

- **Modal Force**

From CFD simulations

- **Blade Frequencies**

From experiments/FEM simulations

- **Damping**

From CFD simulations and/or from identified properties from experimental data

- **Aerodynamic Mistuning**

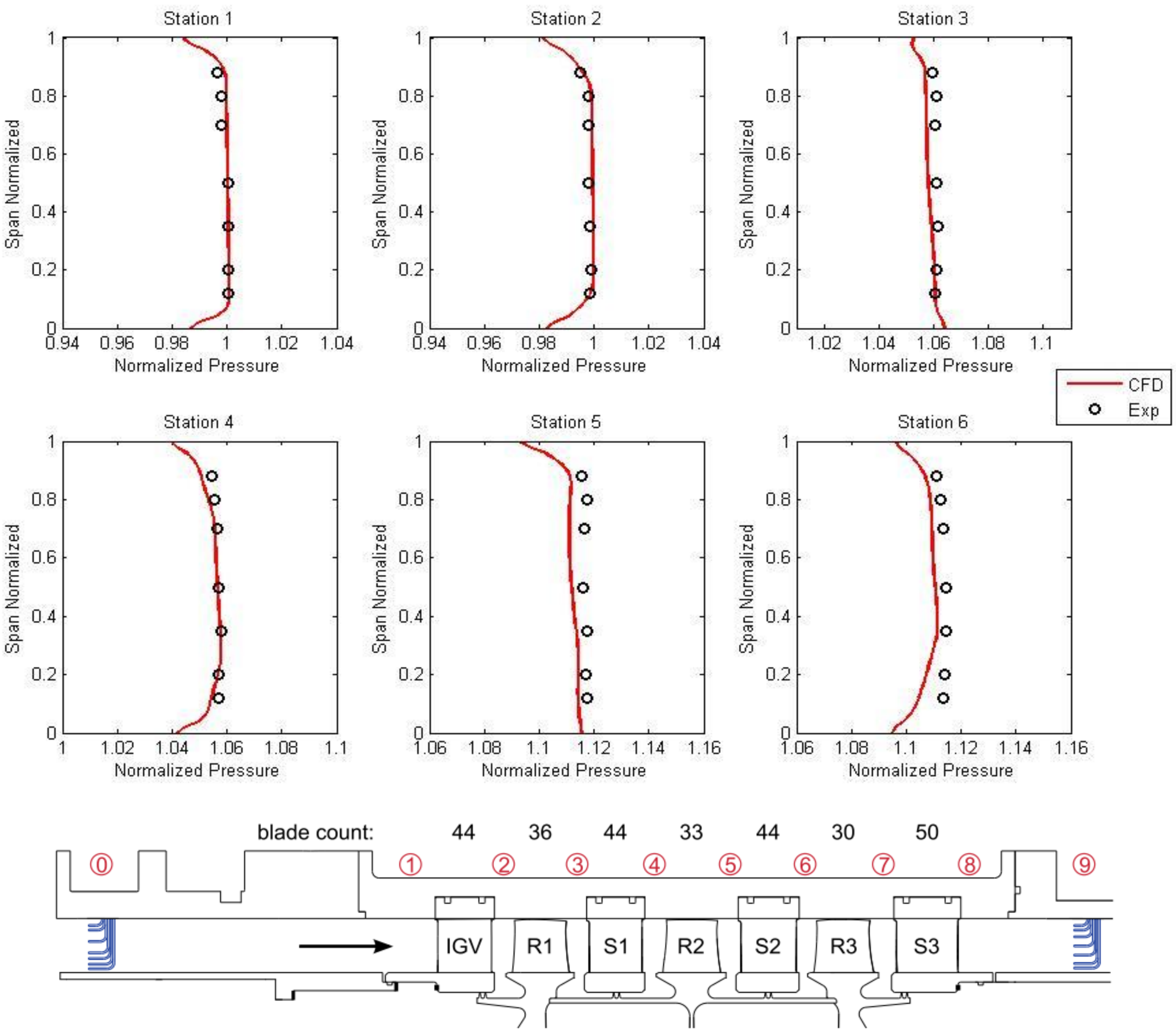
Perturbations of aerodynamics can be assigned

- **Frequency Mistuning**

Both random and deterministic mistuning can be achieved.

- MISER is a fast tool to obtain a decent estimate on the response of the blades with mistuning.

Time-averaged Aerodynamic Results, Total Pressure



Verification of TT Reduced Model – Work in Progress

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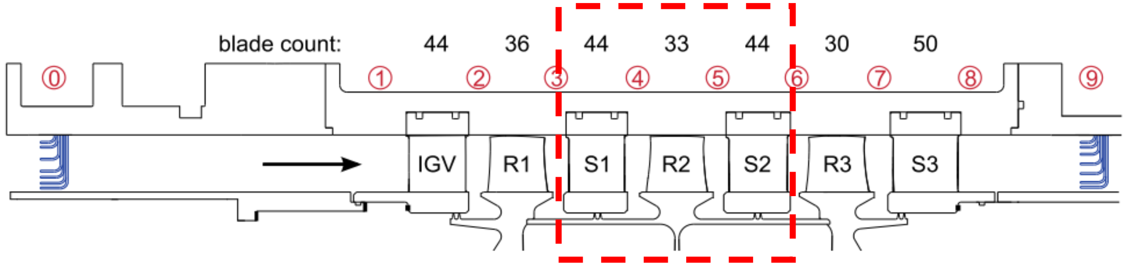


A thin slice at the mid span is used and three rows are included

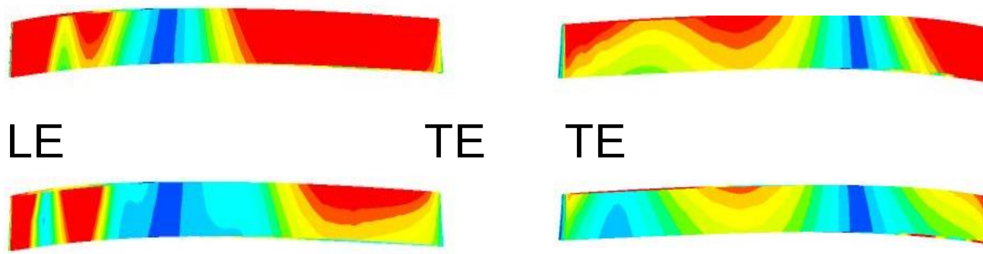
R2 50% Span

PS

SS

Reduced Model, TT

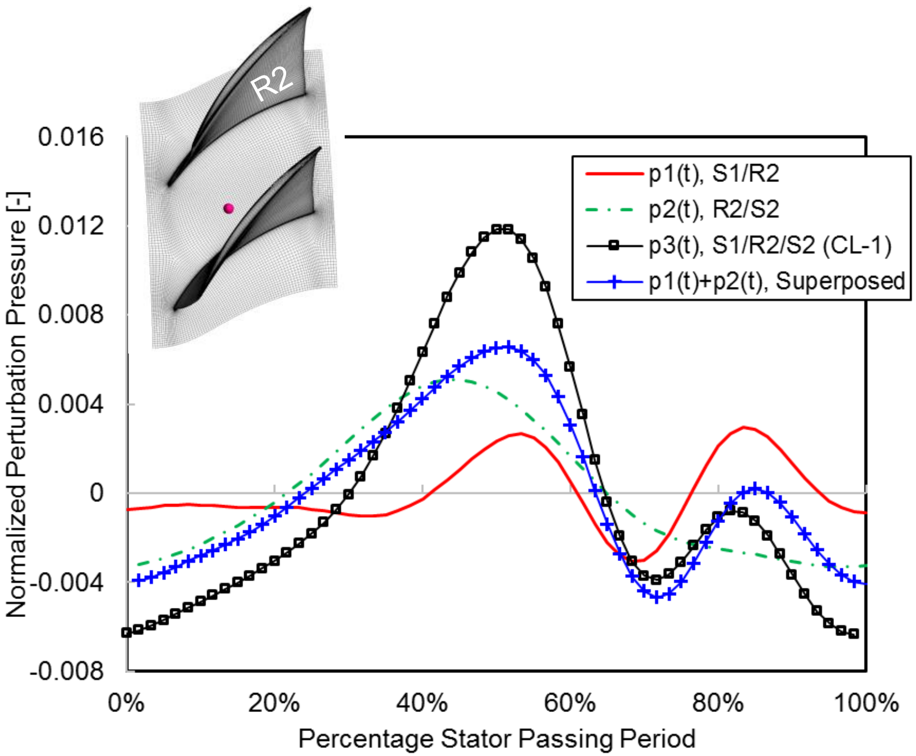
Full Wheel

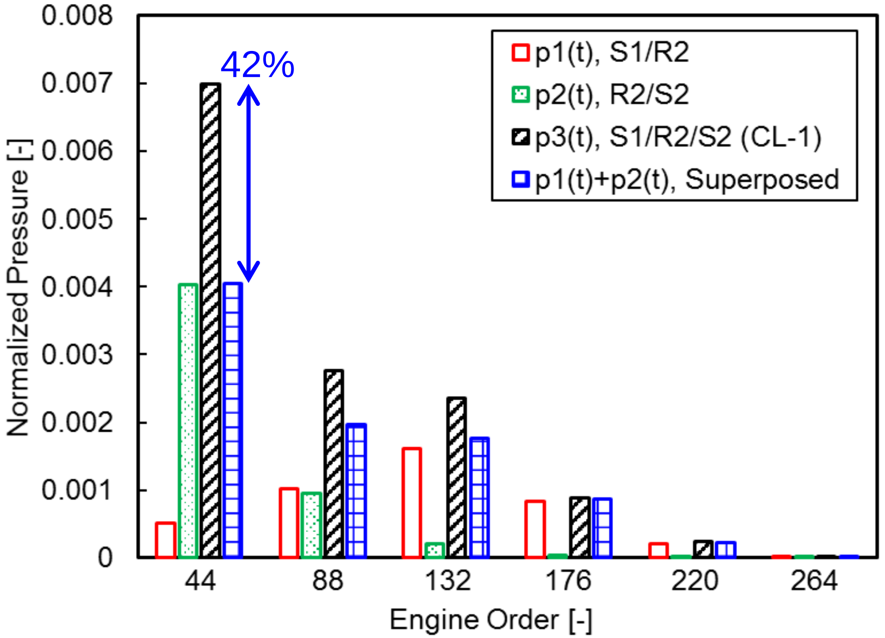


Case	Modal Force [N]	Computation Resource
Reduced model	10.85	~11 units
Full Wheel	10.27	~121 units
Difference	**5.3%**	**~10 times**

- The agreement between the two methods is good.
- Only 5.3% of difference is seen, with a benefit of 10 times of saving on computation resource.
- Preliminary study and will be continued in G6.

Superposing the pressure signals of a monitor point in R2 flow field:

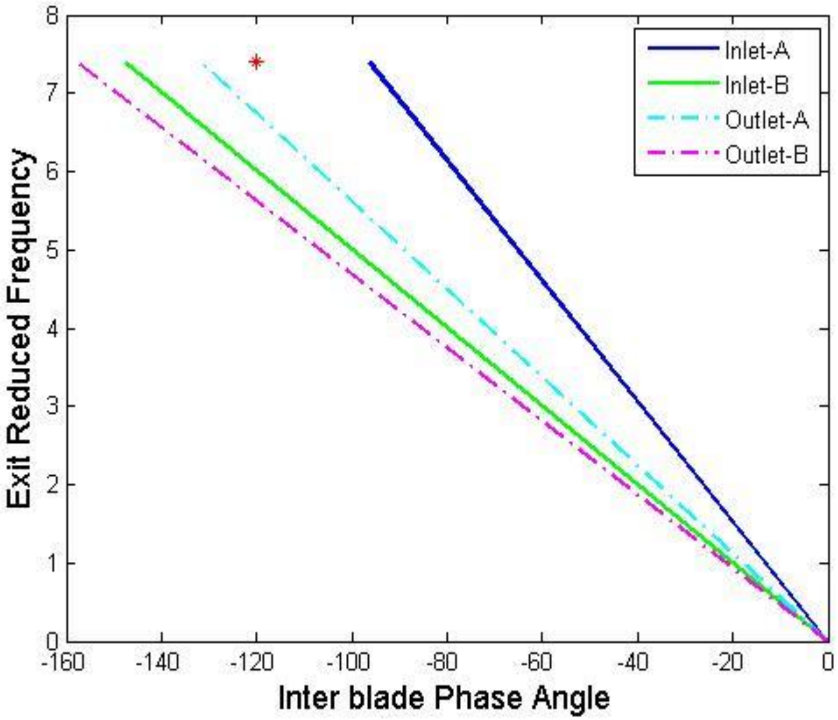




- The superposed solution is in qualitative agreement with the 3-row solution.
- Superposed press is underpredicted by 42% .

S1/R2/S2/R3, Cut-on Wave

$$\left(\frac{\beta_r + 2\pi n}{s/c}\right)^2 + \frac{4M^2}{M^2 - 1} k \left[k + \frac{(\beta_r + 2\pi n)}{s/c} sin\gamma\right] = 0$$



Parameters used for IBPA calculation.

Parameters	Value
V Inlet(m/s)	114.7
V Exit(m/s)	82.01
Mach Number-Inlet	0.3447
Mach Number-Exit	0.2477
Chord-c (m)	0.071
Pitch-s (m)	0.052
Stagger Angle (^{0})	46.2
Reduced Frequency-Inlet	5.3173
Reduced Frequency-Outlet	7.3979

IBPA at the inlet and outlet of the compressor

Location	Inter Blade Phase Angle
Inlet	-96.1 -147.46
Outlet	-131.46 -157.43

- The wave traveling downstream is cut-on. This characteristic constributes to the high reflection value.

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Frequency and ND

Analysis is conducted at a 1T-44EO, frequency in R2 is

$$\omega_{R2} = (B_{IGV}M_{IGV} + B_{s1}M_{s1} + B_{s2}M_{s2} + B_{s3}M_{s3})\ \Omega$$

$$44 * \Omega = (B_{IGV}M_{IGV} + B_{s1}M_{s1} + B_{s2}M_{s2} + B_{s3}M_{s3})\ \Omega$$

Synchronized ND is thus calculated:

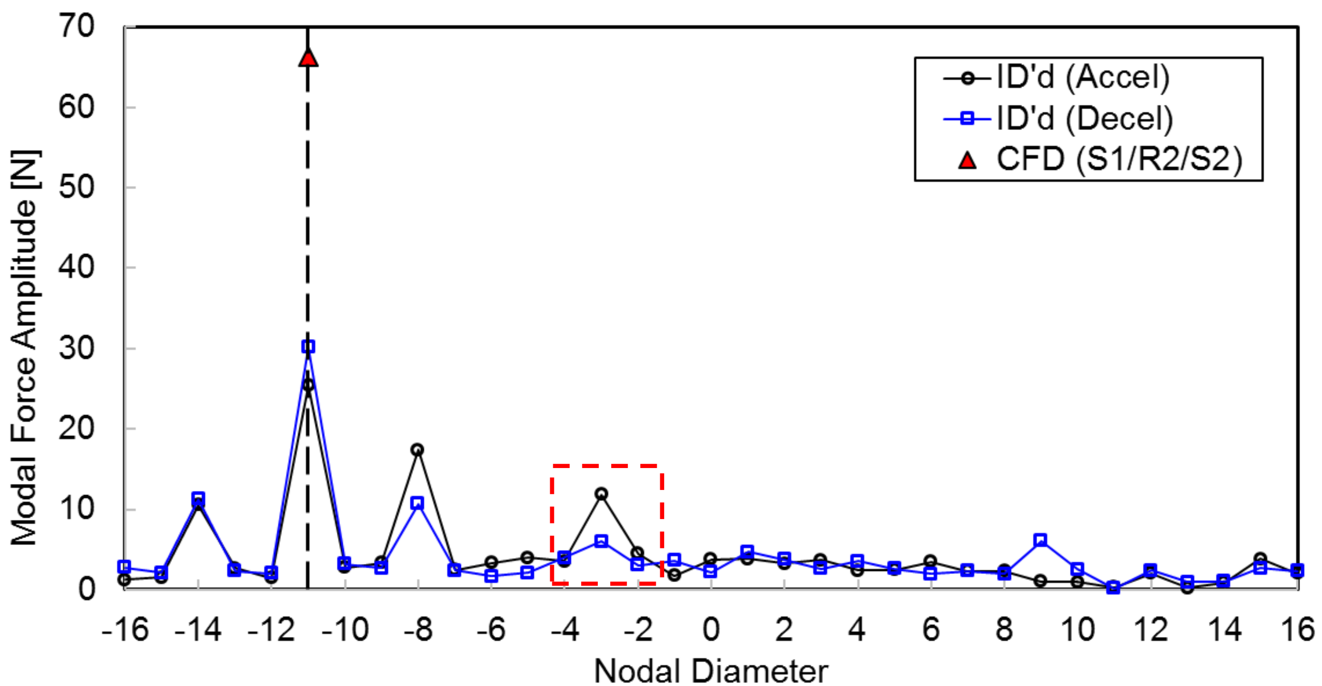
$$ND = (B_{R1}M_{R1} + B_{R2}M_{R2} + B_{R3}M_{R3} + B_{IGV}M_{IGV} + B_{s1}M_{s1} + B_{s2}M_{s2} + B_{s3}M_{s3})$$

$$-11 = -(36 * 0 + 33 * -1 + 30 * 0 + 44)$$

$$-14 = -(36 * 1 + 33 * -2 + 30 * 0 + 44)$$

$$-8 = -(36 * -1 + 33 * 0 + 30 * 0 + 44)$$

-3 -- **Can not be calculated by using synchronized vibration theory**

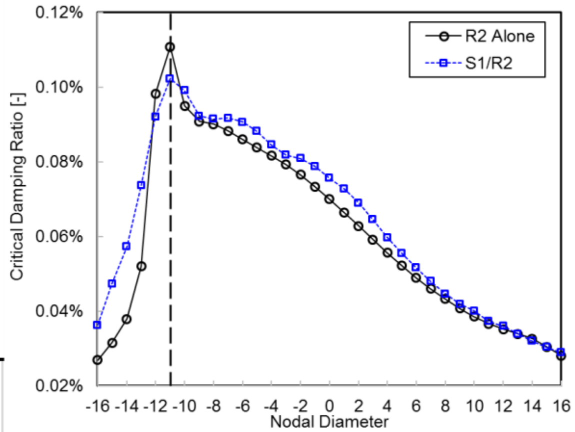


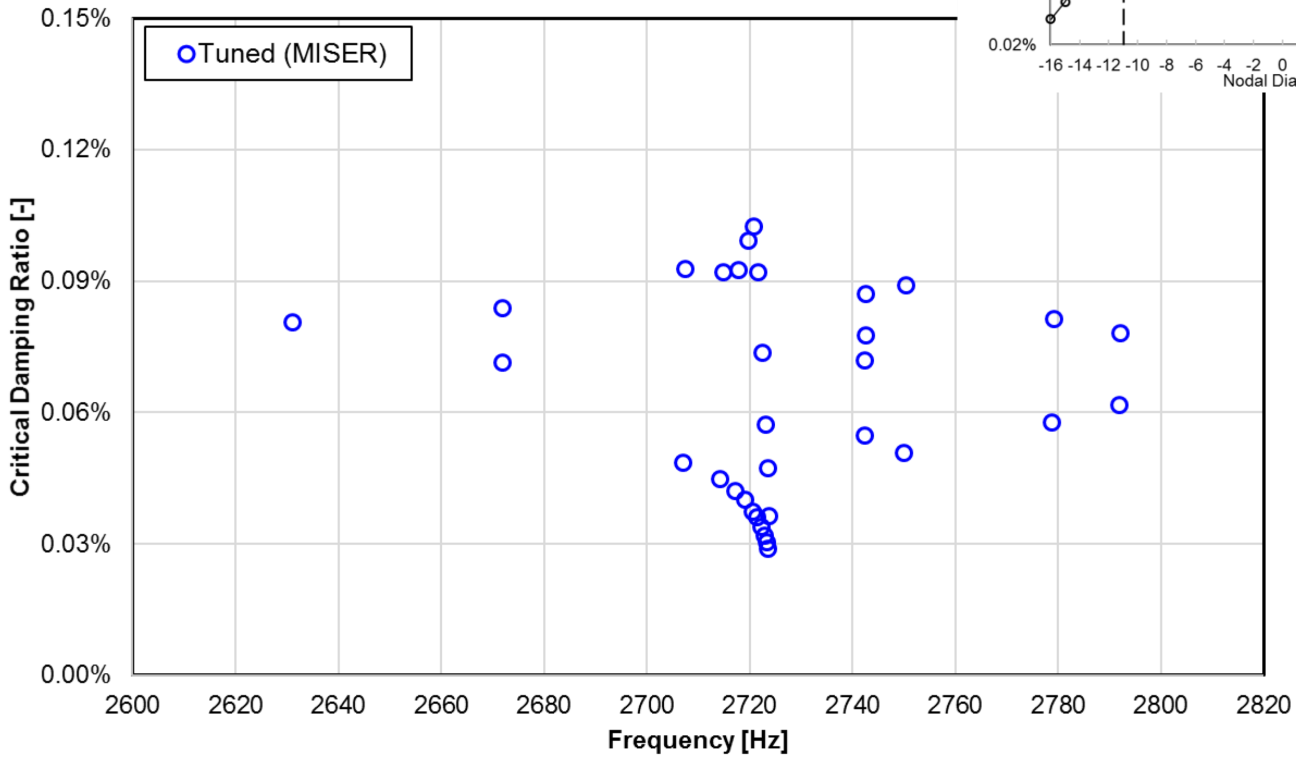
Damping: Prediction and System ID

Tuned eigenvalues prediction:

Damping is considered to include

1) Hysteretic: Estimated to be 0.0072% based on material properties;
2) Aerodynamic: Predicted by MUSTANG 1, S1/R2 configuration.





1T/44EO, PE, Experimental vs. Computational

1T/44 Response, PE, Comparisons (mils P-to-P, tip, near TE)							
1T/44 PE	Experimental			Computational			
	Accel	Decel	Exp Average	4R	Total Error	MF Error	Other Error
Max of Max	13.67	13.19	13.43	10.32	-23.1%	-10.0%	-14.6%
Max of Avg	3.36	3.37	3.365	2.95	-12.3%		
Max/Avg	4.07	3.91	3.99	3.50			
Avg/Tuned	0.68	0.68	0.68	0.68			
Max/Tuned	2.78	2.68	2.73	2.39	-12.3%		