

Hypersonic Boundary Layer Transition and Airframe Noise: Fertile Grounds for Doak's Decomposition?

Meelan Choudhari
NASA Langley Research Center, Hampton, VA

Ohio State University
Columbus, OH, May 15, 2017



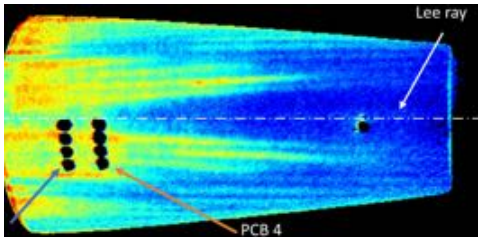
Secondary Instability of Crossflow Disturbances in Hypersonic Boundary Layers

Meelan Choudhari, Fei Li, and Pedro Paredes
NASA Langley Research Center, Hampton, VA
Lian Duan
Missouri University of Science and Technology, Rolla, MO

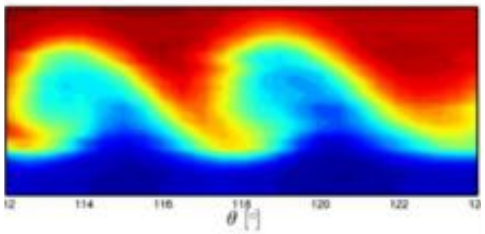
NATO STO AVT-240 & RTG-082 Working Group Meeting
Hypersonic Boundary-Layer Transition Prediction
Tullahoma, TN, April 10-11, 2017

Measurements on 7° Cone, AoA ≈ 6°

- **Purdue BAMQT data** (Schneider, Ward, Edelman,…)
  - **Multiple peaks: 100 kHz to 400+ kHz**
  - **Secondary instability of stationary crossflow?**



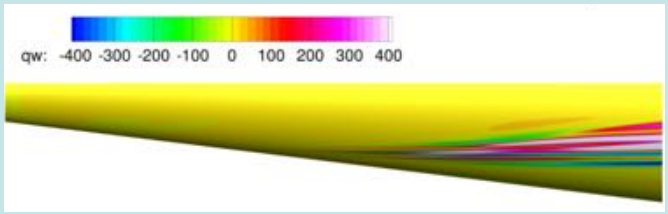
- **TAMU measurements** (Craig & Saric)
  - **Two bands:**
    15 kHz-60 kHz (traveling crossflow?)
    80 kHz-130 kHz (**spanwise-shear mode** of secondary instability?)

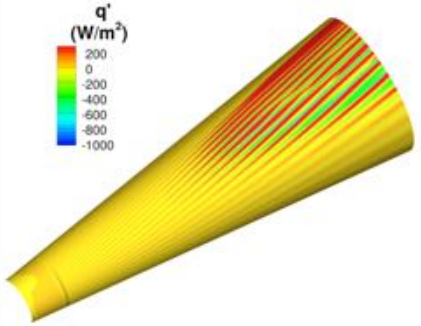


- **TU Braunschweig measurements** (Munoz et al.)
  - **Two bands:**
    20 kHz-50 kHz : 60 to 70 deg propagation angle (traveling crossflow?)
    300 kHz-350 kHz (**second mode disturbances?**)

Measurements on 7° Cone at AoA ≈ 6° and HIFiRE-5

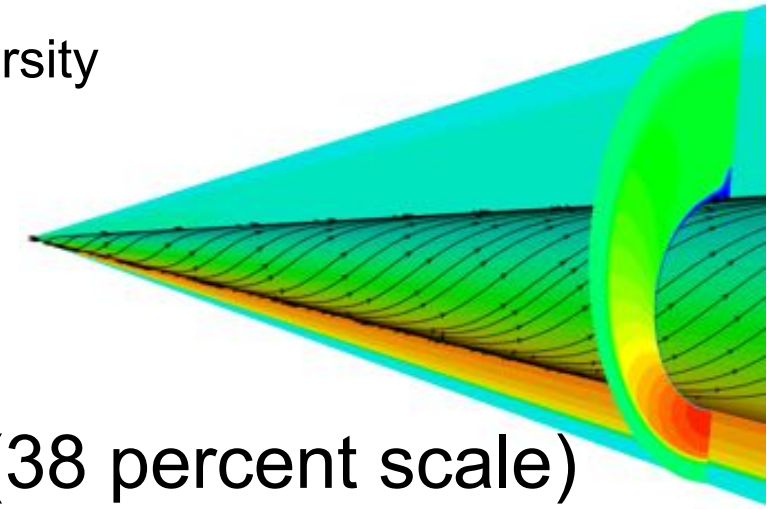
- **Objectives**
  - Help reconcile measurements and guide follow-on experiments by using DNS and secondary instability theory
  - Use computational data to guide the application of primary and secondary instability theory for transition prediction over 3D bodies
- **Strategy**
  - Use relatively simple controlled forcing in DNS to excite stationary crossflow pattern that resembles naturally occurring crossflow disturbances in wind tunnel experiments in terms of azimuthal length scale and range of amplitudes
    - Previous work: Azimuthally periodic, axially localized, non-compact "bracelet" source
    - Current work: Azimuthally compact source



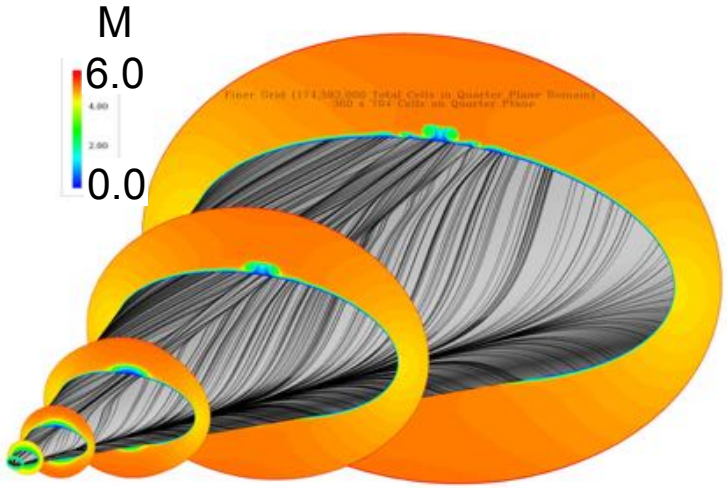


Flow Configurations

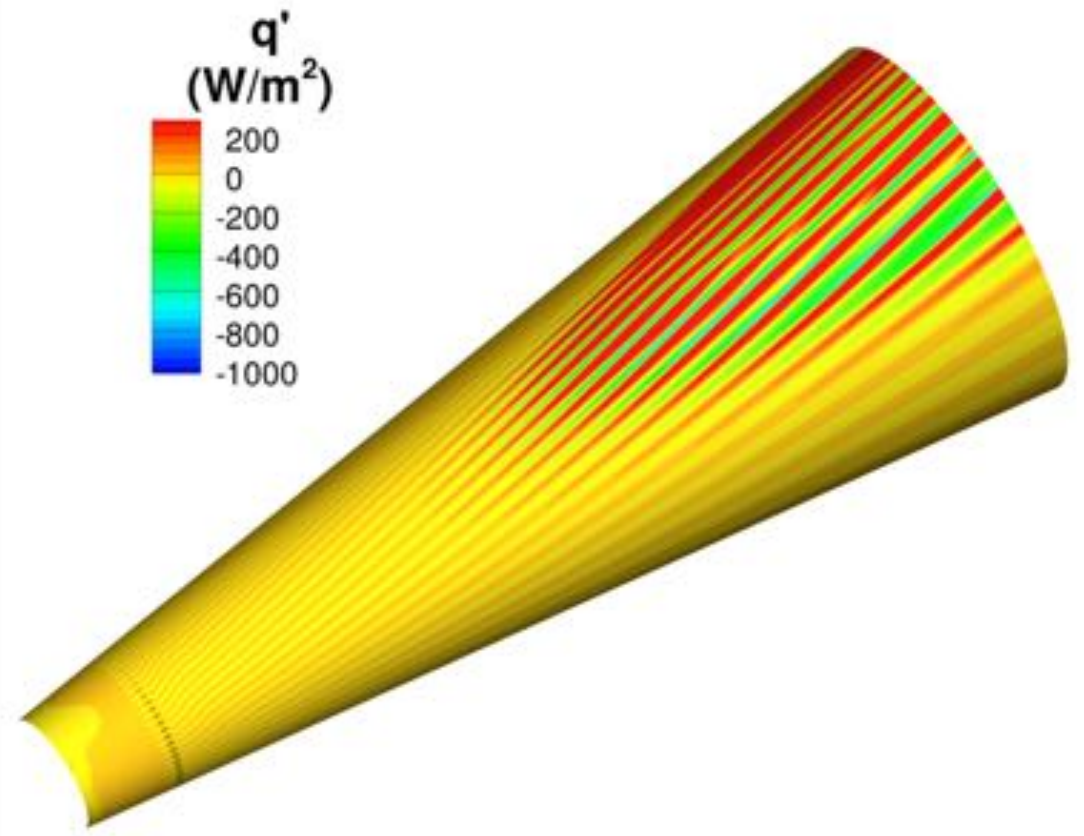
- 7° Circular Cone at 6° AoA
  - Mach 6 quiet tunnel at Purdue University
  - Re = 3×10^6/ft



- HiFIRE5 wind tunnel model (38 percent scale)
  - AFRL experiments in Mach 6 quiet tunnel at Purdue University, Re = 2.5×10^6/ft

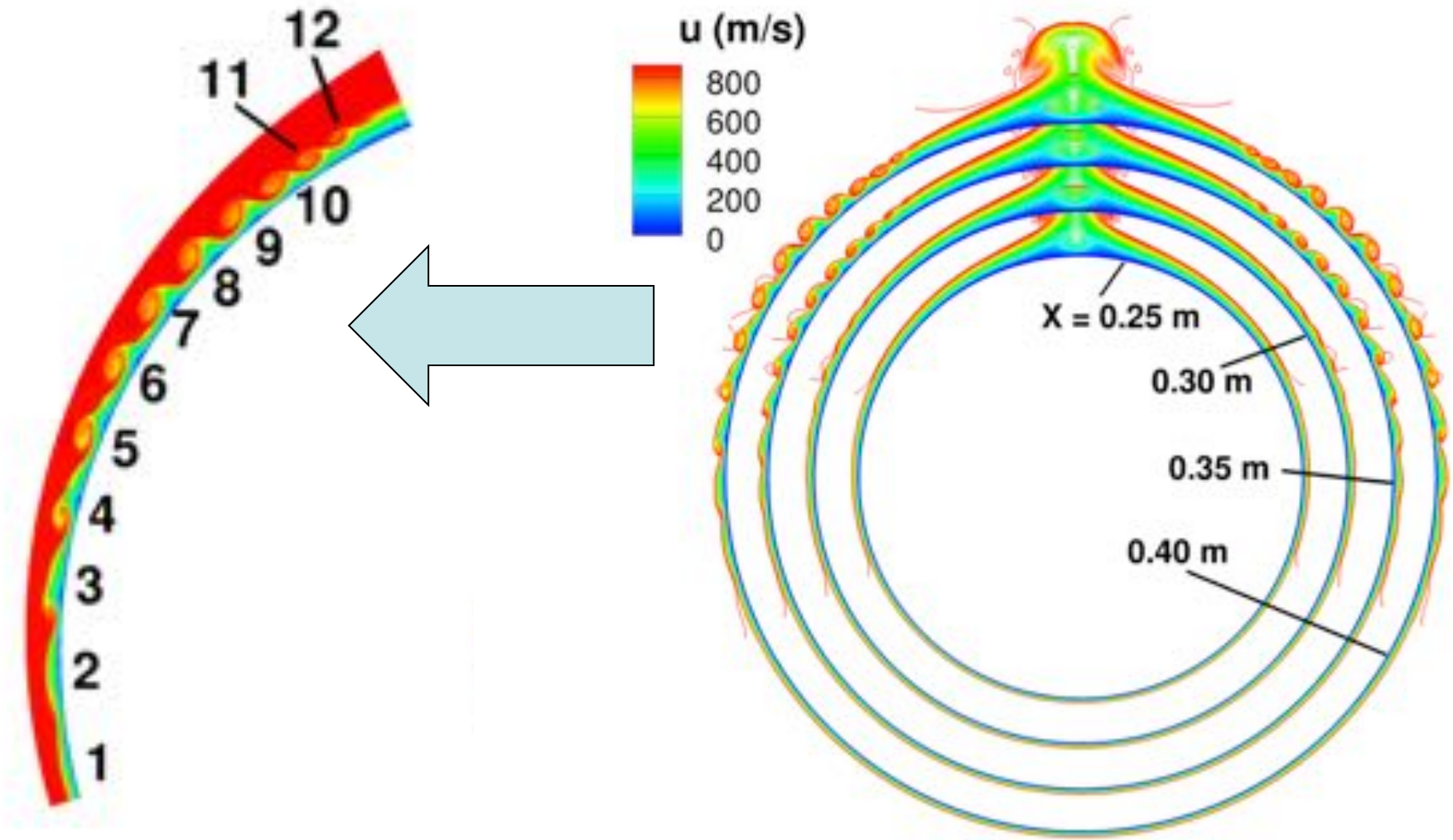


Evolution of Vortex Pattern: Periodic Source

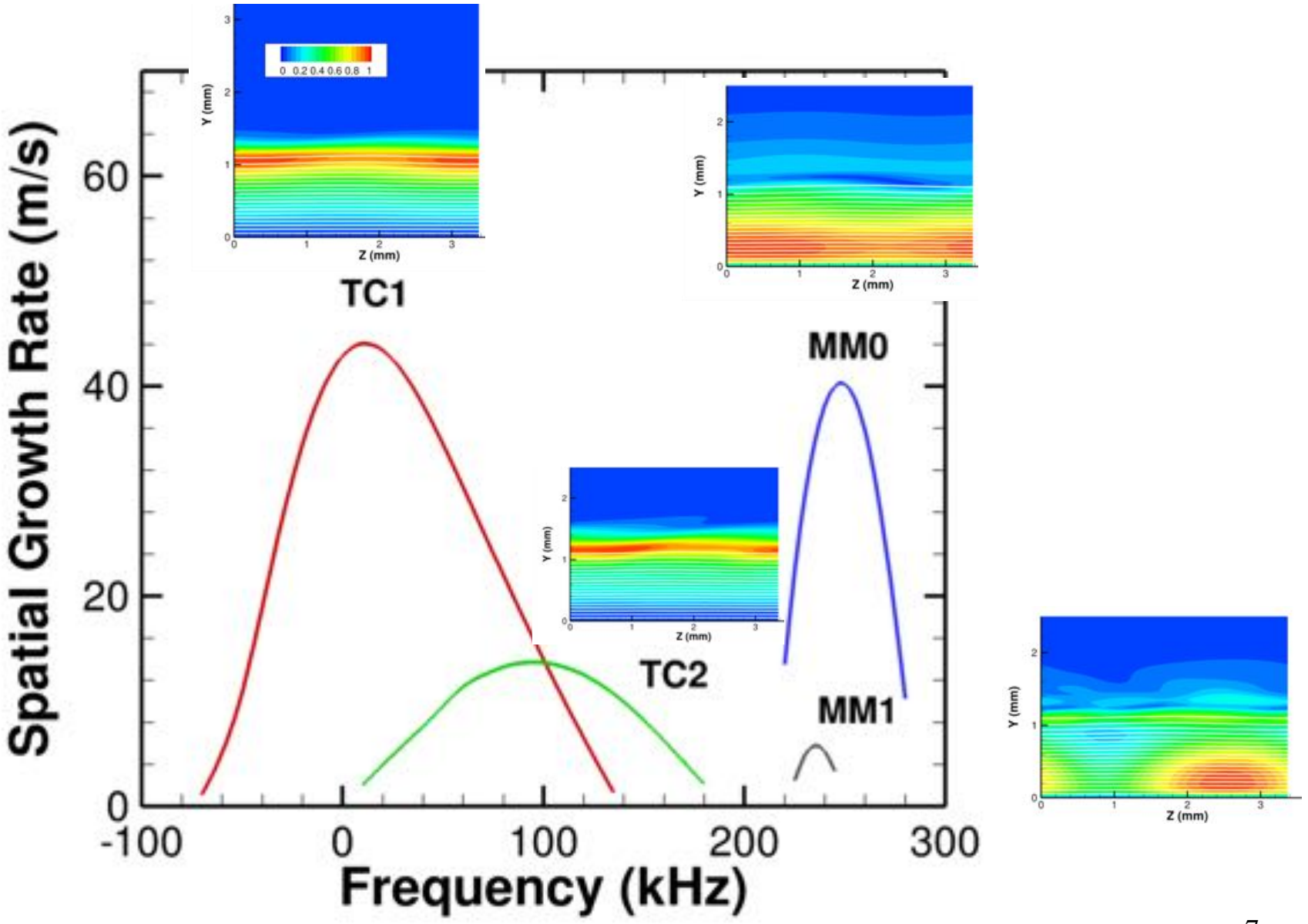


- Li, F., Choudhari, M., and Paredes, P., "Nonlinear Evolution and Secondary Instability of Crossflow Disturbances in Hypersonic Boundary Layer over a Cone," NATO-STO AVT-240 & RTG-082 Meeting on Hypersonic Boundary Layer Transition, Prague, Czech Republic, Oct. 15-16, 2015.
- Li, F., Choudhari, M., Paredes, P., and Duan, L., "Secondary Instability of Stationary Crossflow Vortices in Mach 6 Boundary Layer over a Circular Cone," NASA/TM-2015-218997, Dec. 2015.
- Li, F., Choudhari, M., Paredes, P., and Duan, L., "High-Frequency Instabilities of Stationary Crossflow Vortices in a Hypersonic Boundary Layer," Phys. Rev. Fluids, 1, 083601.

Axial Velocity Contours

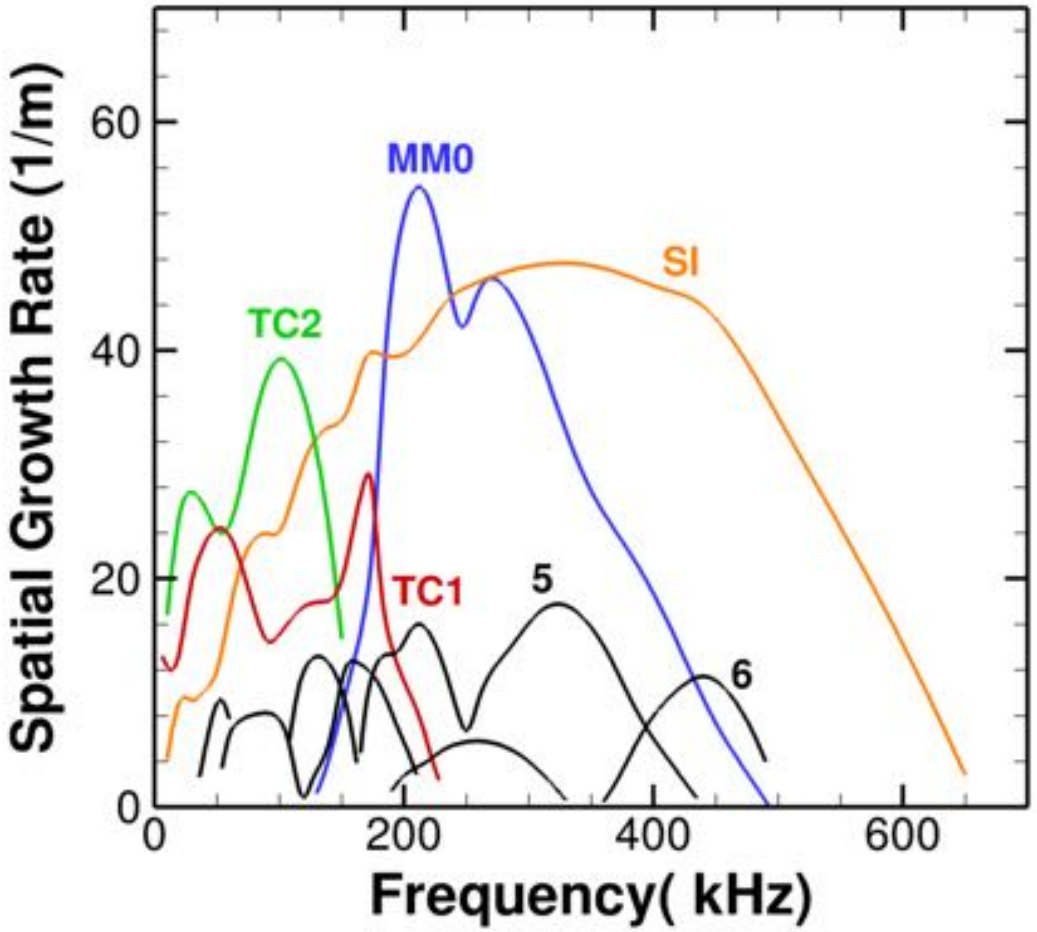


Local Growth Rates (V10, X = 0.25 m)

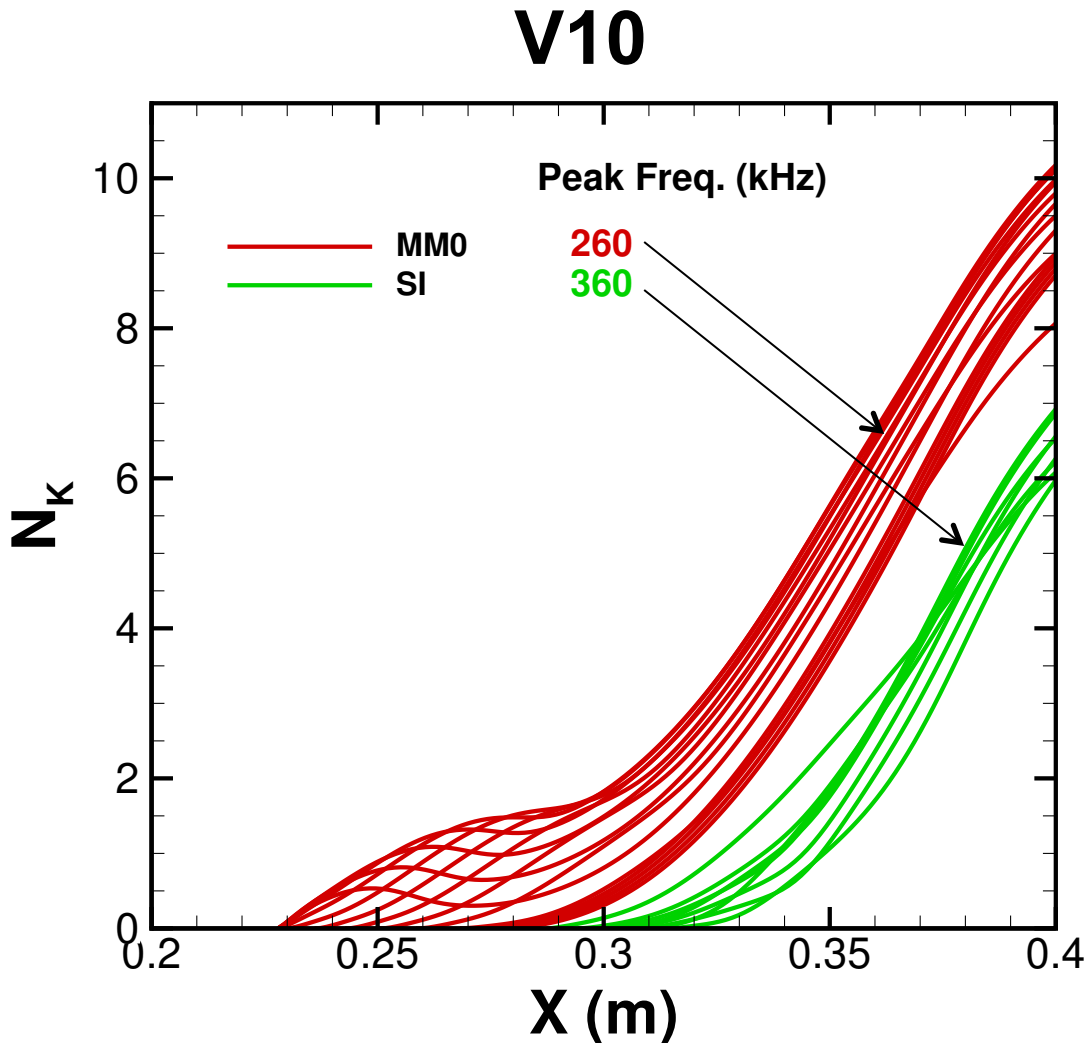


Local Growth Rates: Downstream Locations

X = 0.33 m

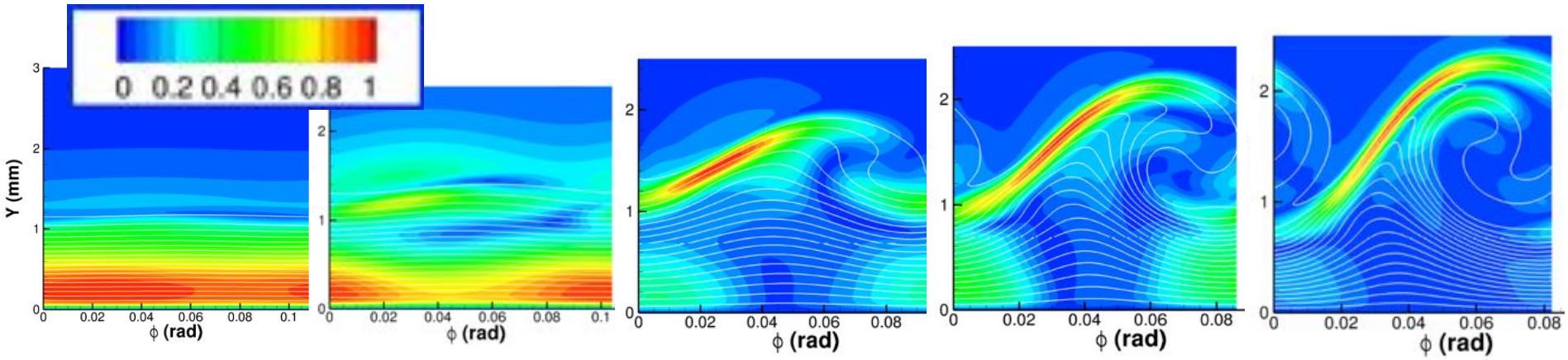


PSE Predictions: N-Factor Evolution



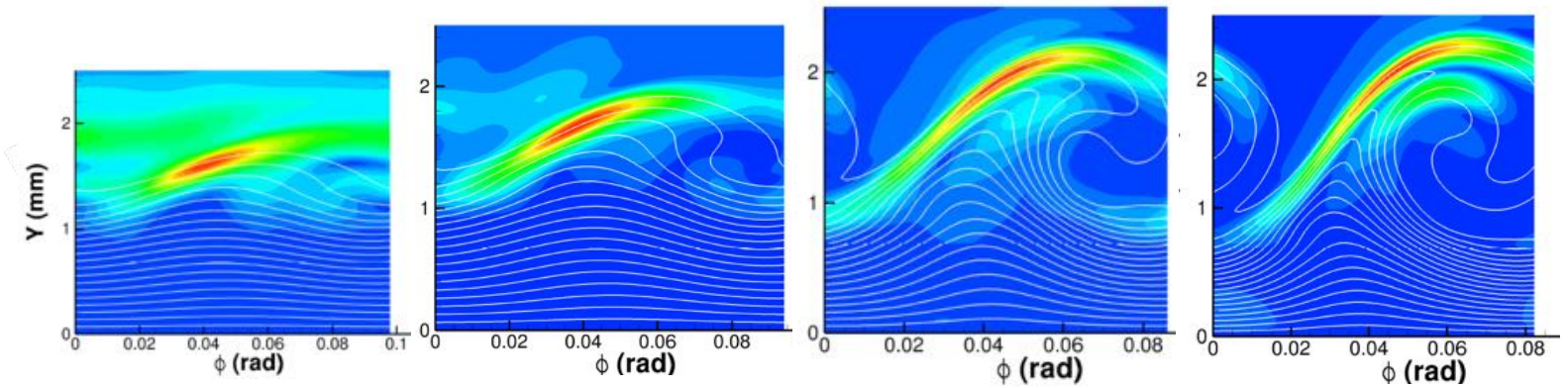
|u'| Mode Shape Evolution for V10 (PSE)

Mode MM0 (260 kHz)

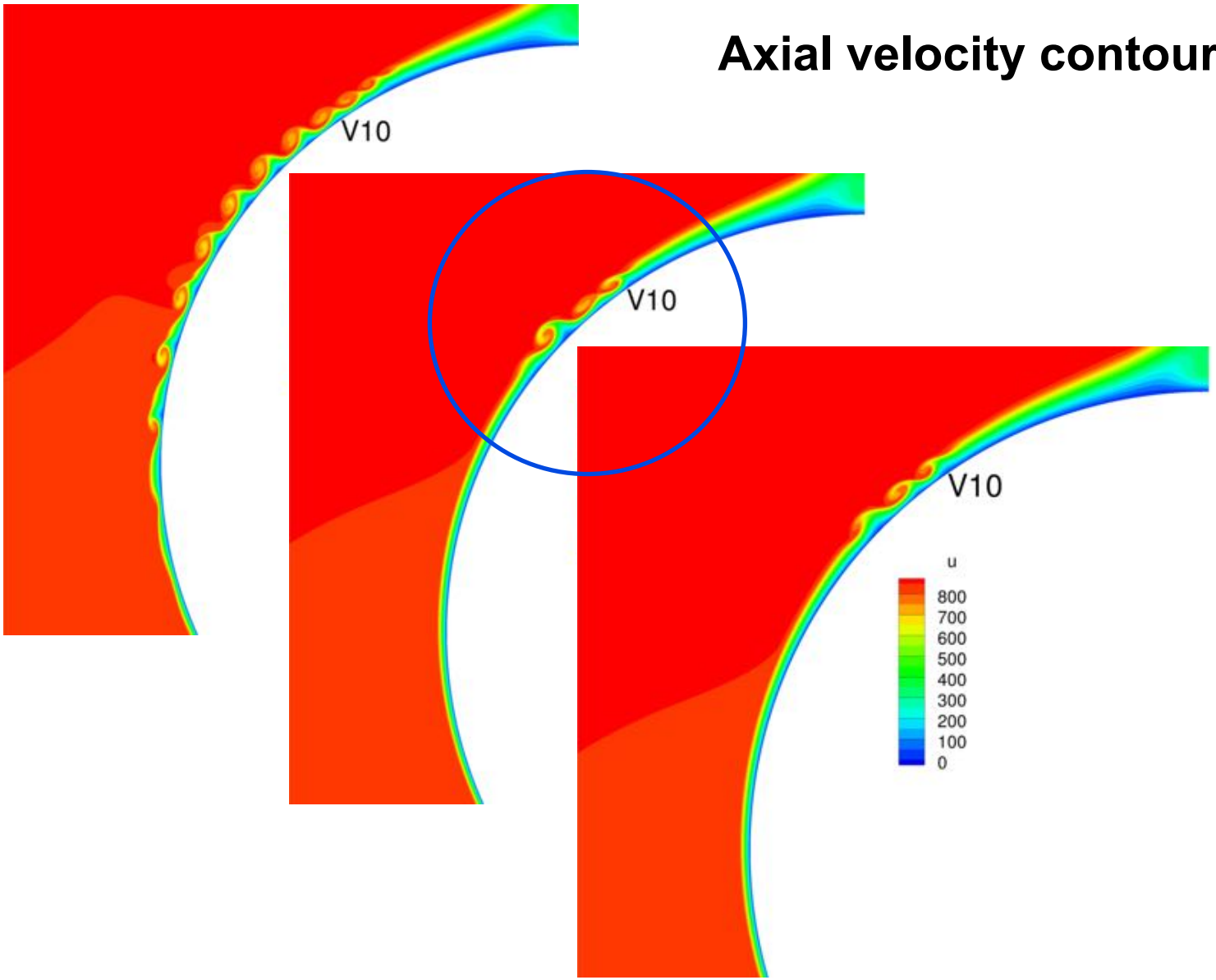


X ➔

Mode SI (360 kHz)

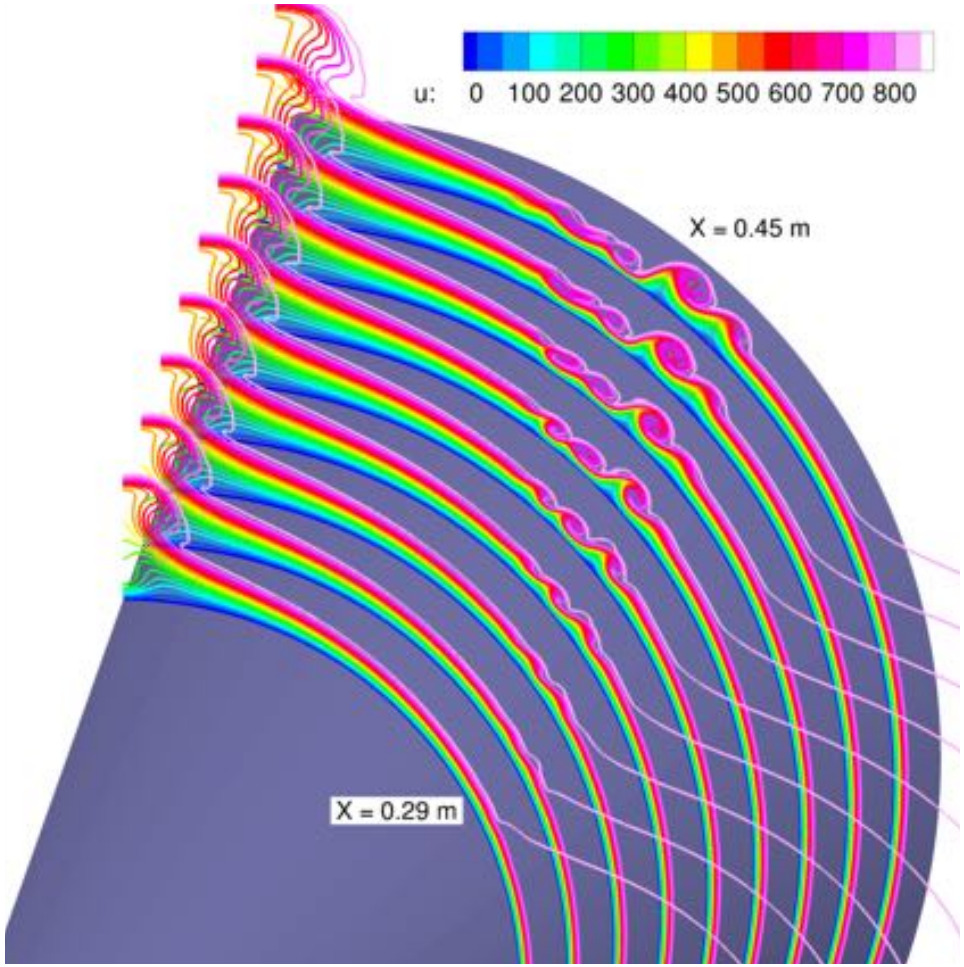


Effect of Azimuthal Extent of Source

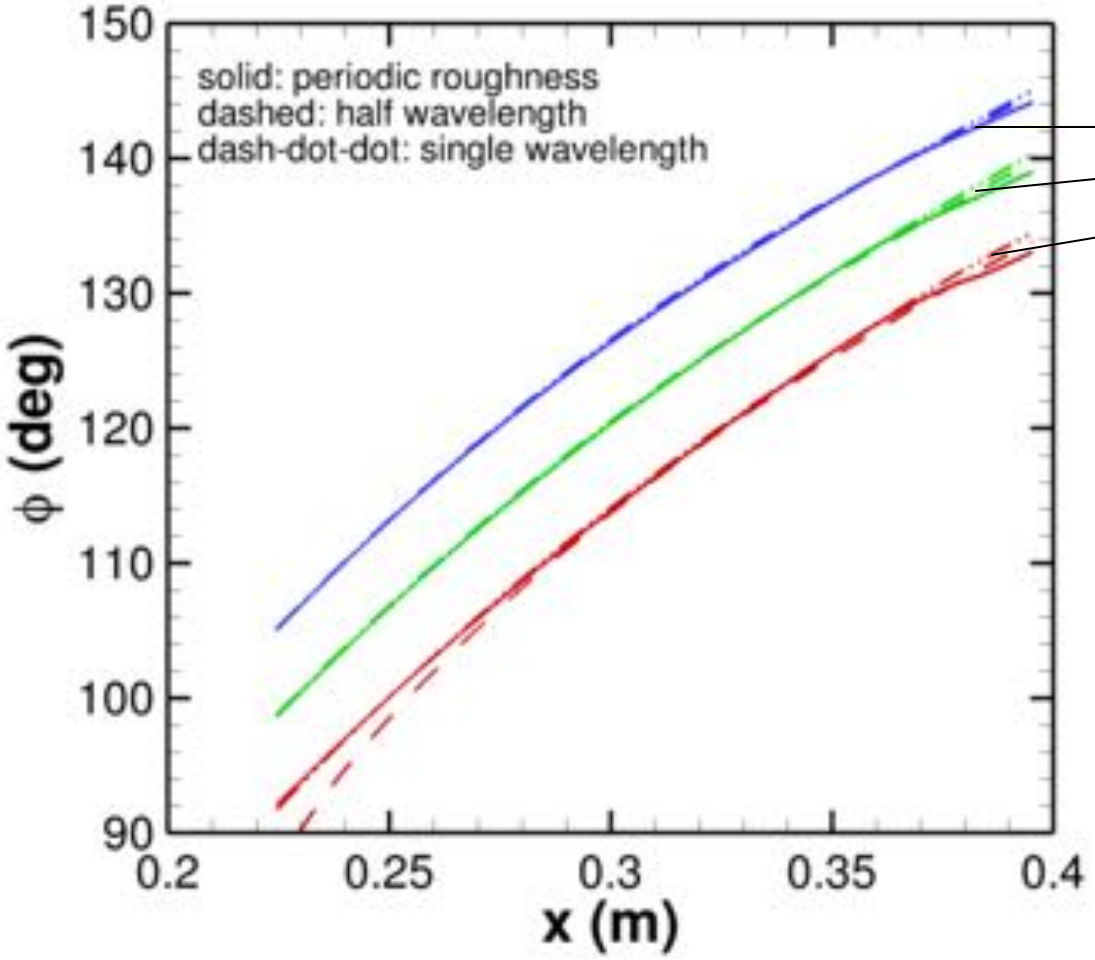


Localized Source

Axial velocity contours

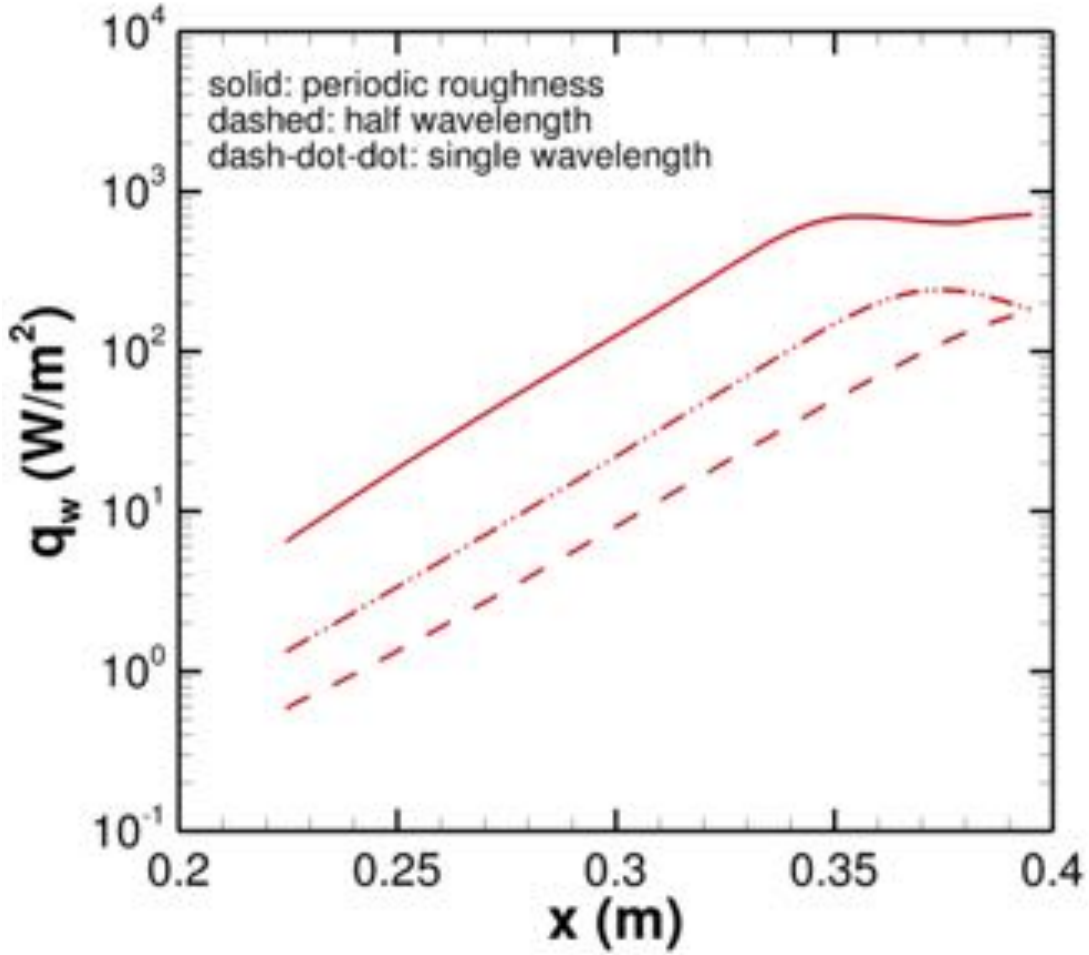


Vortex Trajectories: Effect of Azimuthal Source Distribution

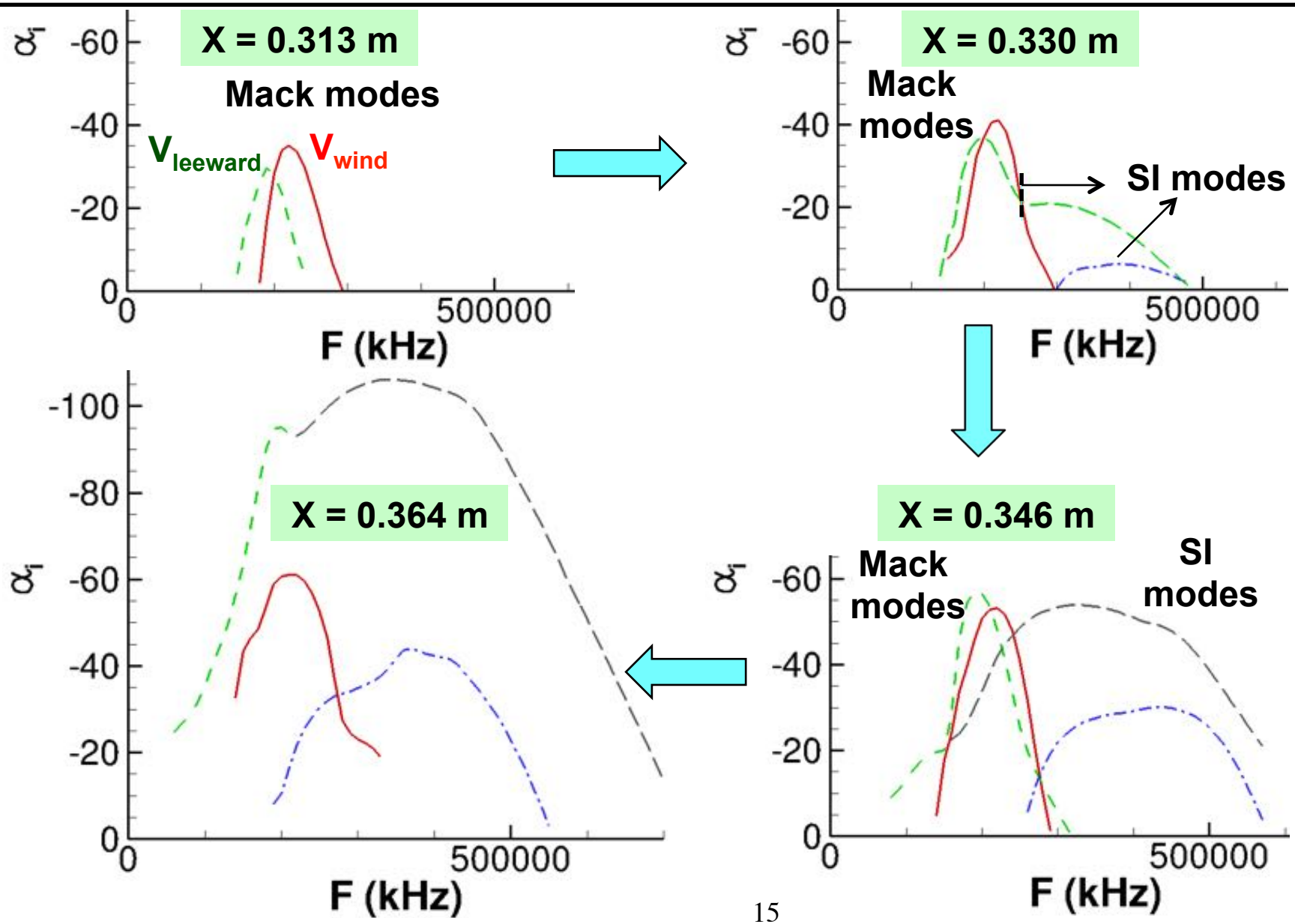


vortex trajectories

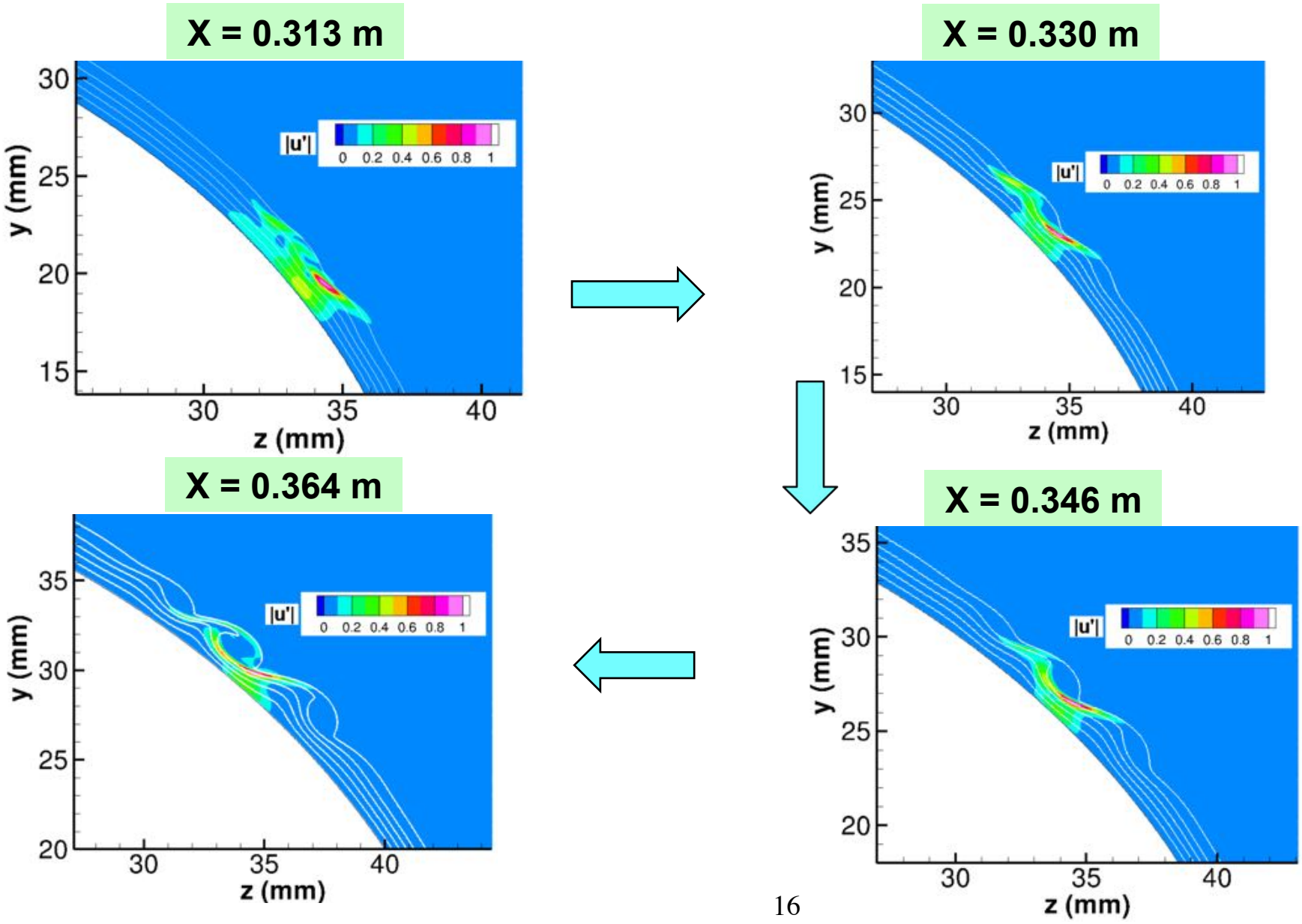
Vortex Amplitudes: Effect of Azimuthal Source Distribution



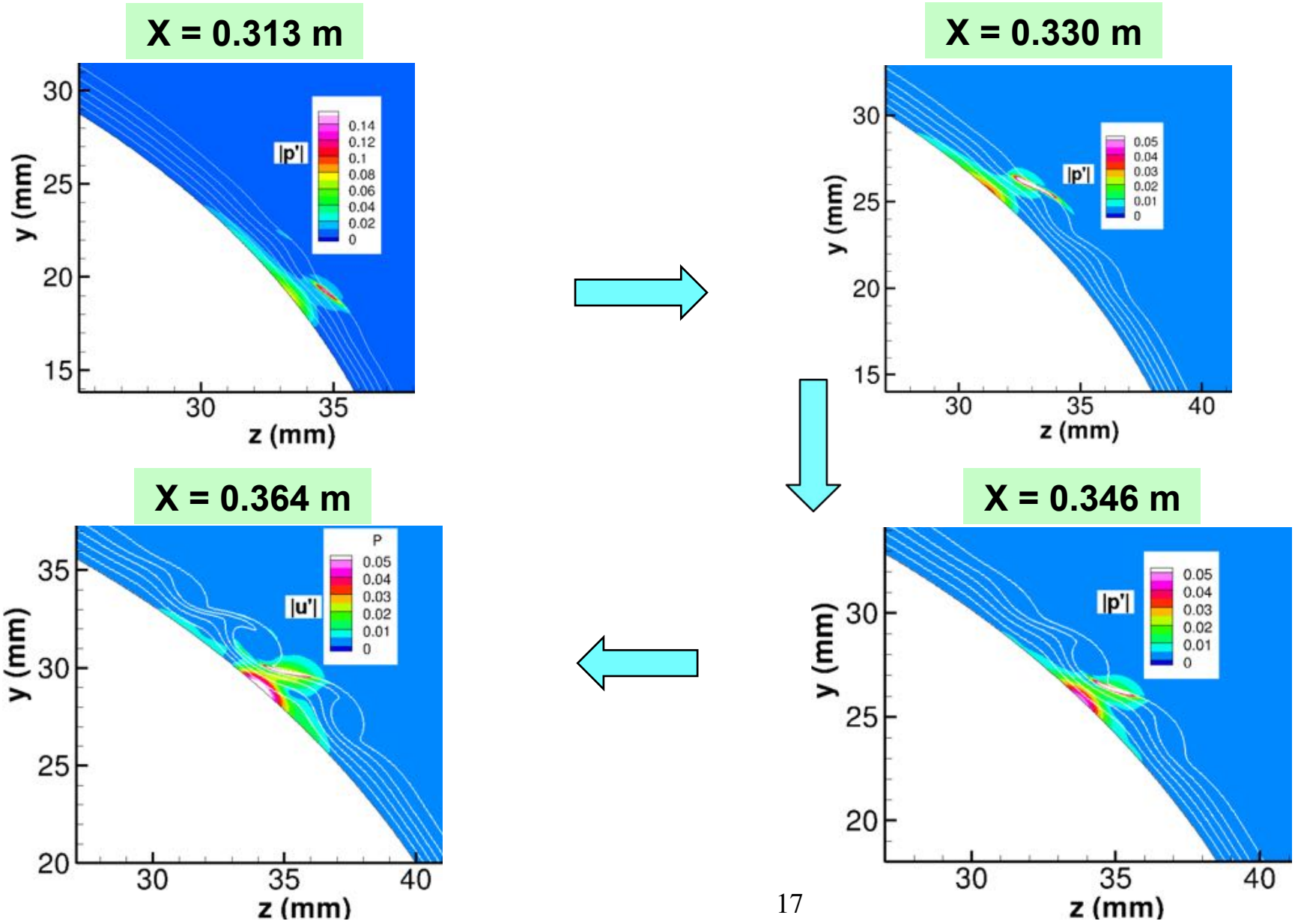
Growth Rate Spectra at Selected Stations



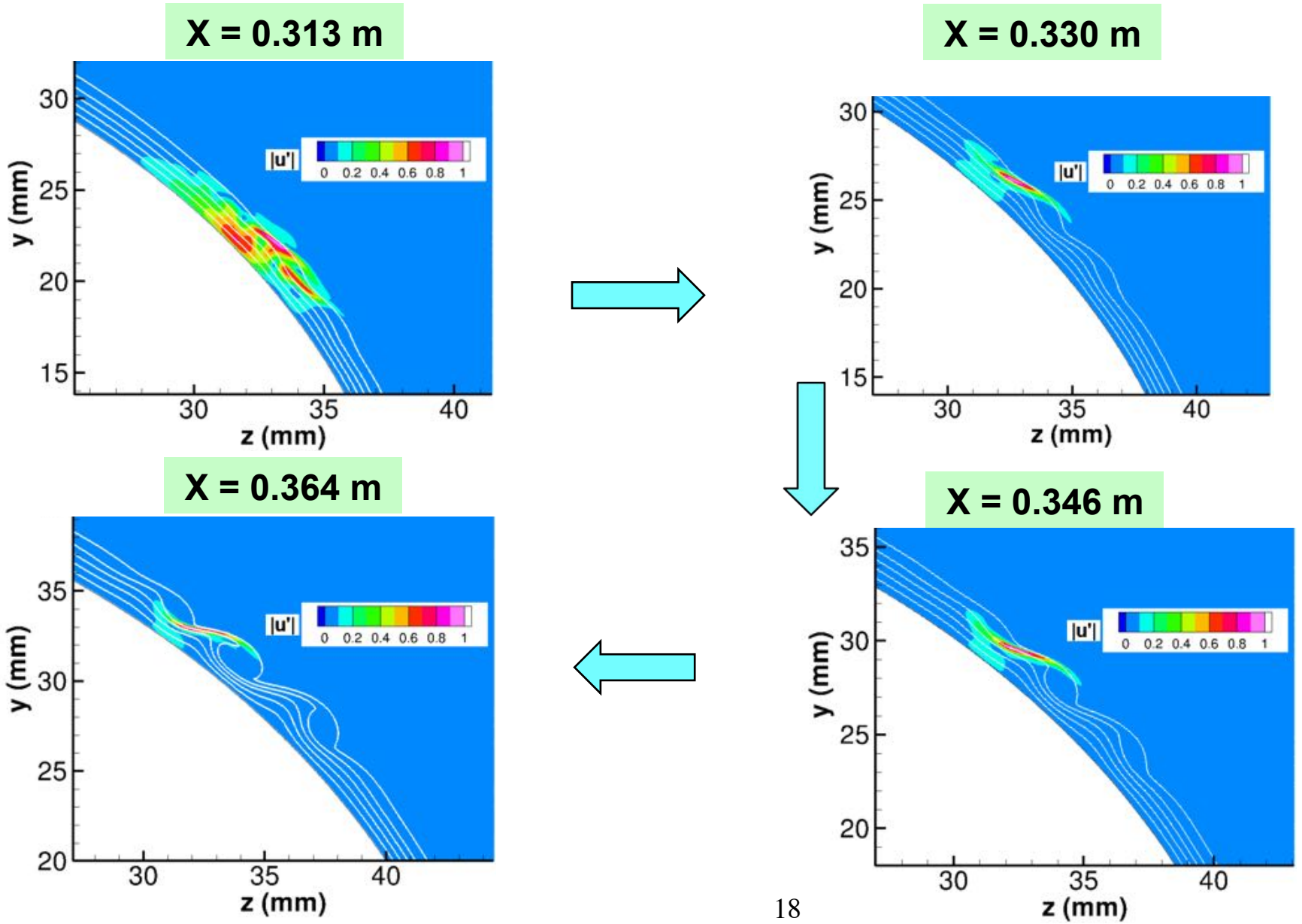
|u'| Mode Shapes for Windward Vortex: Mack Mode



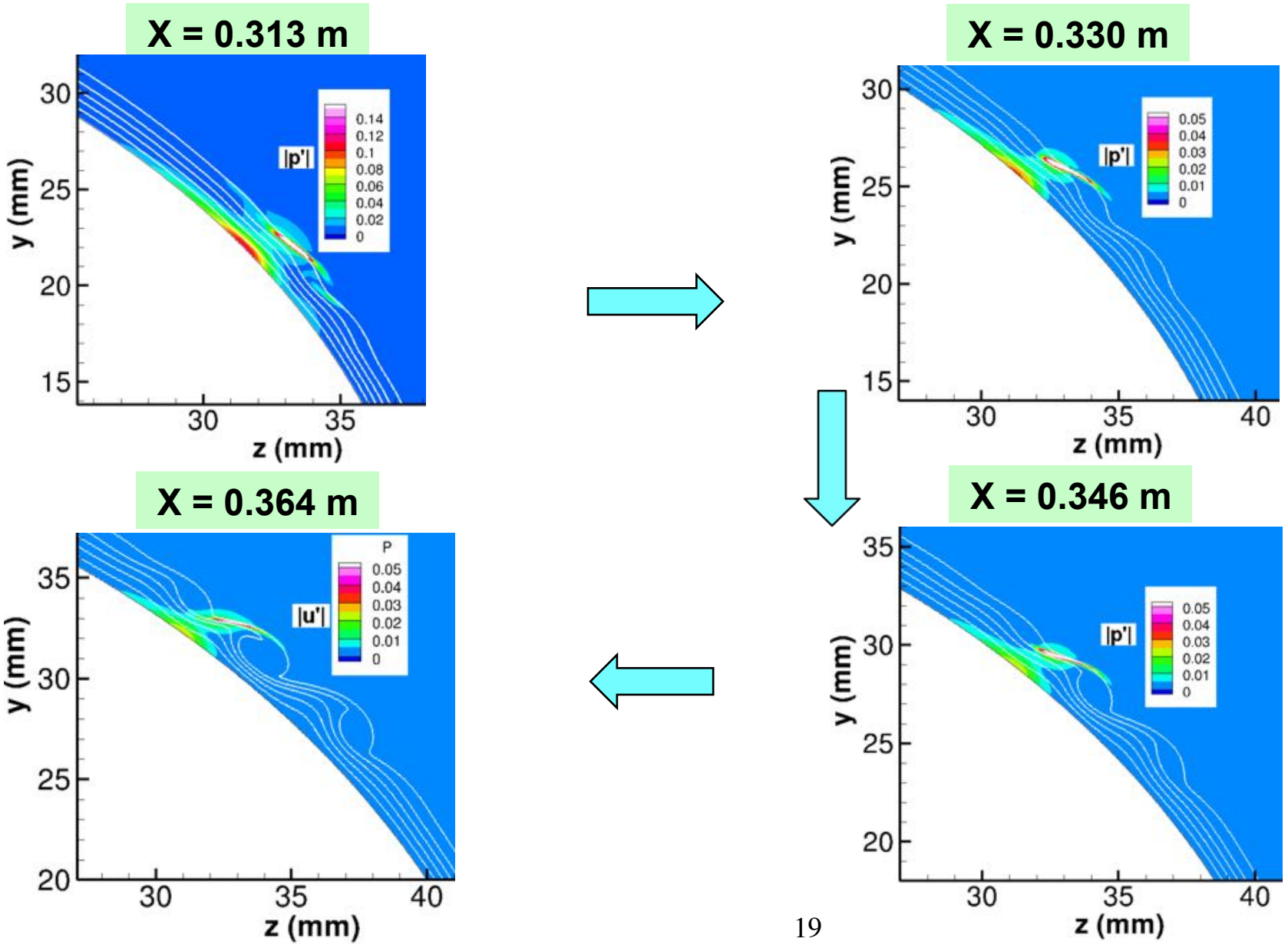
|p'| Mode Shapes for Windward Vortex: Mack Mode



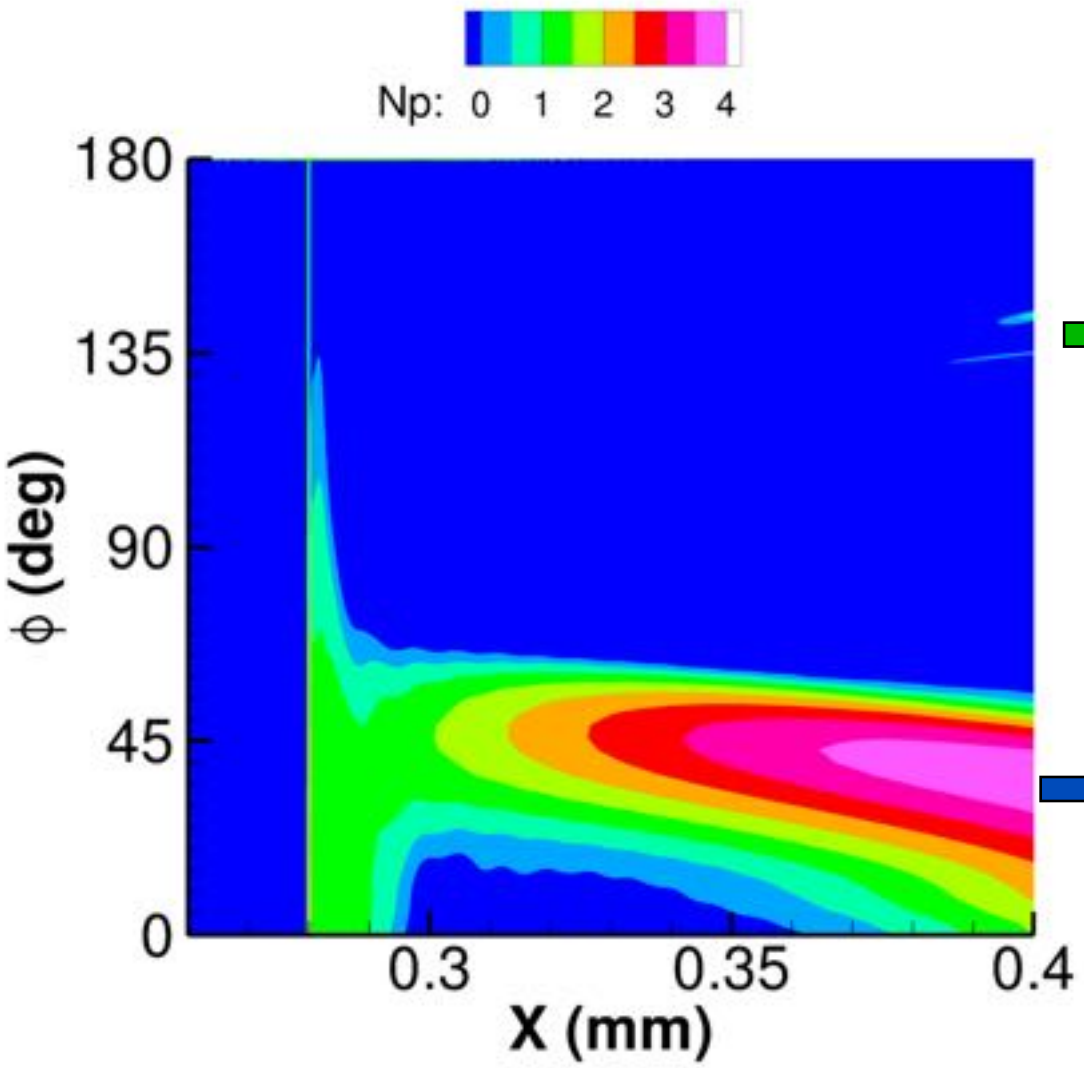
|u'| Mode Shapes for Leeward Vortex: Mack Mode



|p'| Mode Shapes for Leeward Vortex: Mack Mode



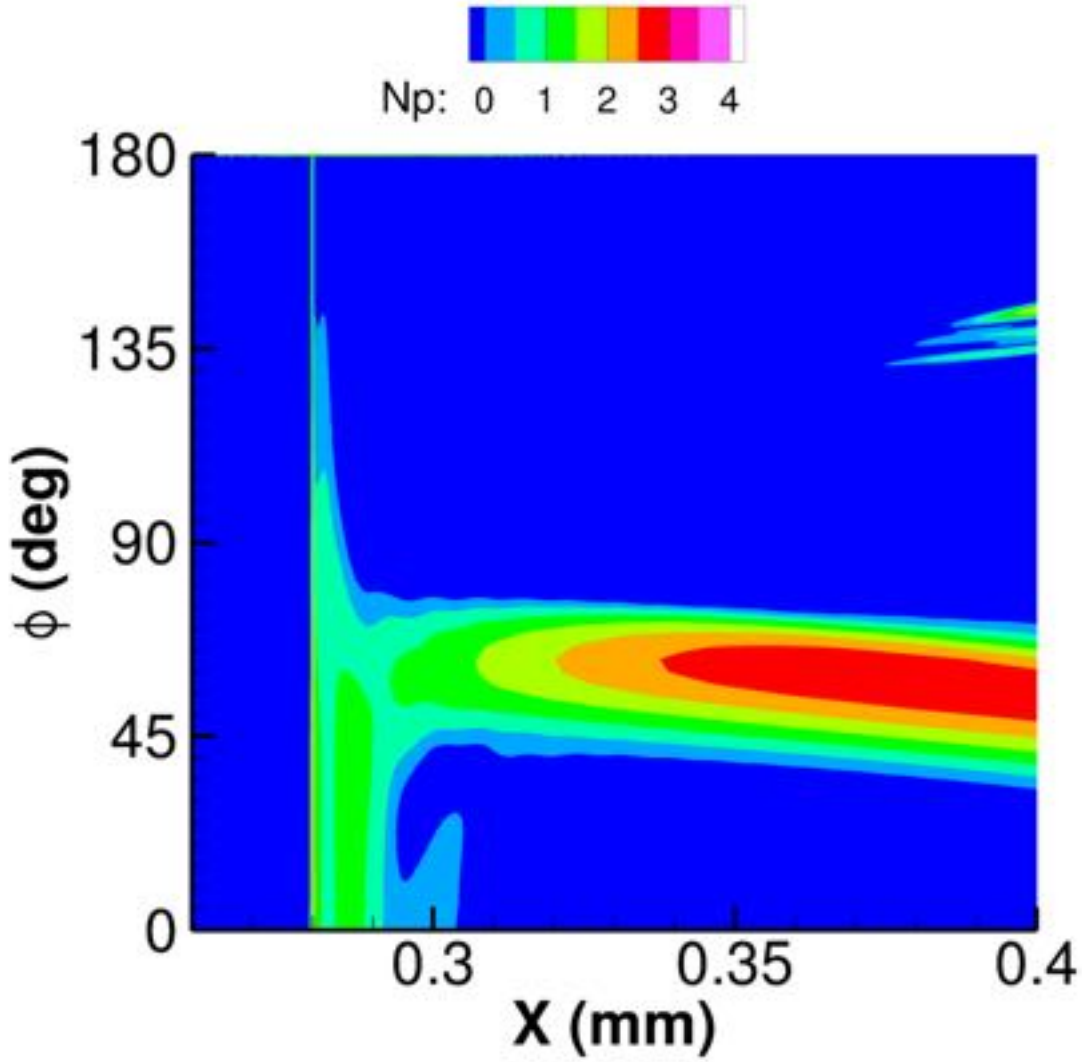
DNS Data
N-Factor Distribution: 440 kHz



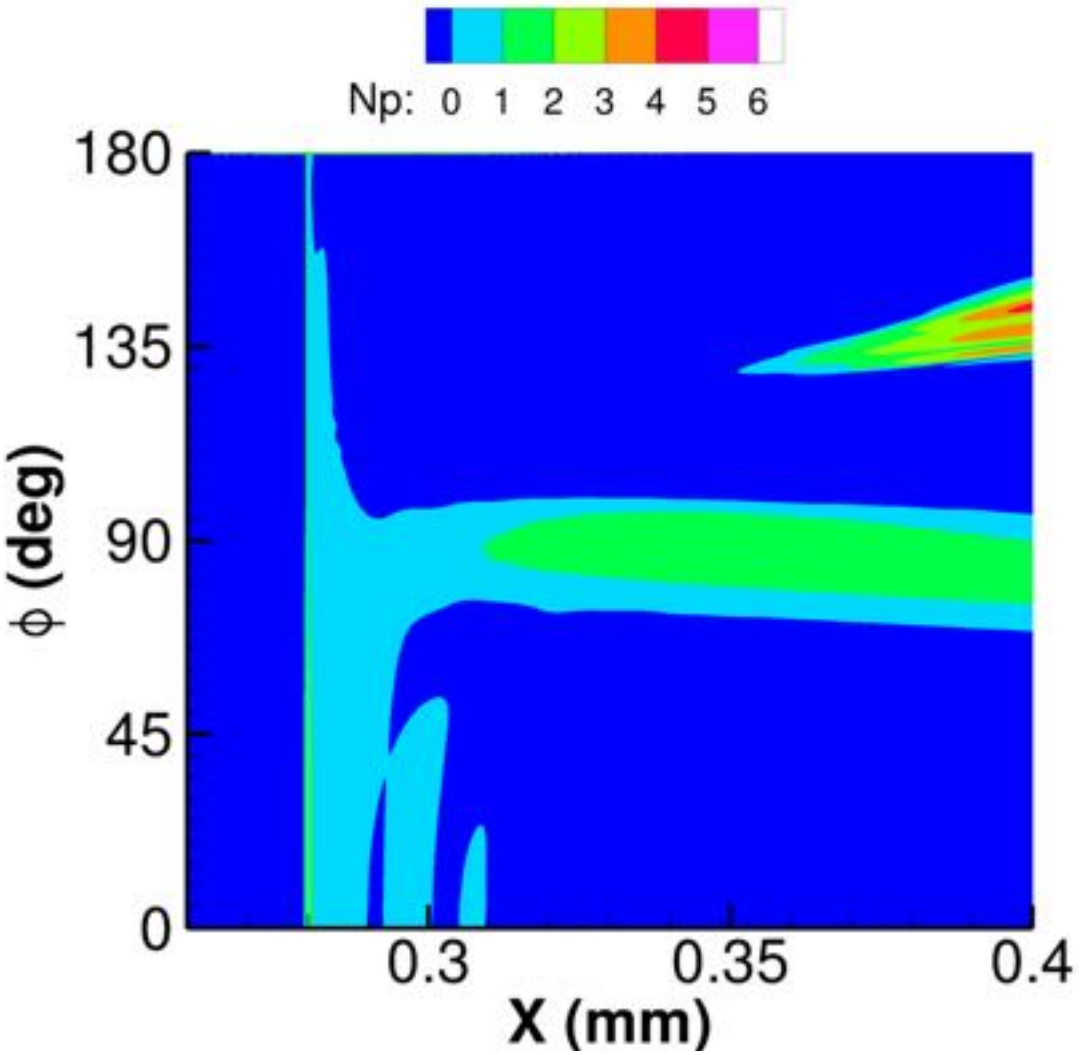
High-frequency Secondary instabilities

Mack modes

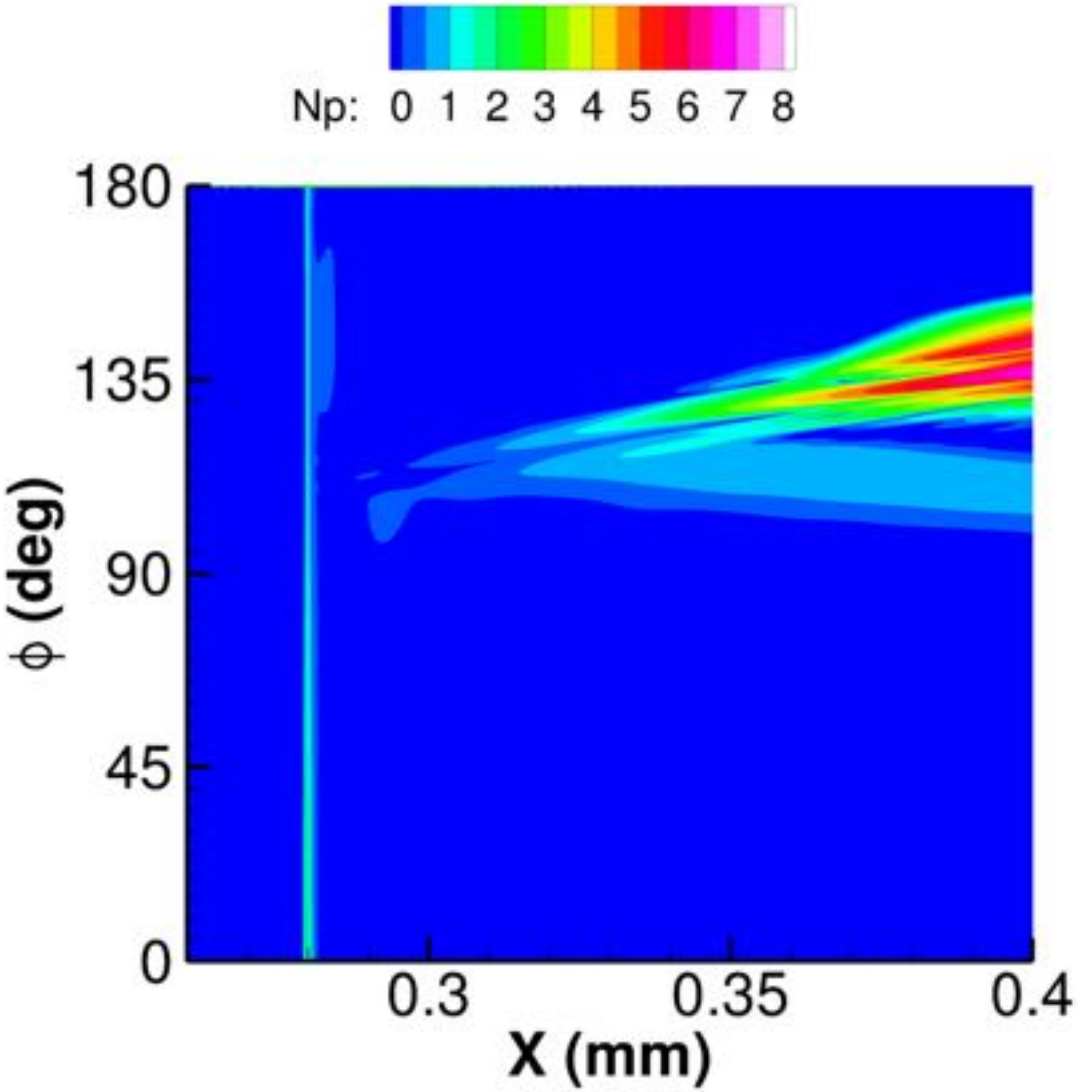
N-Factor Distribution: 400 kHz



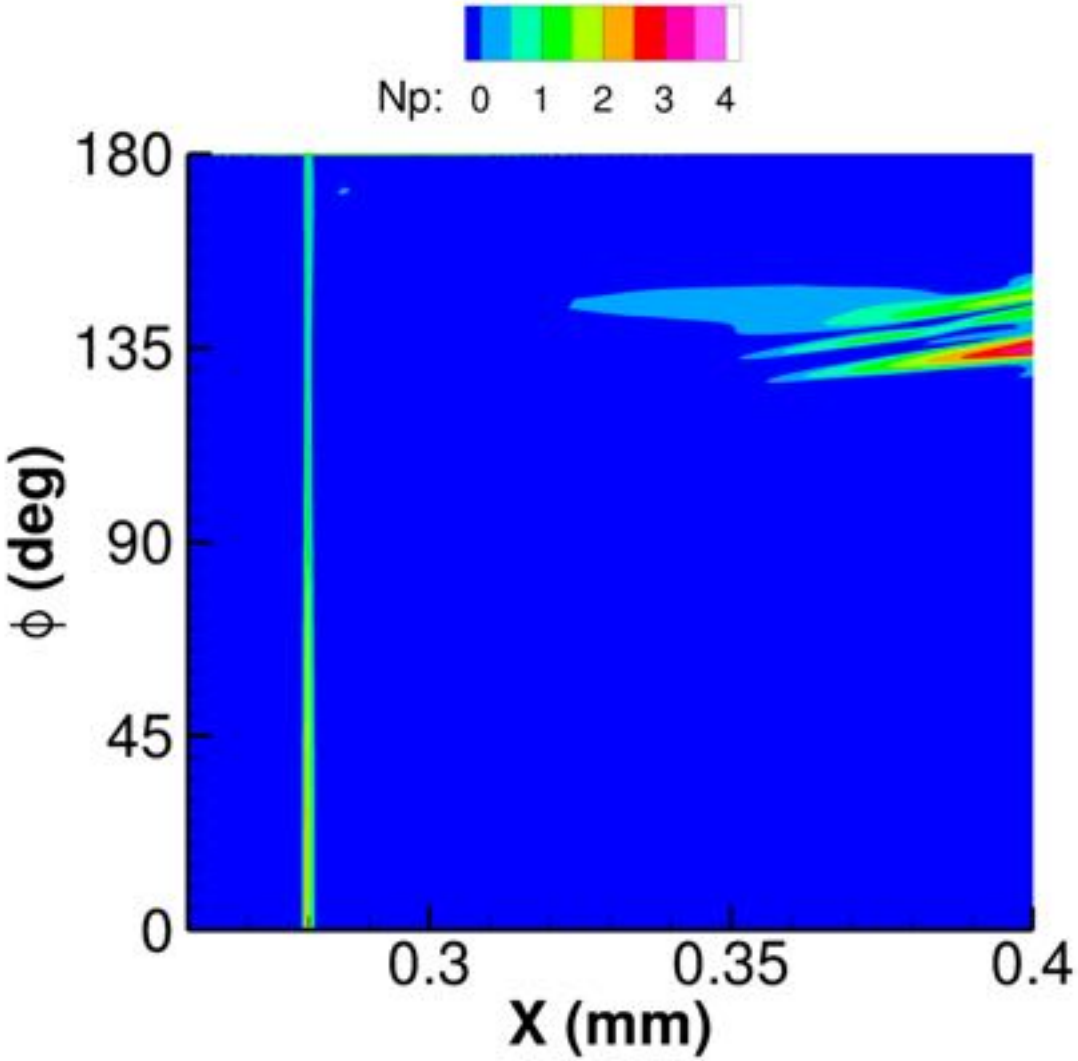
N-Factor Distribution: 320 kHz



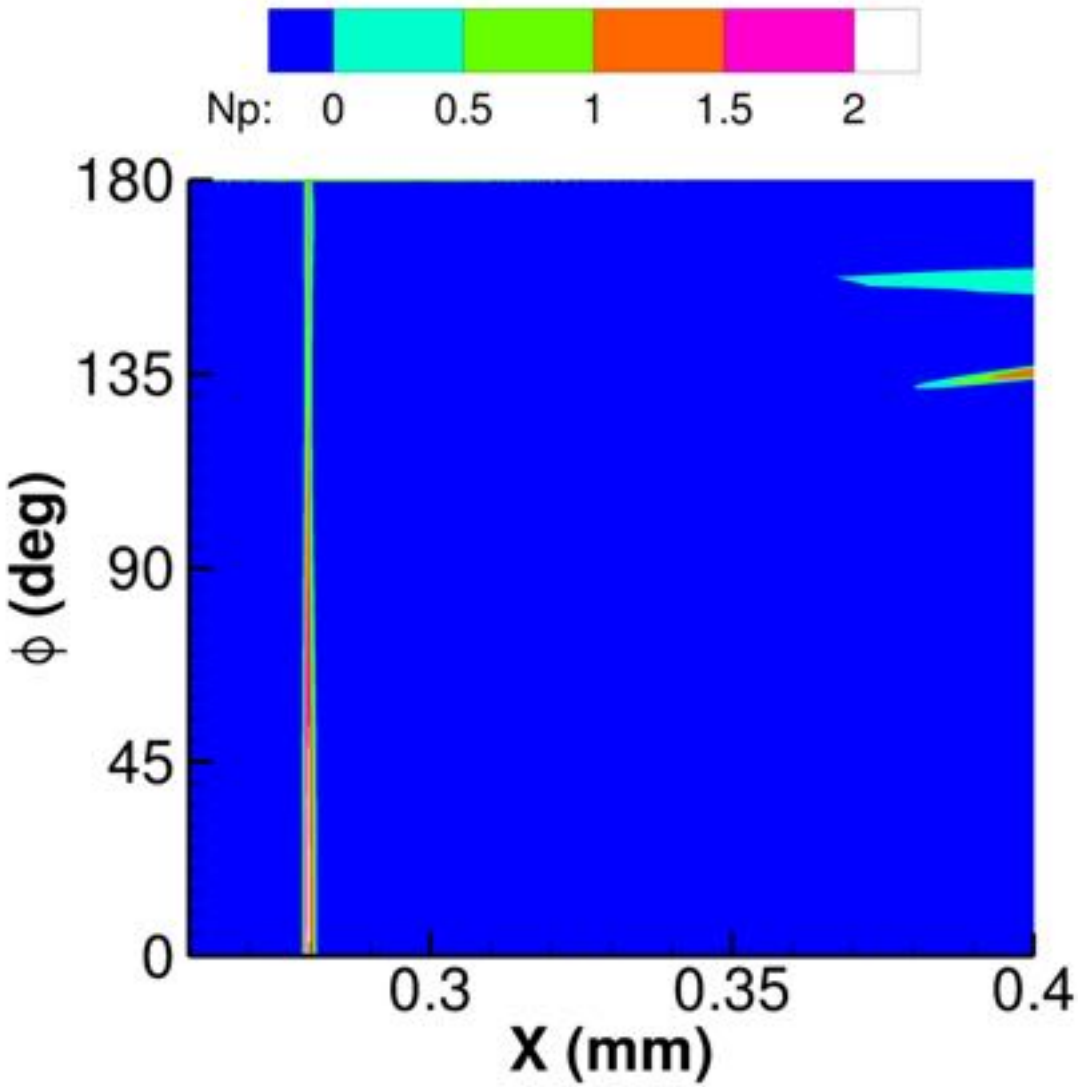
N-Factor Distribution: 240 kHz



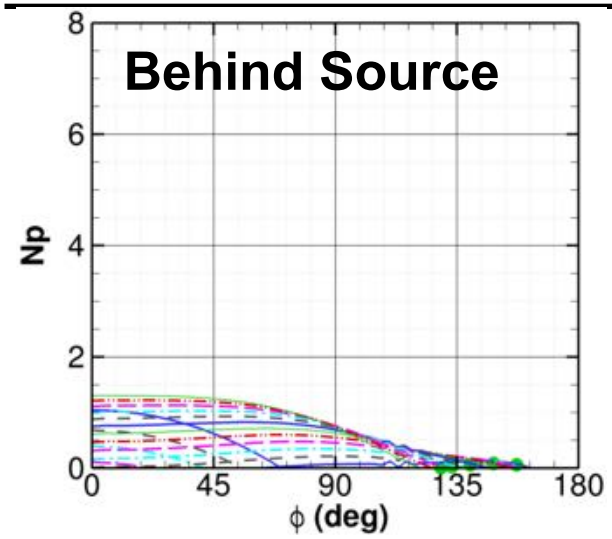
N-Factor Distribution: 160 kHz

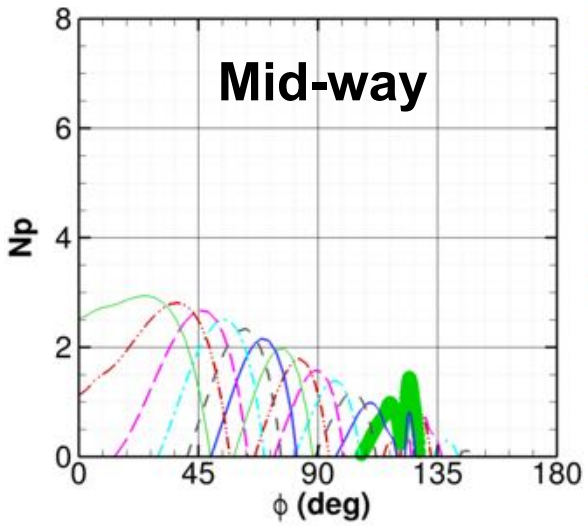


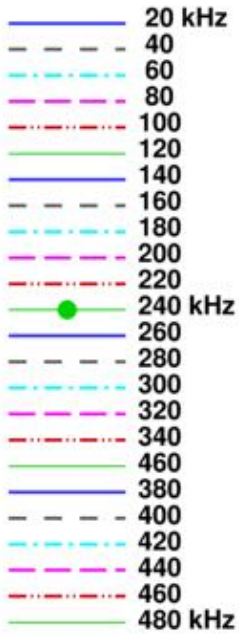
N-Factor Distribution: 120 kHz

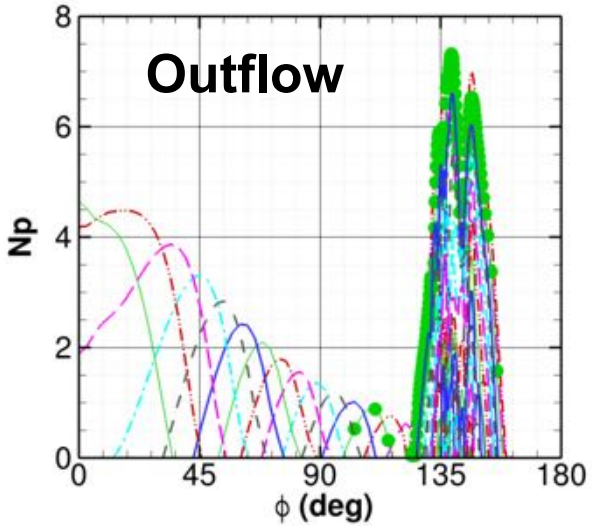


N-Factor Evolution





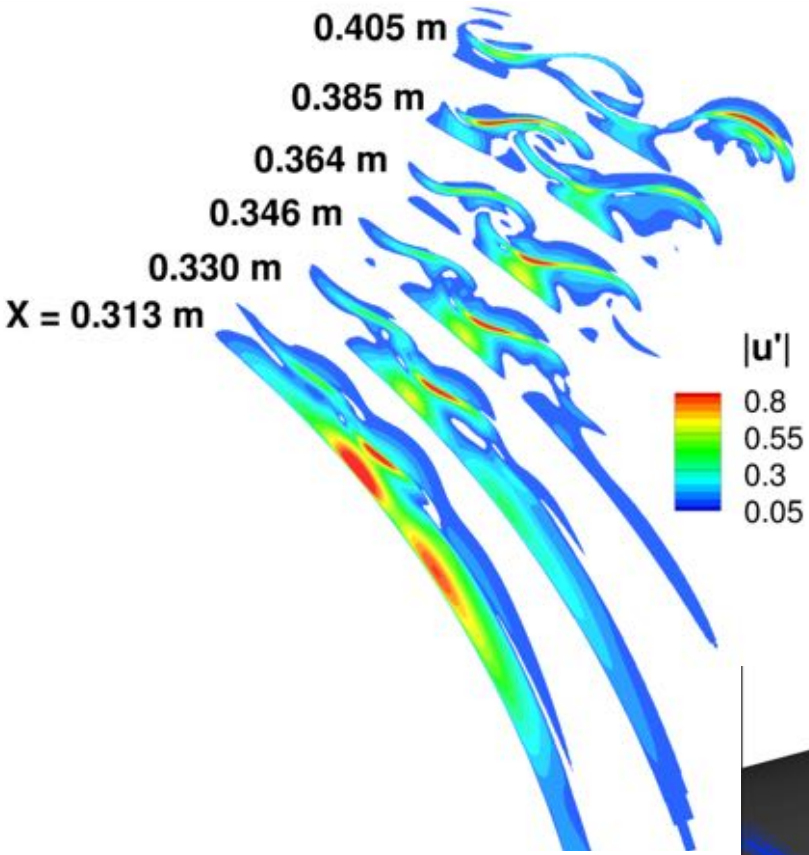


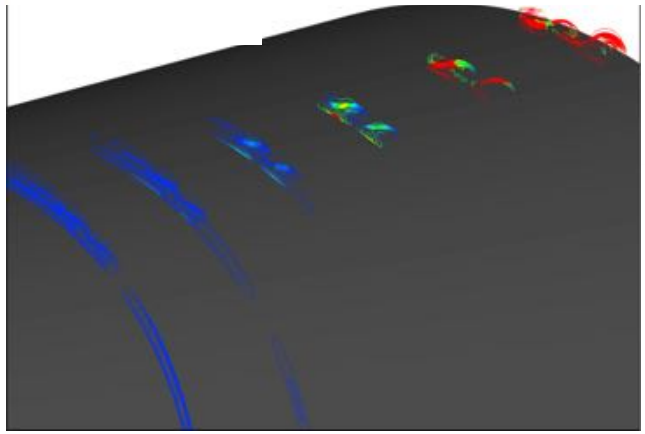


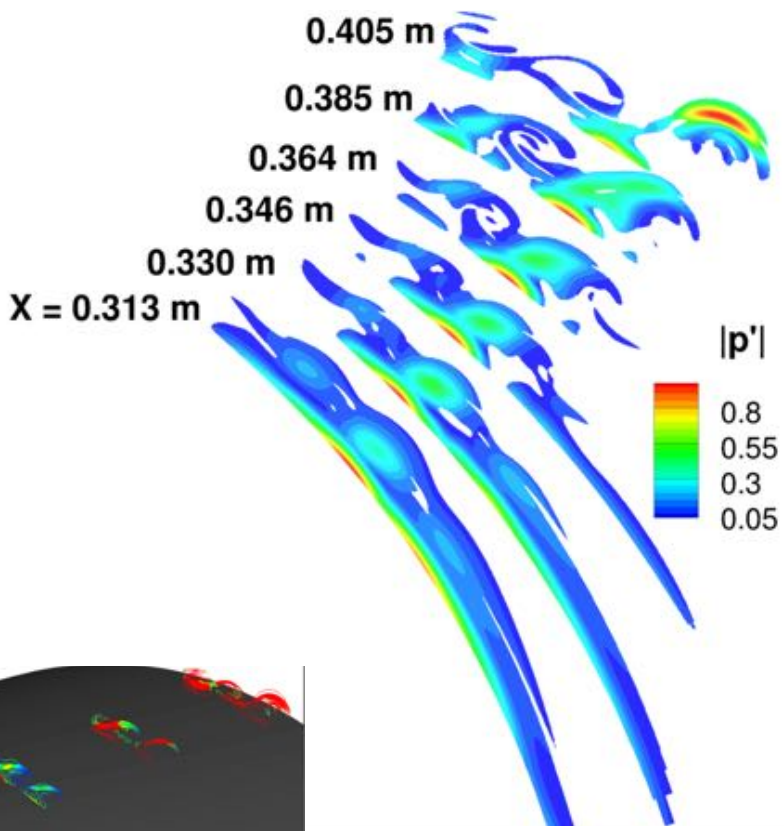


O(20°)

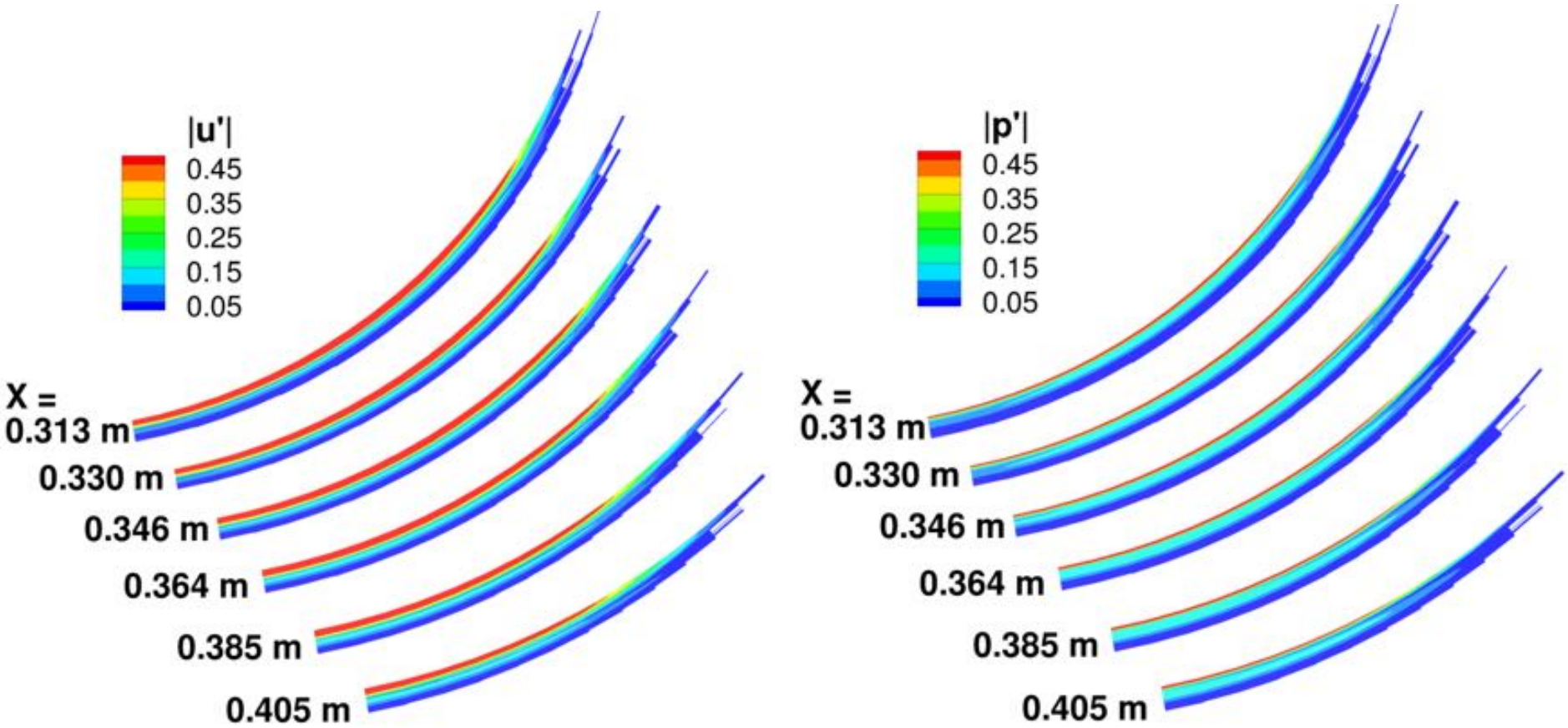
Mode Shape Evolution: 240 kHz



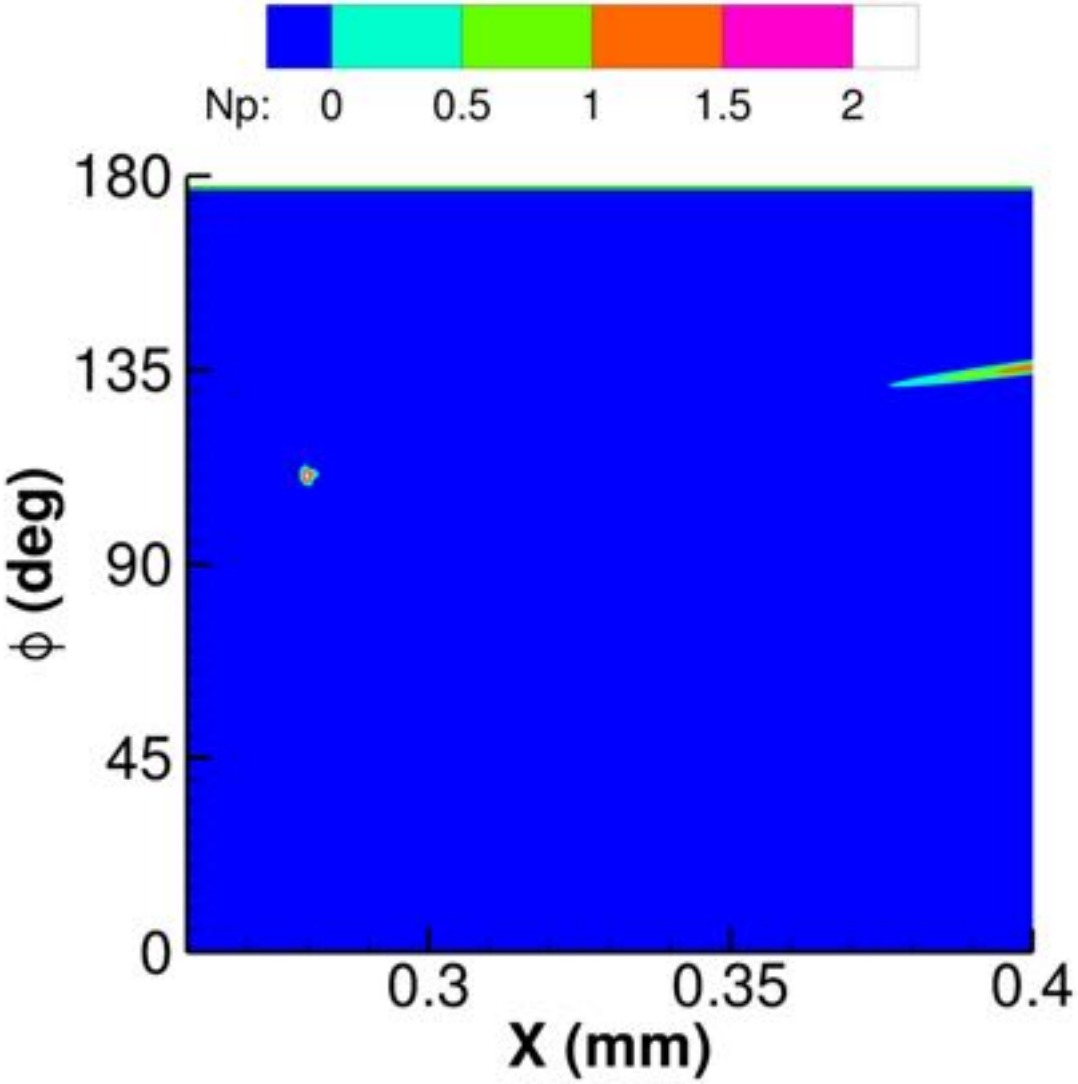




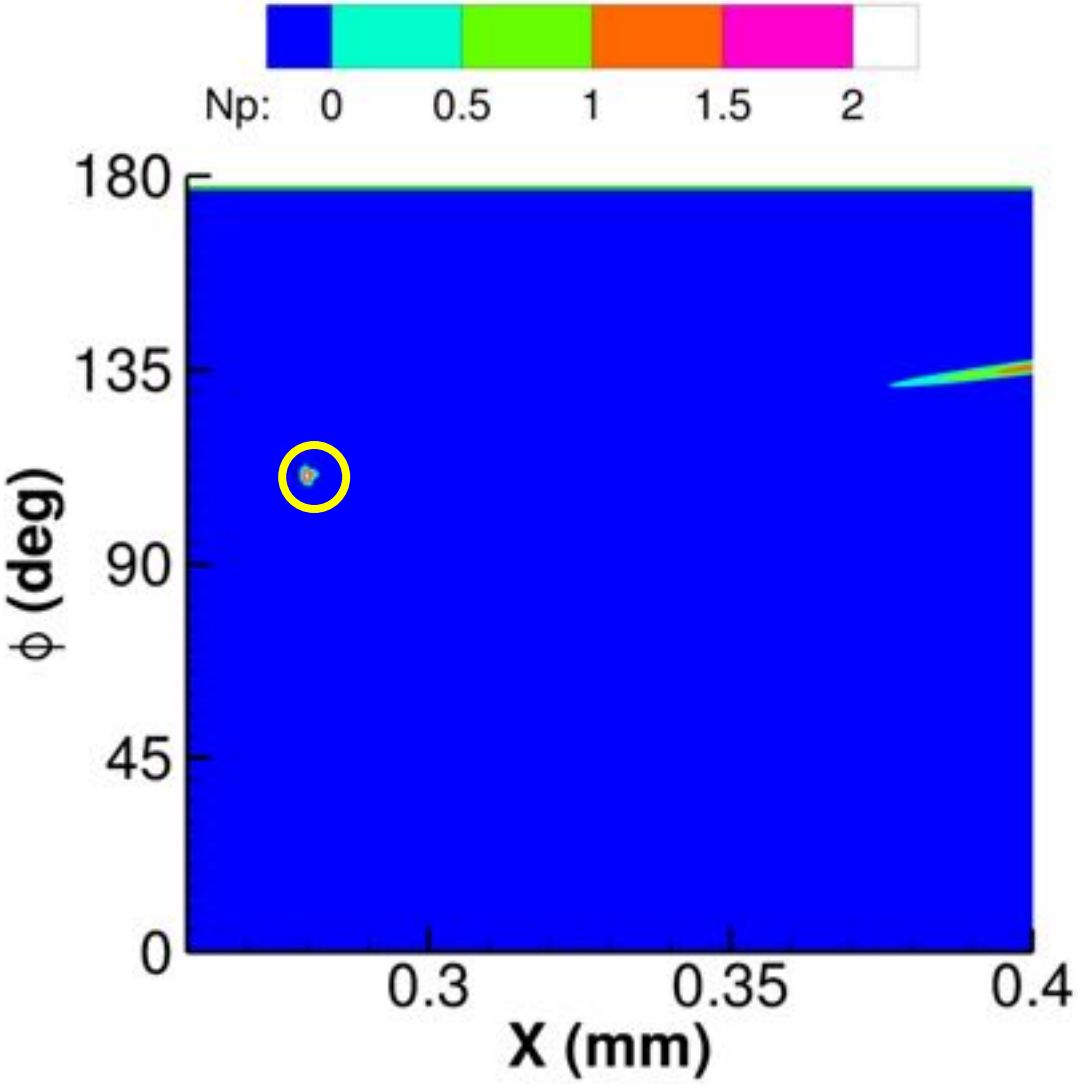
Mode Shape Evolution: 440 kHz



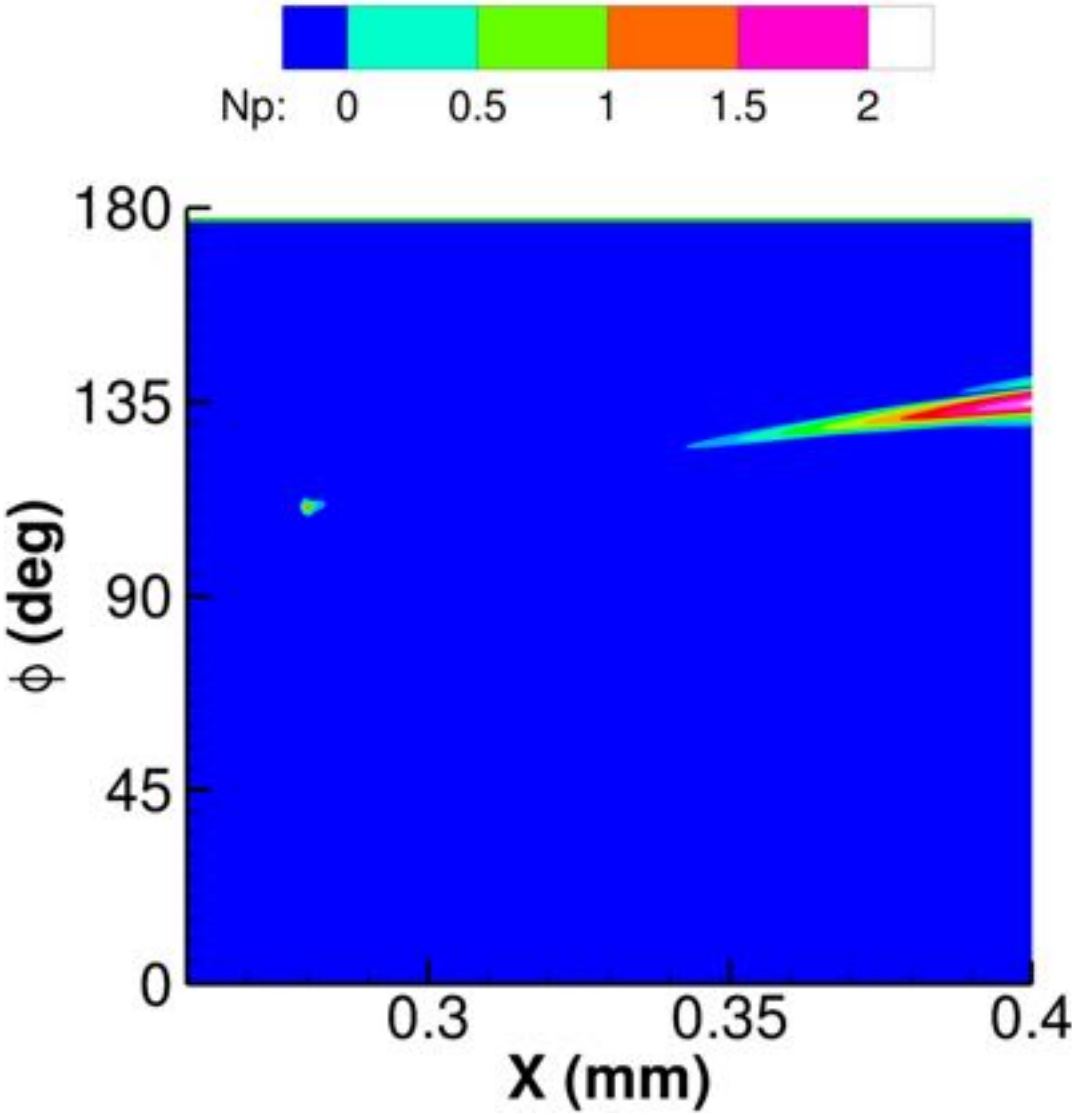
Localized Unsteady Forcing
N-Factor Contours: 100 kHz



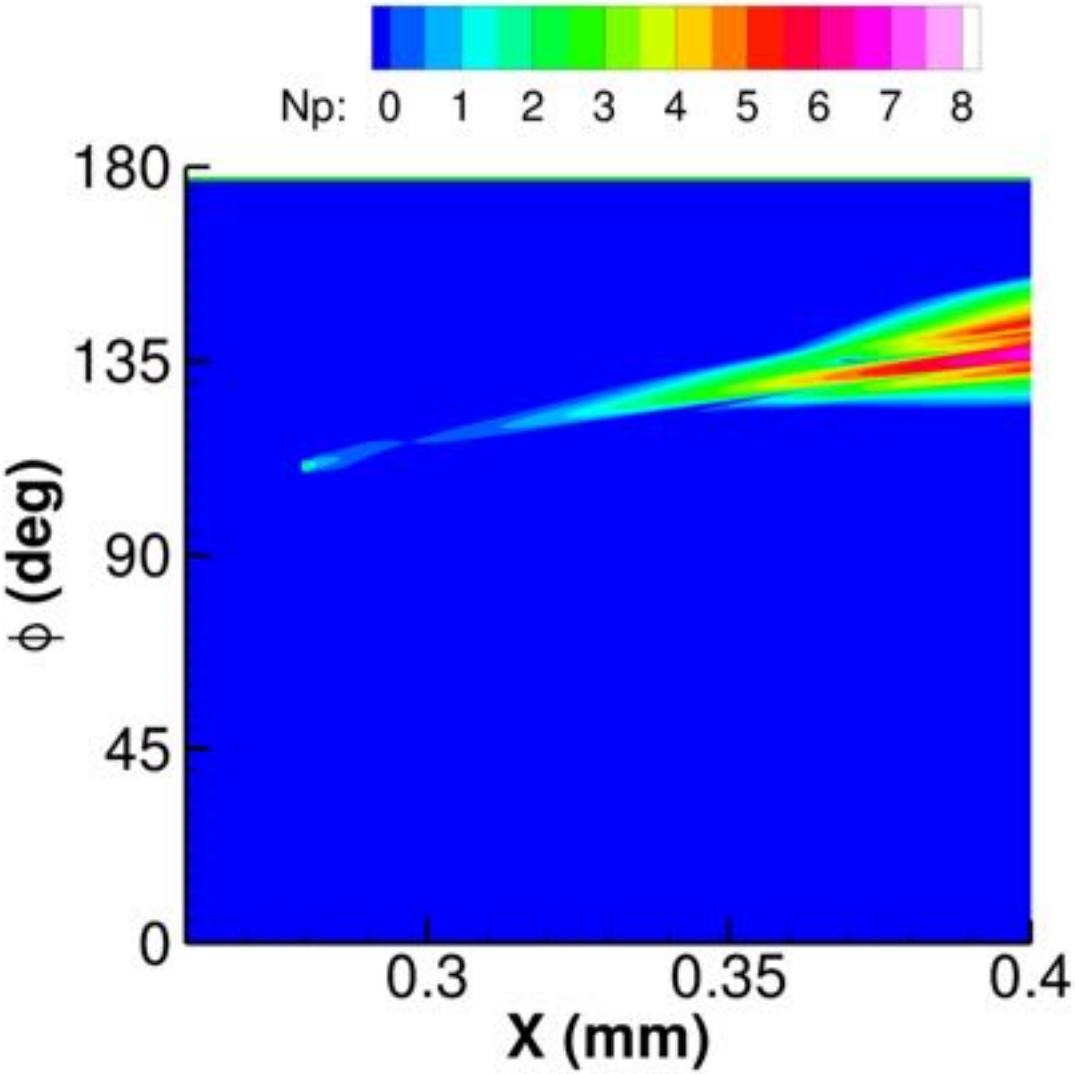
N-Factor Contours: 100 kHz



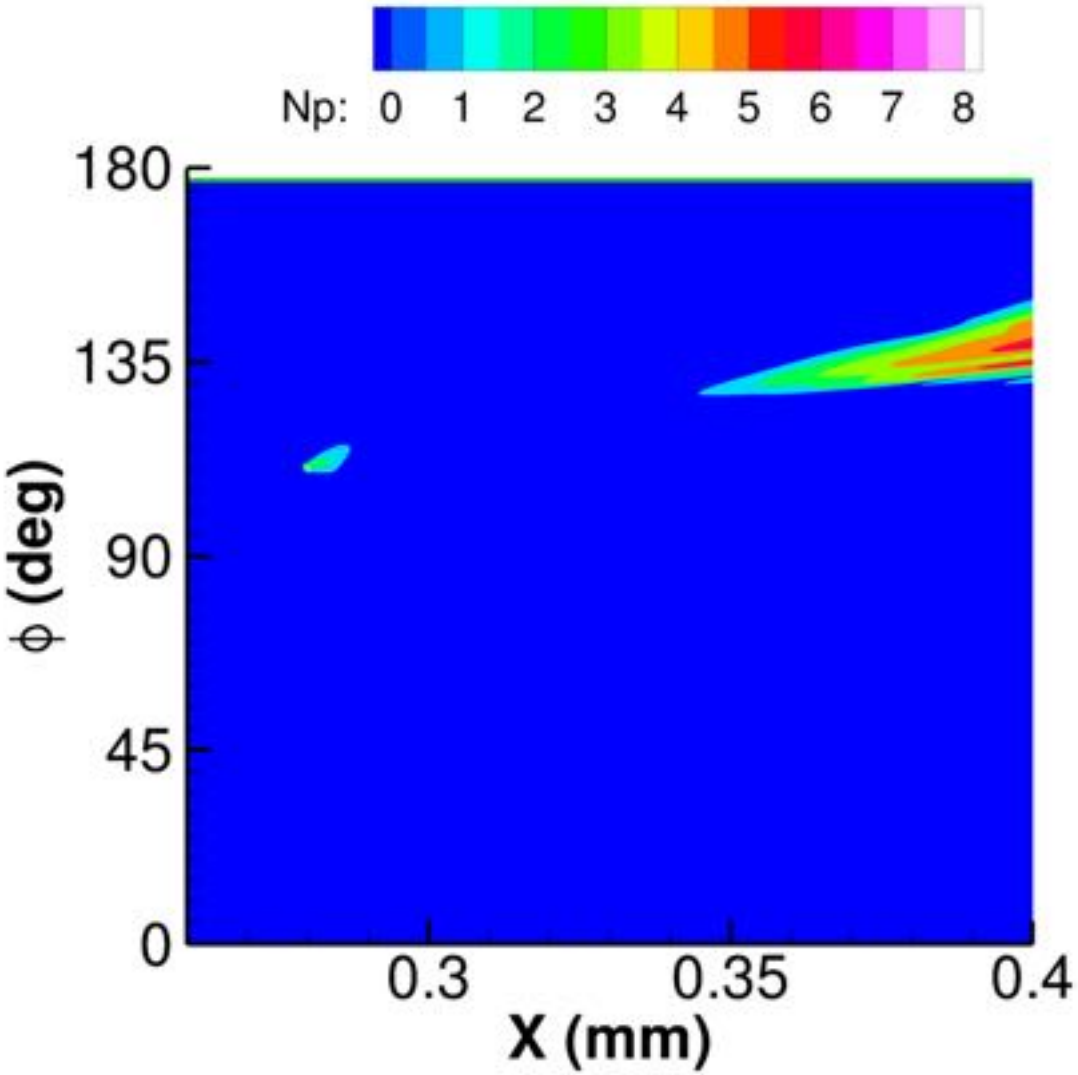
N-Factor Contours: 160 kHz



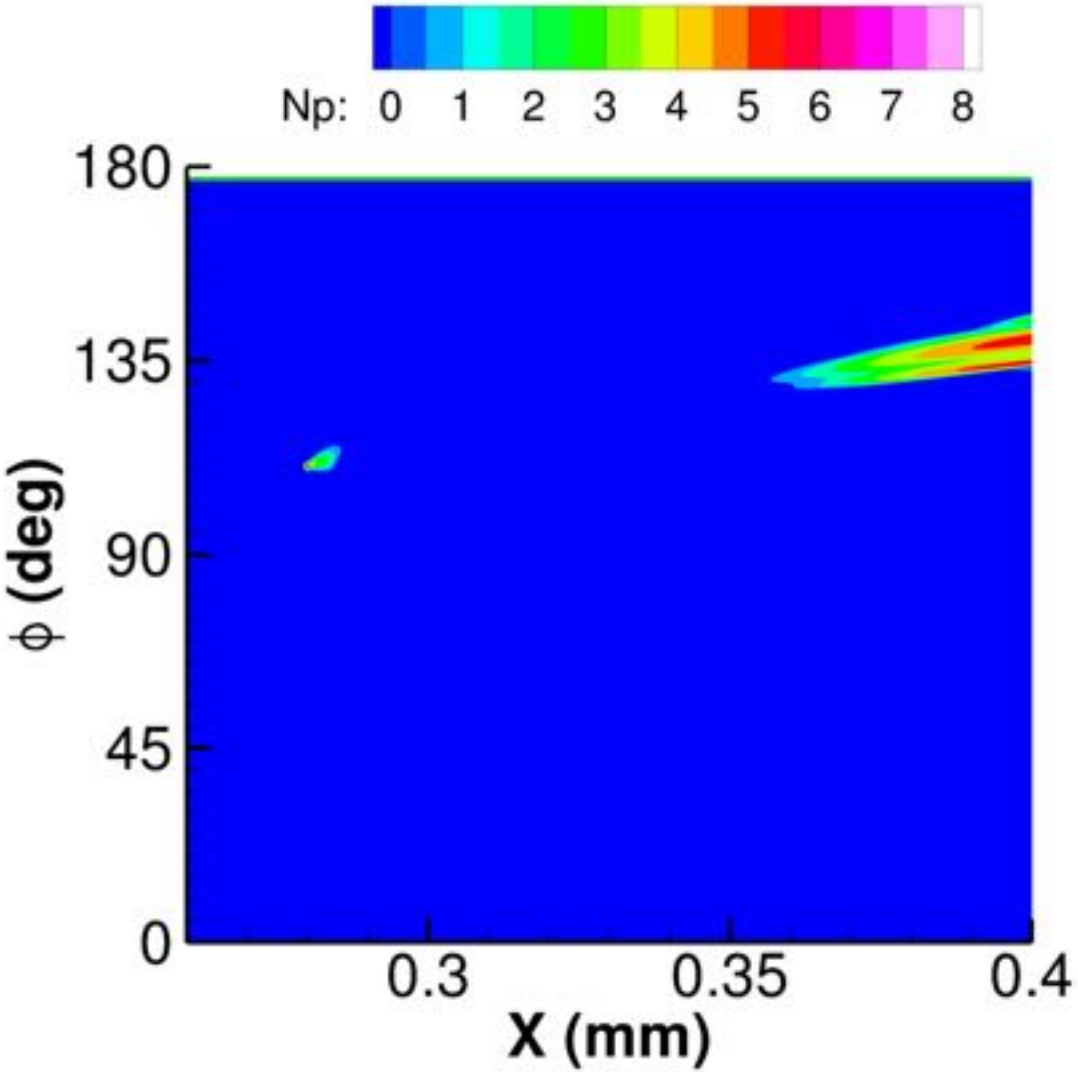
N-Factor Contours: 240 kHz



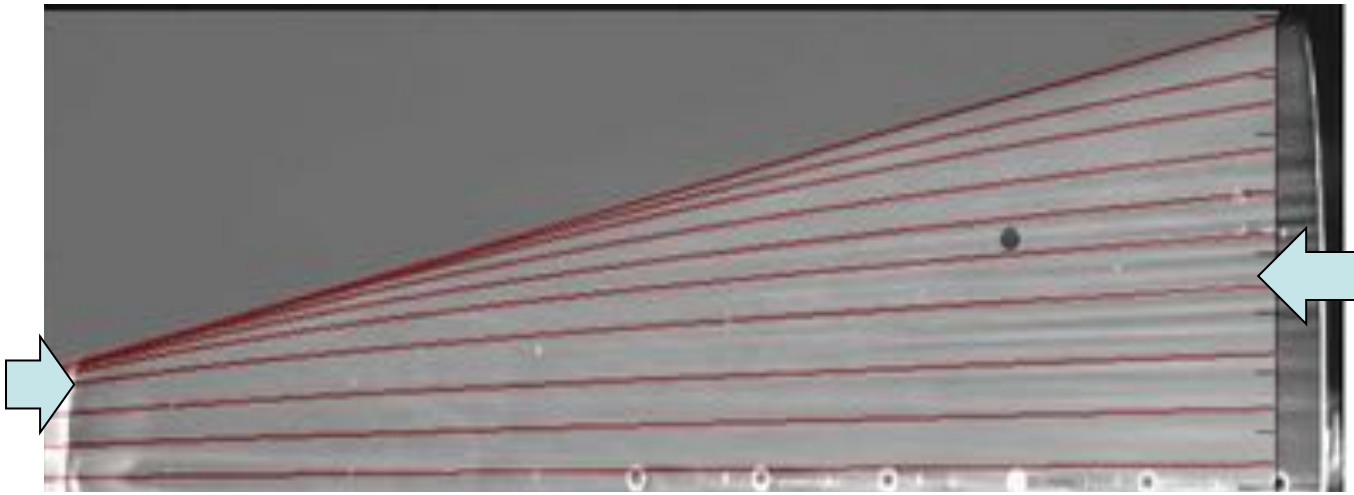
N-Factor Contours: 320 kHz



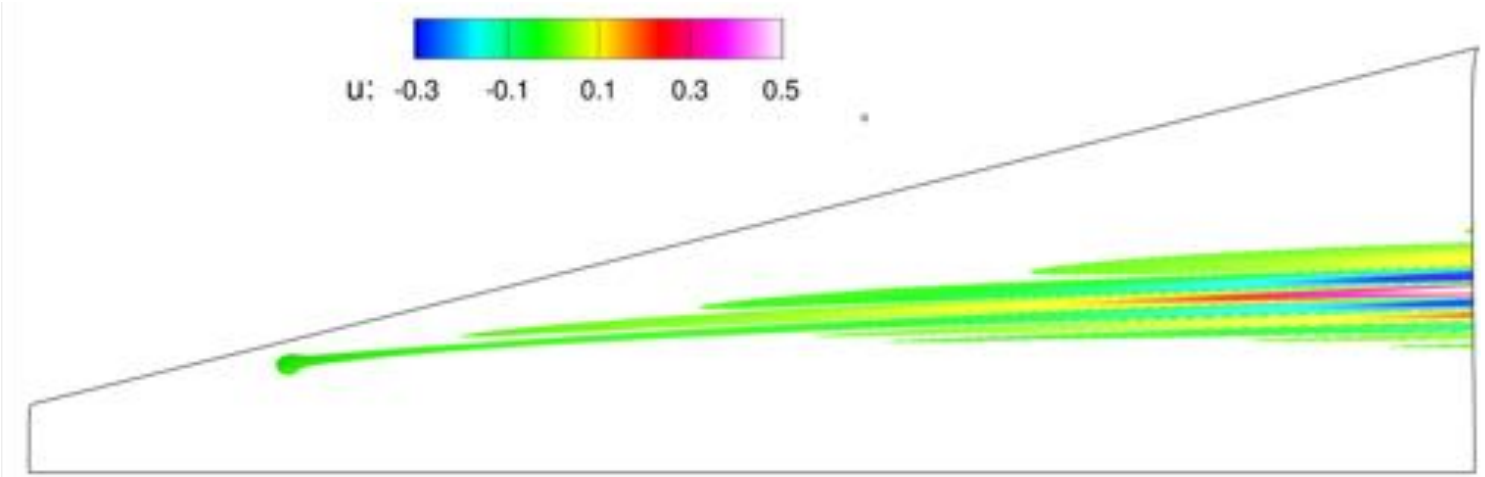
N-Factor Contours: 360 kHz

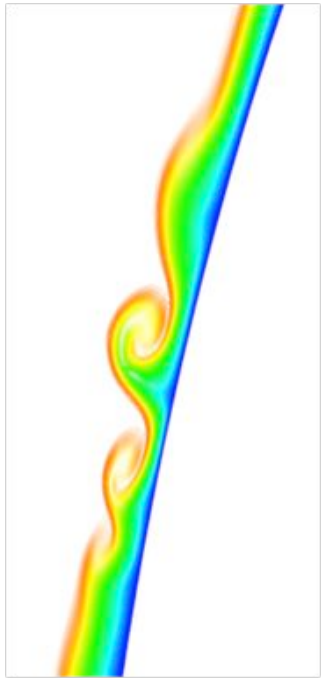


Pattern of Stationary Crossflow Vortices Due To Point Source

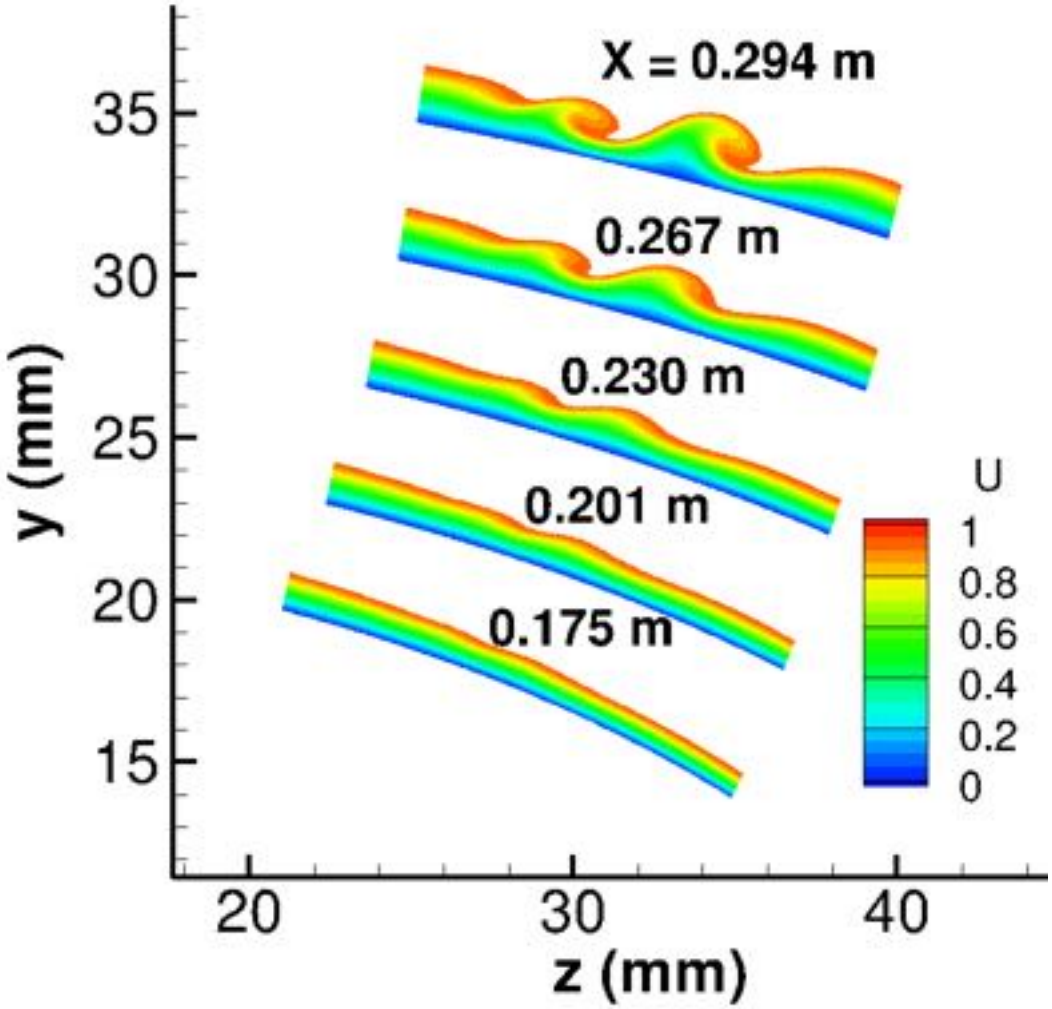




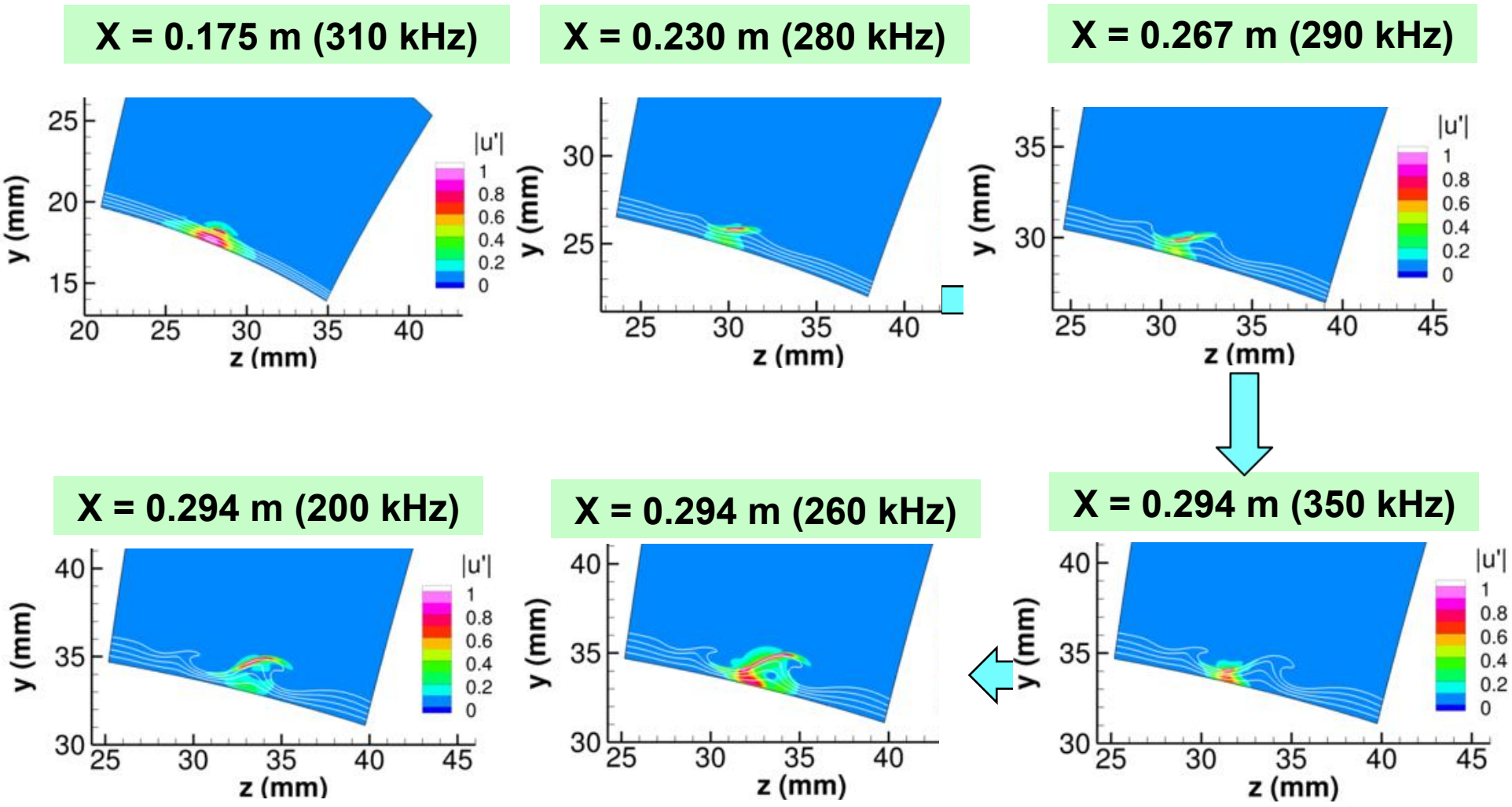




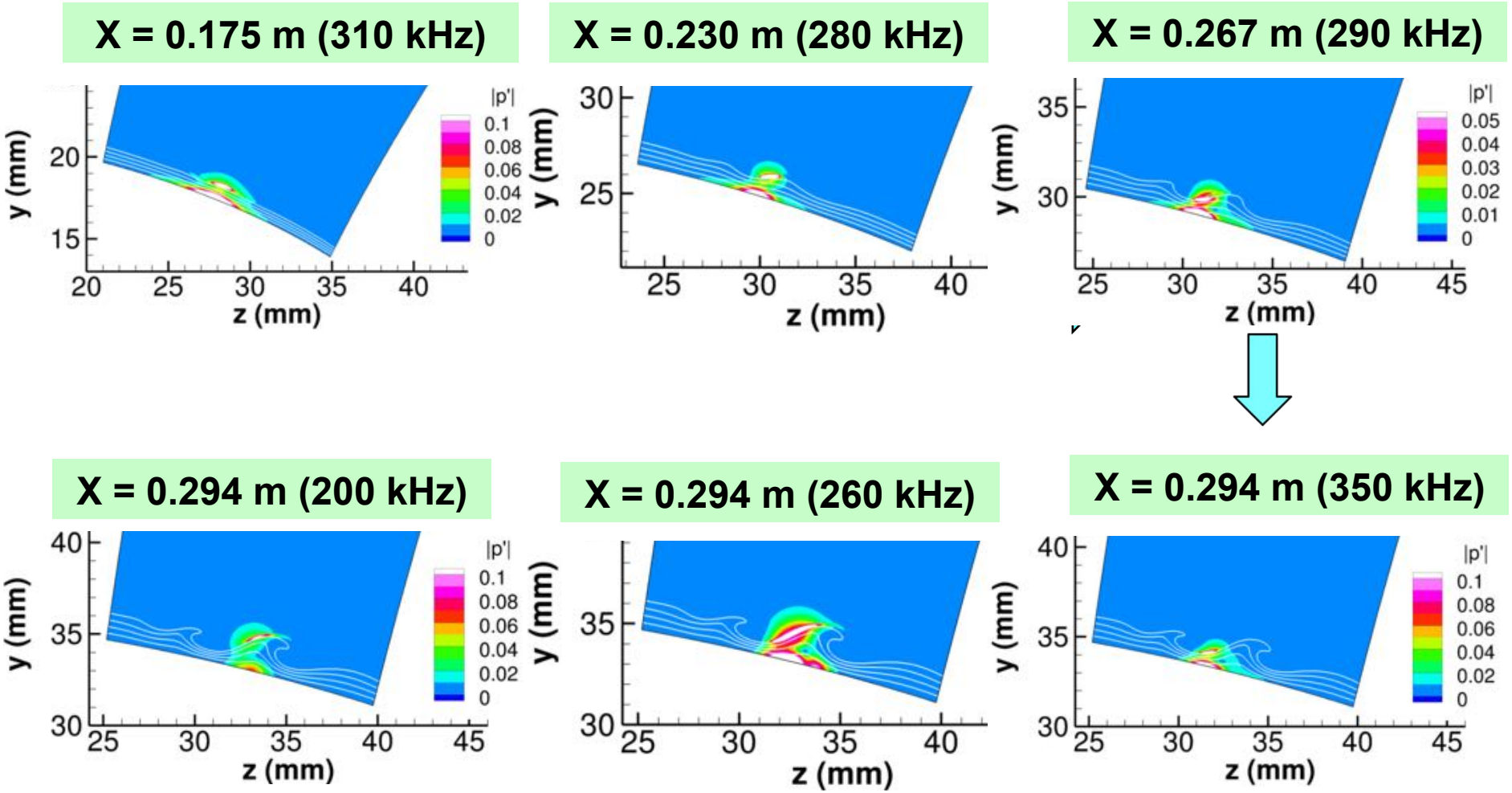
HIFiRE-5 Localized Source: Axial Velocity Contours



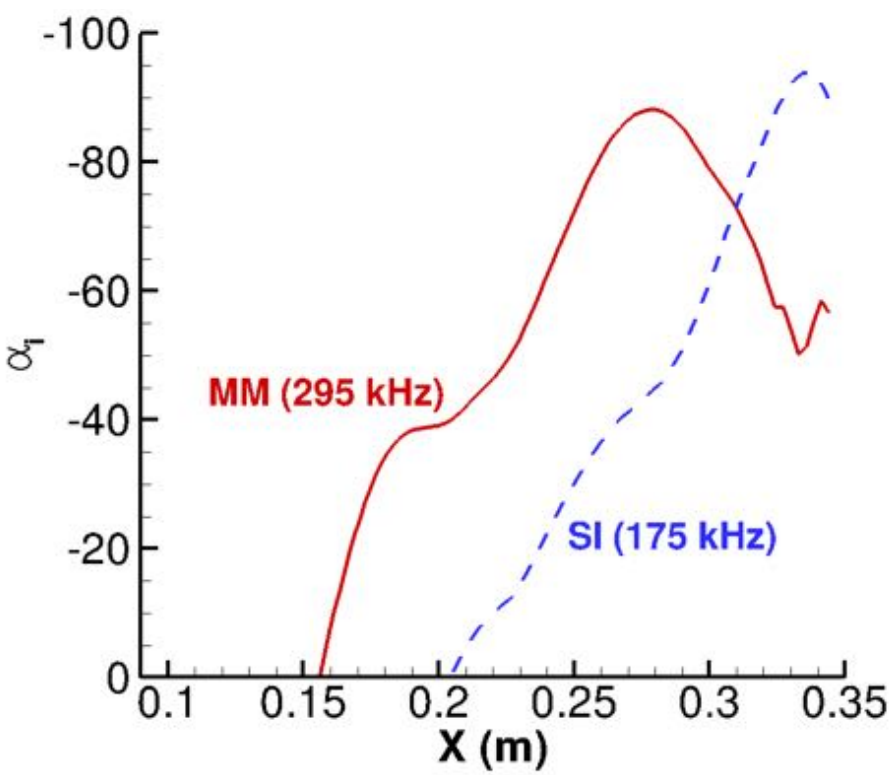
|u'| Mode Shapes: Mack Mode

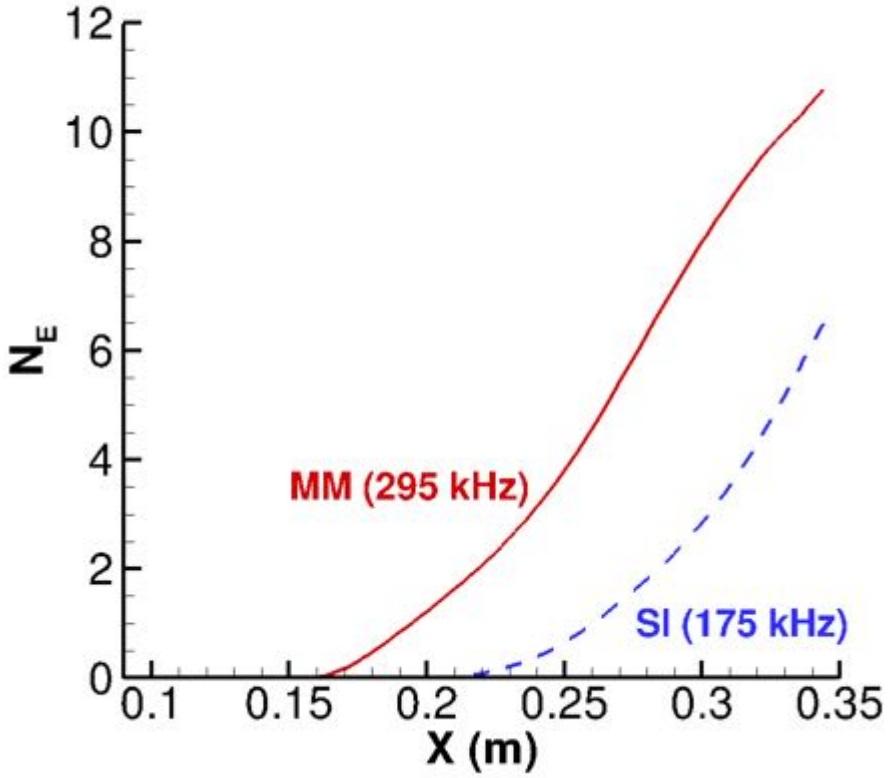


|p'| Mode Shapes: Mack Mode

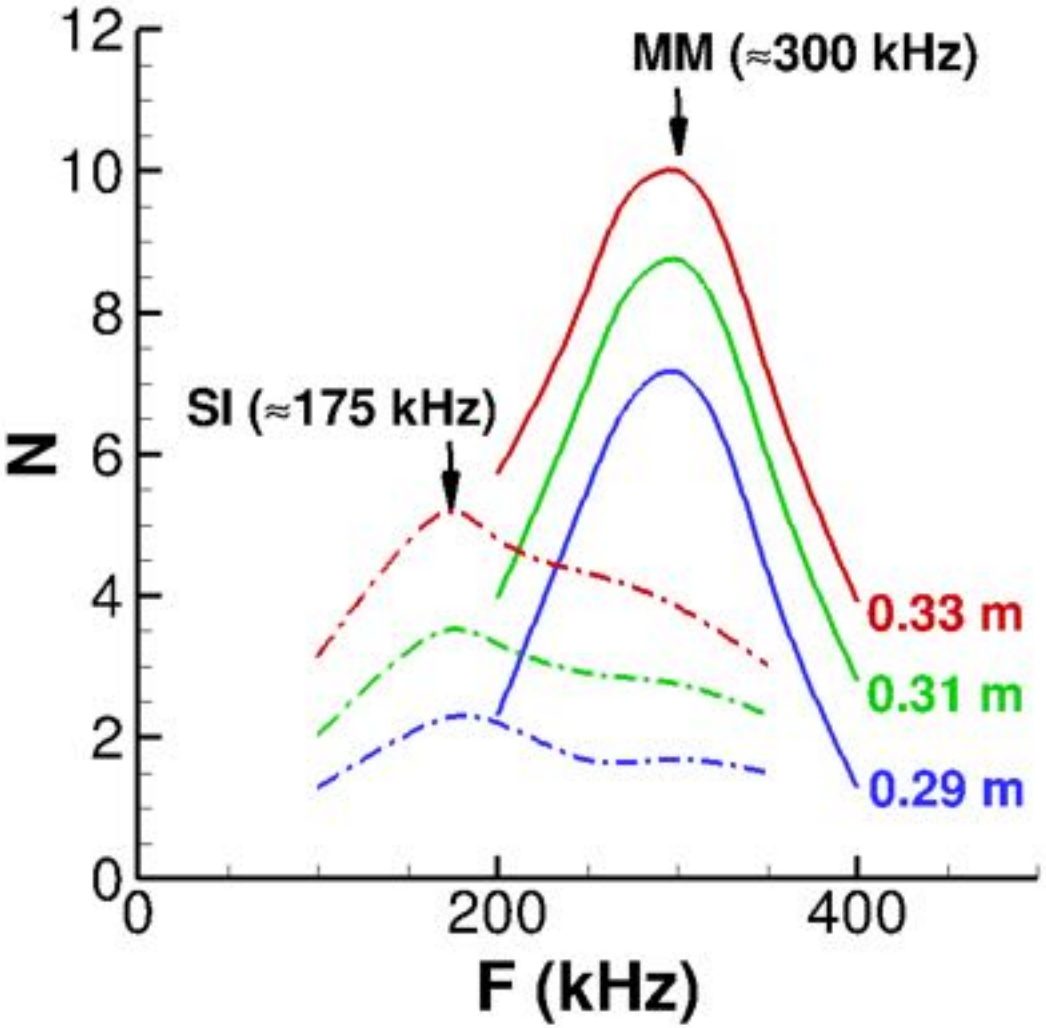


HIFiRE-5: Spatial Evolution

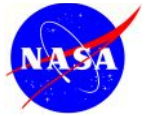




HIFiRE-5: N-factor Spectra



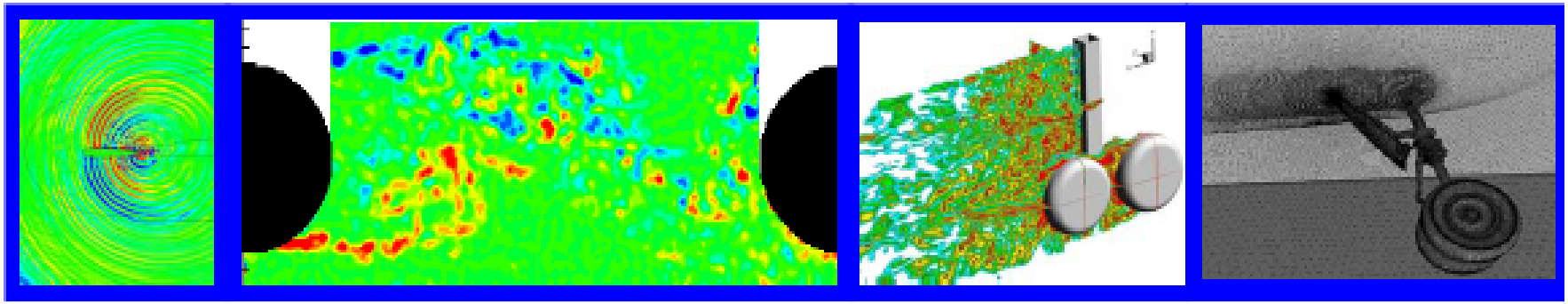
Summary



- DNS + secondary instability analysis for nonlinear evolution of crossflow disturbances over cones
  - Azimuthally compact vortex patterns over circular cone and HIFiRE5 model in BAMQT
- Simulated vortex structures resemble those from quasi-periodic vortex pattern
  - Provides conceptually easier path to interpret results from planar eigenvalue + PSE analysis for entire vortex pattern
- Secondary instability of compact crossflow vortex pattern
  - Mode shapes of dominant modes concentrated in individual vortices
  - Intricate modal structure with concentration of peak fluctuations along inclined shear layer ("Z" modes) and b.l. edge in region of downwelling
  - Modes along the top of the rolled up vortex generally subdominant
  - Broad range of frequencies with similar range as Purdue BAMQT measurements
- Disturbance evolution from DNS resembles predictions of secondary instability theory
  - Need to perform quantitative comparisons

BANC* Workshops: Collaboratively Advancing Simulations and Measurements of Airframe Noise

* Benchmark Problems for Airframe Noise Computations



M. Choudhari, M. Khorrami, D. Lockard

Computational AeroSciences Branch

C. Bahr, L. Lopes, and N. Zawodny

Aeroacoustics Branch

NASA Langley Research Center

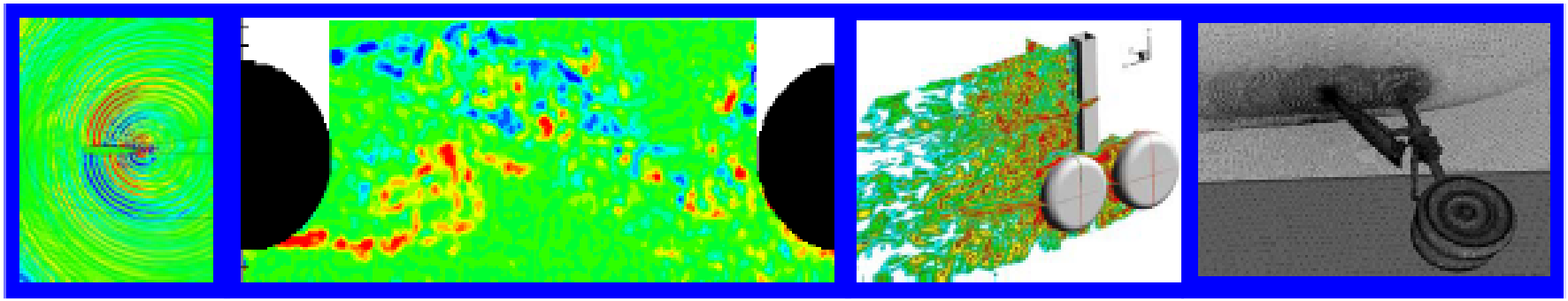
NASA Acoustics Peer Review

Oct 31-Nov. 2, 2016

Outline

- **Introduction to BANC Workshops**
- **Ingredients of integrated studies combining CFD, CAA, and experiments**
- **Examples of collaborative integration within BANC Workshops**
  - Quasi-2D configurations
  - 3D landing gear configurations
- **Lessons learned**
  - ✓ Wake interference between inline tandem cylinders
  - ✓ Slat cove noise
  - ✓ Landing gear noise
- **Summary**

BANC Workshops
(Benchmarks in the making!)

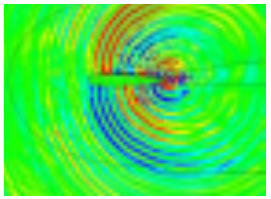


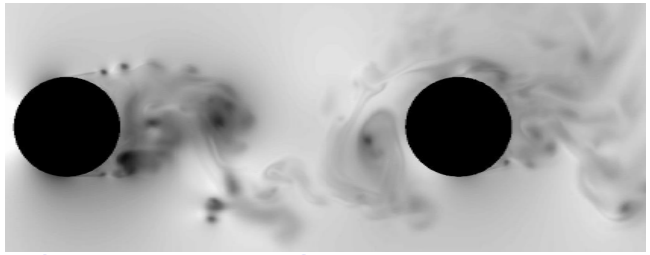
Goal: Enable systematic progress in the understanding and high fidelity predictions of airframe noise via **collaborative investigations that integrate CFD, CAA, and in-depth measurements of selected configurations** to advance the state-of-the-art in multiple respects

- ❑ **BANC-I : Stockholm, Sweden (2010)**
- ❑ **BANC-II: Portland, OR (2012)**
- ❑ **BANC-III: Atlanta (2014)**
- ❑ **BANC-IV: Lyon, France (2016)**
  - ➢ 50-85 participants on average from up to 12 countries

BANC-I Problem Categories

(component level / specific physics of noise generation)





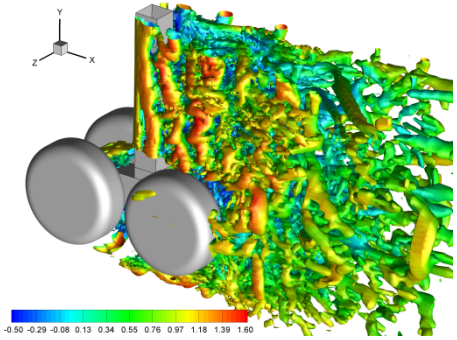
1. Airfoil Trailing Edge Noise

-- Canonical problem, final frontier for AFN

2. Unsteady Wake Interference Between a Pair of Tandem Cylinders

-- Developed as a model, comprehensive aeroacoustic dataset

-- Deceptively simple: requires substantial compute power, grid convergence difficult to demonstrate



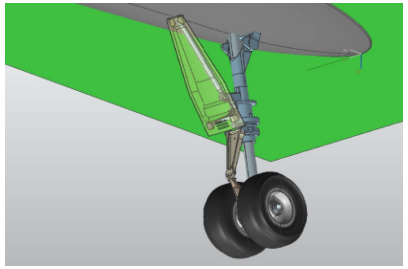
3. Rudimentary Landing Gear (RLG)

-- Grid convergence easier to demonstrate

-- Evolving nature of experiment allows greater interplay between simulations and experiment design

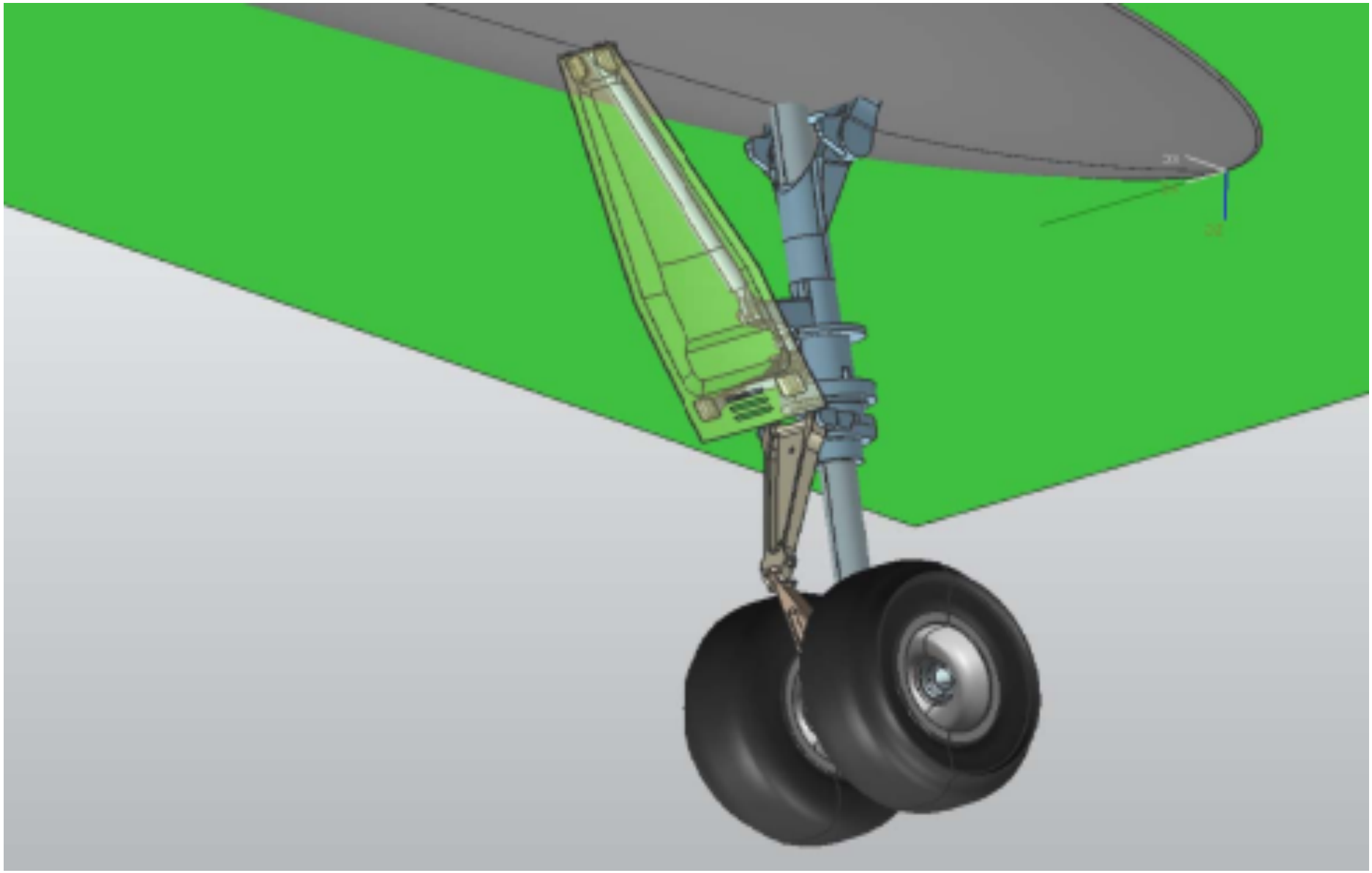
4. Partially Dressed Cavity Closed Nose Landing Gear (PDCC-NLG)

-- Reflects complexity of real landing gears



BANC-I Problem Categories

(component level / specific physics of noise generation)

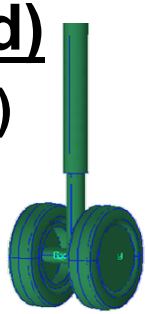


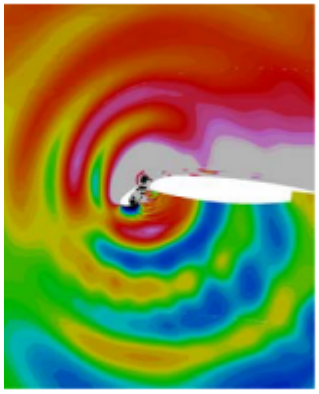
BANC Problem Categories (BANC-II Onward)

5. LAGOON simplified landing gear (Airbus-ONERA)

-- Complementary to RLG & PDCC-NLG

-- Rich, holistic measurement database





6., 7. Slat cove noise:

F16 (DLR) and 30P30N (NASA) datasets

-- Canonical high-lift configurations with and without installation effects, respectively

-- Rich legacy of prior aerodynamic benchmarking

-- Evolving benchmarks enabling true impact of collaborative efforts

8. Acoustic propagation phase of airframe noise prediction

-- Isolate propagation phase to allow meaningful comparisons for the other categories

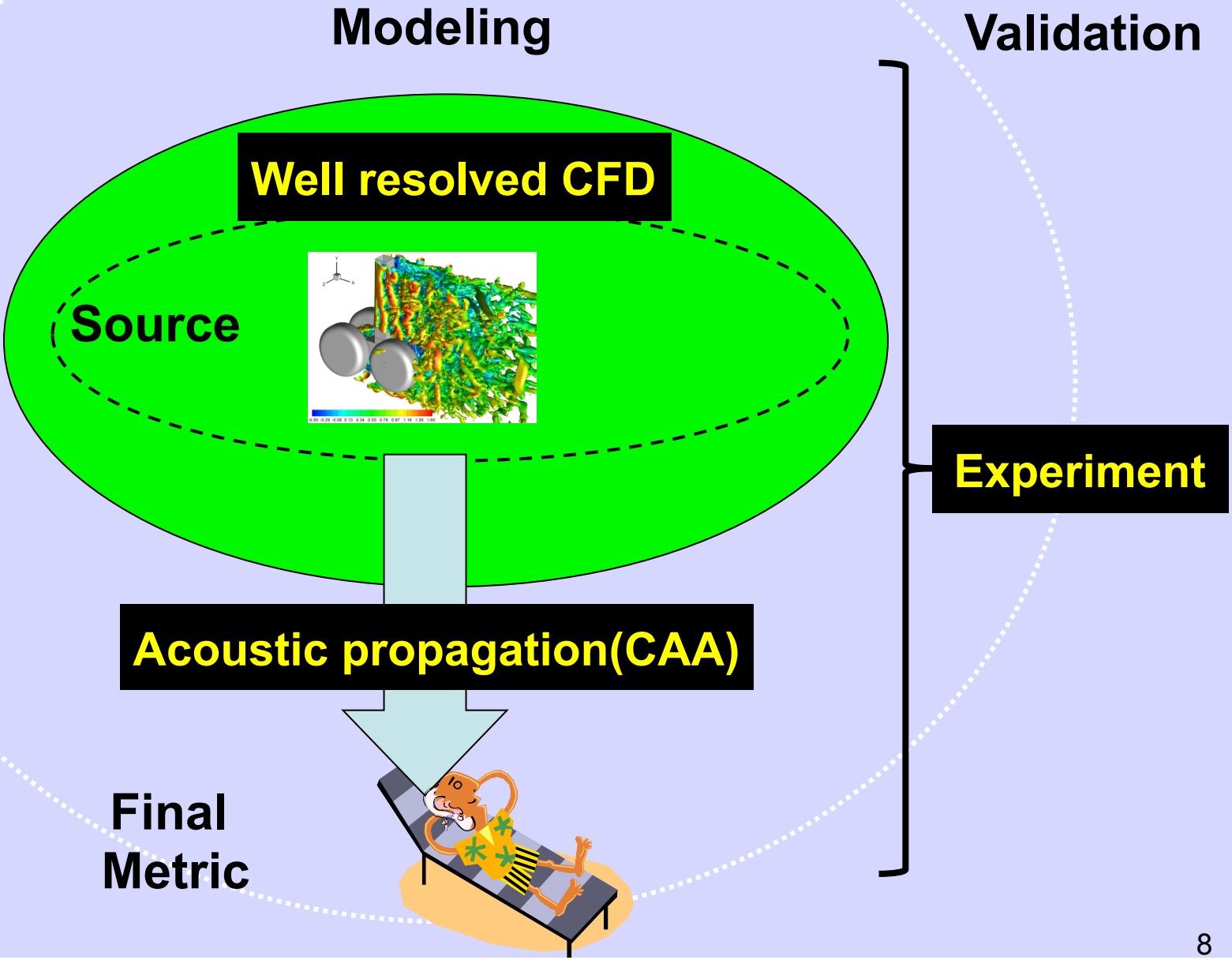
Category Leads & NASA Investments + Collaborations

1. Michaela Herr (DLR), Chris Bahr (NASA), Mohammad Kamruzzaman (Vestas Technologies UK Ltd.)
2. David Lockard (NASA)
3. Philippe Spalart (Boeing)
4. Mehdi Khorrami (NASA), Thomas Van de Ven (Gulfstream)
5. Eric Manoha (ONERA), Caruelle Bastien (Airbus)
6. Michael Pott-Pollenske, Jan Delfs (DLR), Eric Manoha (ONERA)
7. Meelan Choudhari, David Lockard, Mehdi Khorrami, (NASA)
8. Leonard Lopes, Nikolas Zawodny (NASA), Tomoaki Ikeda (JAXA) Stephane Redonnet (ONERA), Taro Imamura (U. Tokyo)

+ others (Hutcheson, Brooks, Stead, Neuhart, Jenkins, …)

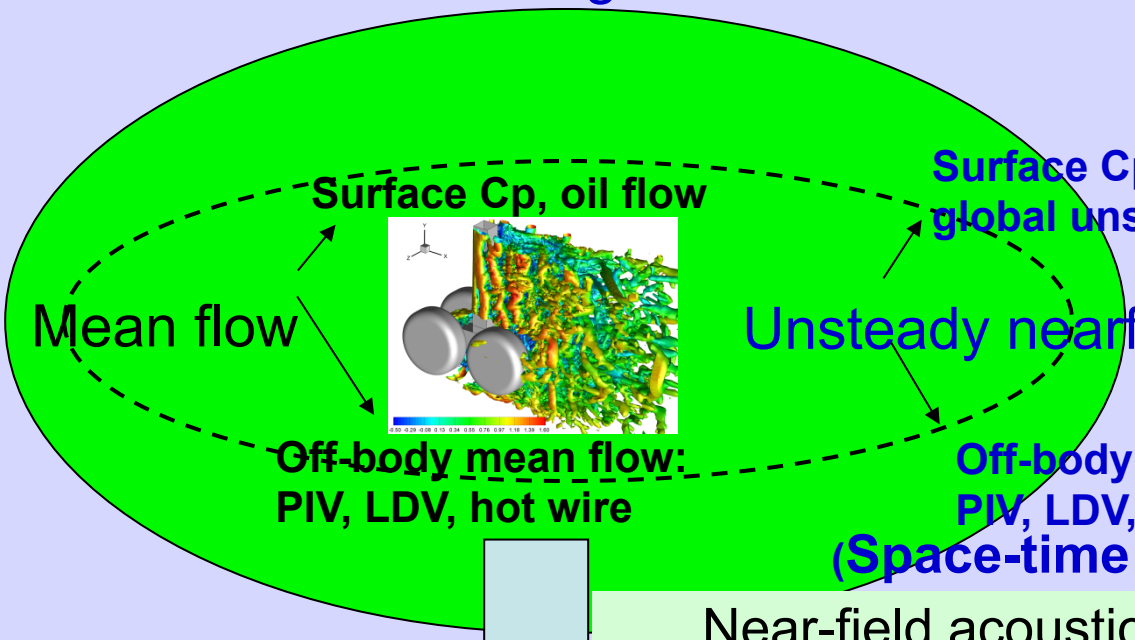
- NASA investment via stewardship for categories, model fabrication, **measurements, and simulations**

Hybrid Aeroacoustic Prediction (CFD + CAA Integration)



Measurement Strategy (Nearfield-Farfield Integration)

Holistic data + computational metrics addressing full chain of acoustic causality



Near-field acoustics
Mics, in-flow mics



Far-field acoustics
Microphones: individual, arrays

Key Features of BANC Workshops

- Intrinsically multi-disciplinary focus (fluid dynamics+acoustics)
- Holistic rather than predictive emphasis

  ≠ CFD validation against experiments

  = Equal role for both (cross-comparison to ensure common focus)

  + understanding of noise sources
- Concurrent, long term evolution of experiments and simulations with powerful interplay

  ⇒ Most categories continue over multiple workshops until the category objectives have been met

Scope of presentation:

- **Illustrate these features for selected BANC problem categories**
- **Outline challenges involved and how they were addressed**

Drivers for Integration = Validation Challenges

- Intricate noise source physics
  - geometric complexity of airframe components
  - high Reynolds number turbulence
  - multiple regions of separation
  - strong interaction between flow unsteadiness and solid surfaces, and between adjacent physical components



- Sensitivity to installation effects and facility details in experiments
  - Closed wall wind tunnels better suited for in-depth flow measurements
  - Open jet anechoic facilities reduce difficulties in farfield noise measurement, but may compromise aerodynamic simulation

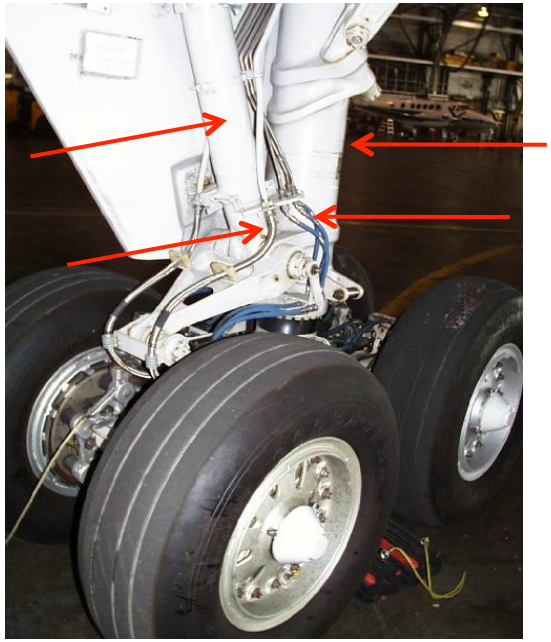
Ingredients of Integration within BANC Workshops

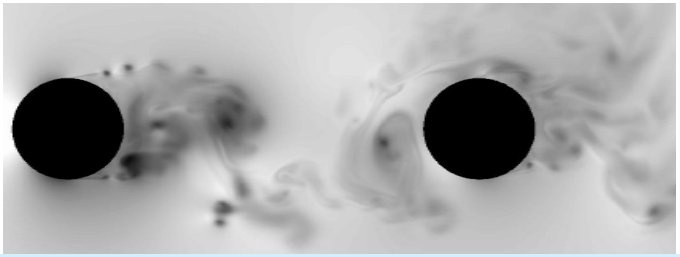
- **Strong role of computational stakeholders in design, conduct, and analysis of experiments**
- **Selection of canonical problem(s)**
  - Realistic, with a balance between geometric complexity, relevant physics, computational requirements, and experimental constraints
  - Multi-facility experiments wherever possible
  - **Multiple configurations** for a given noise source
- **Holistic measurements**
  - Address full causal chain leading up to far field noise
  - Unsteady aerodynamics + spatial coherence distribution in nearfield and nearfield/farfield acoustic data
  - Redundant, multi-facility measurements
- **Continuous interplay between computations and experiments**
  - **Niche workshop contributions to quantify effects of experimental artifacts ("being on same page" is pre-requisite for validation)**
- **Paradigm shift: single group, single facility experiments to multi-organization, multiple facility experiments over multiple entries**

Examples of Integration in BANC Configurations

2. Unsteady Wake Interference Between a Pair of Tandem Cylinders

- Developed as a model aeroacoustic dataset to anchor BANC-I
  - **BANC dataset adopted by EU 7th Framework project Advanced Turbulence Simulation for Aerodynamic Application Challenges (ATAAC)**
  - **Majority of category objectives successfully met**
  - **➔35+ papers thus far**
- Deceptively simple
  - Installation effects, extraneous sources, secondary scatterers
  - Bistable flow behavior in simulations
  - Measurable effects of tripping along rear cylinder

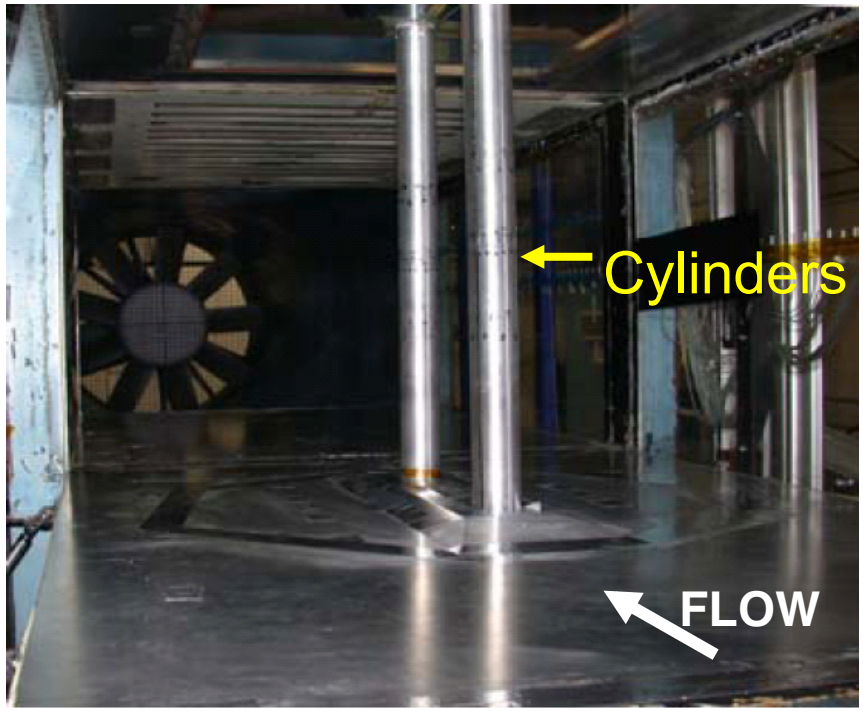




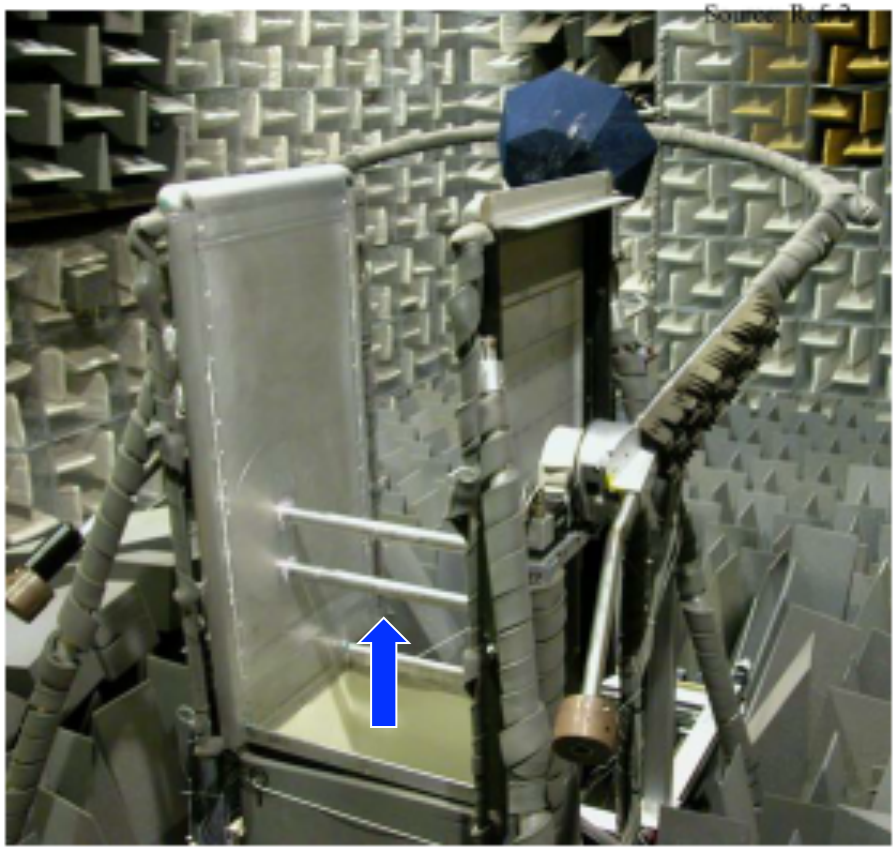
- Spacing = 3.7 D
  → synchronized co-shedding,
  predominantly tonal flow and noise
- Turbulent separation via trips
  - Other challenges:
    Optimal tripping under favorable dp/dx,
    effect on spectra, modeling in LES

Testing in Closed Wall and Open Jet Facilities

BART Facility

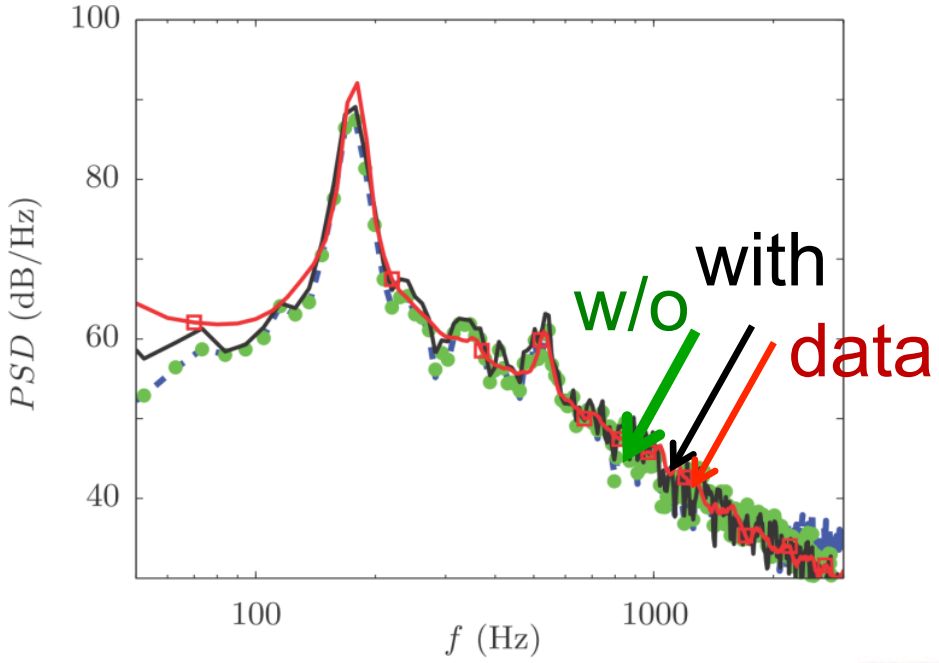


Tandem Cylinders in QFF

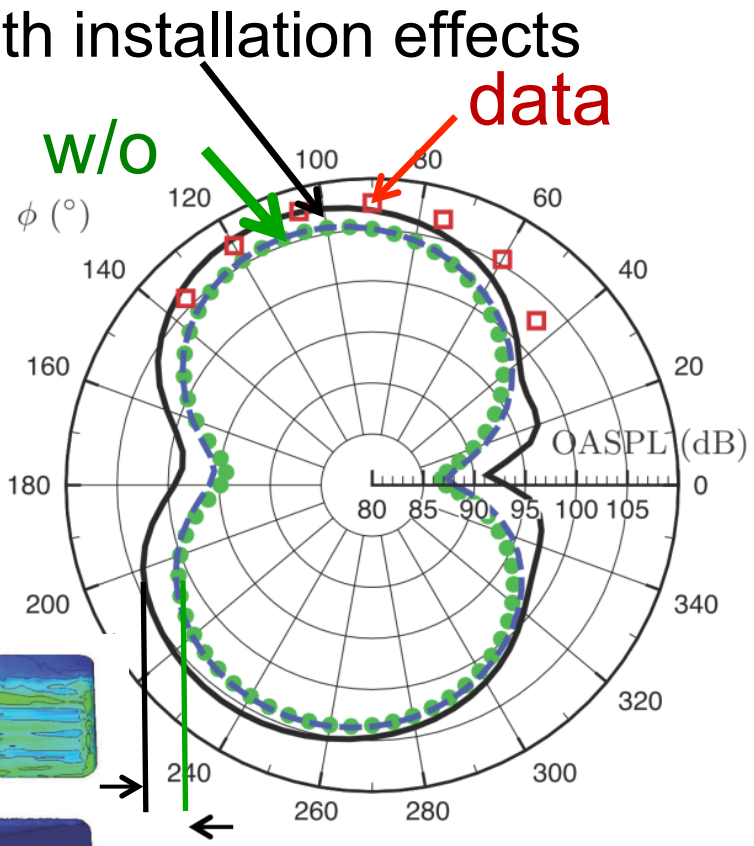


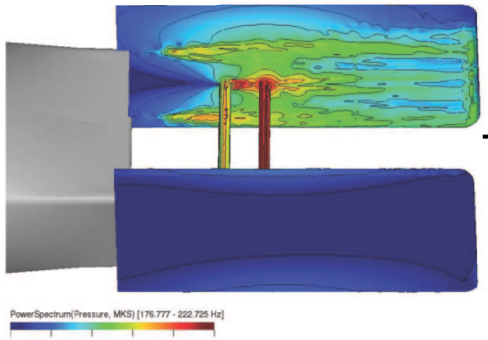
Facility-Scale CFD/CAA Simulation Clarified Installation Effects (Informal Collaboration with Exa Corporation)

Noise spectrum



OASPL Directivity

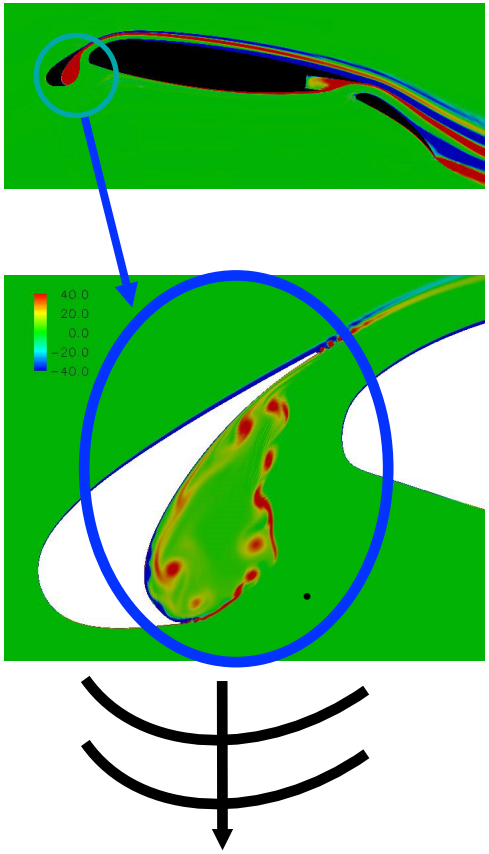


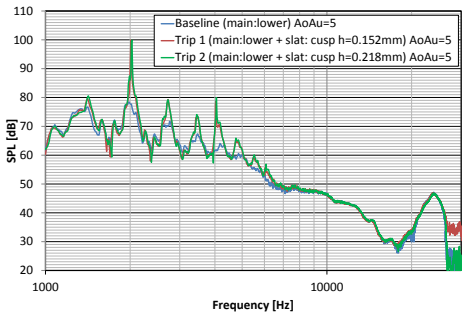


→ Basis for improved assessment of workshop contributions

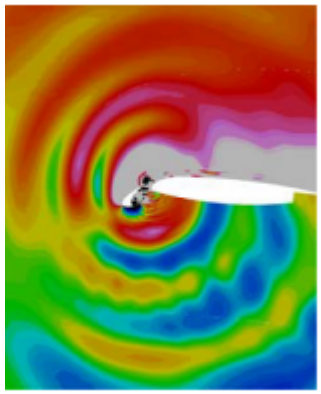
Slat Cove Noise

Cat. 6. LEISA II High-Lift Configuration (DLR, ONERA)
7. 30P30N High-Lift Configuration (NASA, JAXA, FSU, Boeing)





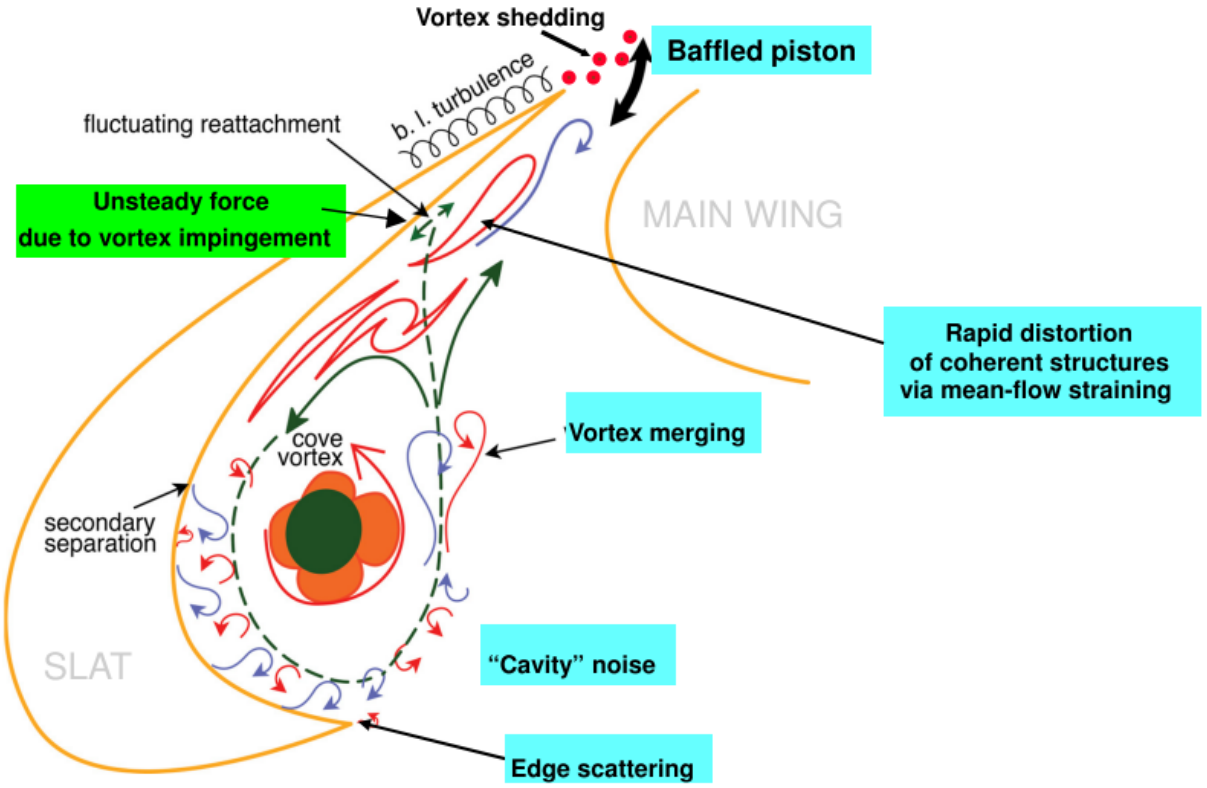
- **Synergistic, 2D configurations to characterize sensitivity to facility + model geometry**
  - **Allow confirmation of trends**
  - **Overlapping & complementary measurements**
  - **Baseline for realistic configurations (sweep, taper, twist, brackets, geometric details)**
- Rich legacy of prior aerodynamic benchmarking
- **Evolving benchmarks, enabling true impact of collaborative efforts**



- Broadband spectra, but with multiple narrow-band peaks (NBPs) due to flow-acoustic resonance
  - Sensitive to model geometry and flow conditions
  - Possible dependence on facility

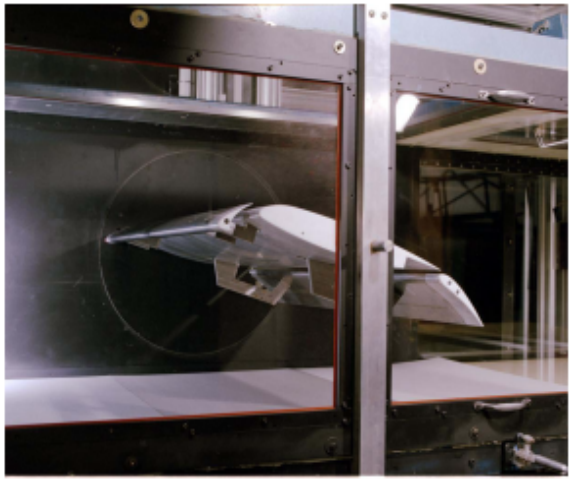
Technical Challenges

- Primarily broadband noise + narrow-band peaks (NBPs) that tend to be sensitive to configuration and facility details
- Complex source physics (multiple competing mechanisms)
- Extraneous, model-intrinsic noise sources (flap separation, wing/flap trailing edges)
- At times, conflicting findings between scaled model measurements and flyover

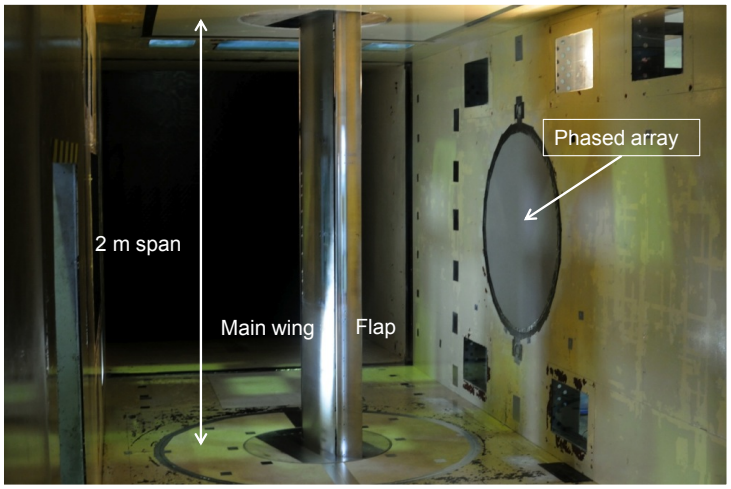


Measurements of 30P30N High Lift Configuration

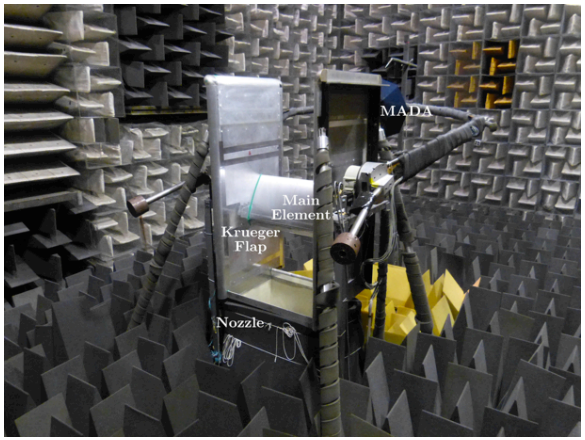
BART Wind Tunnel



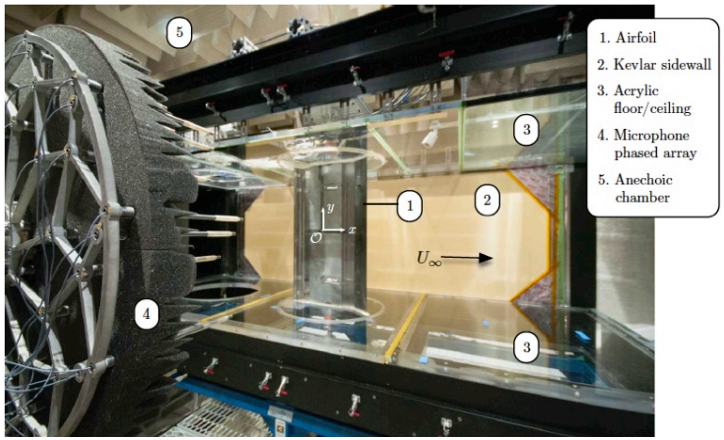
JAXA-LWT2 Wind Tunnel



QFF Open Jet Facility



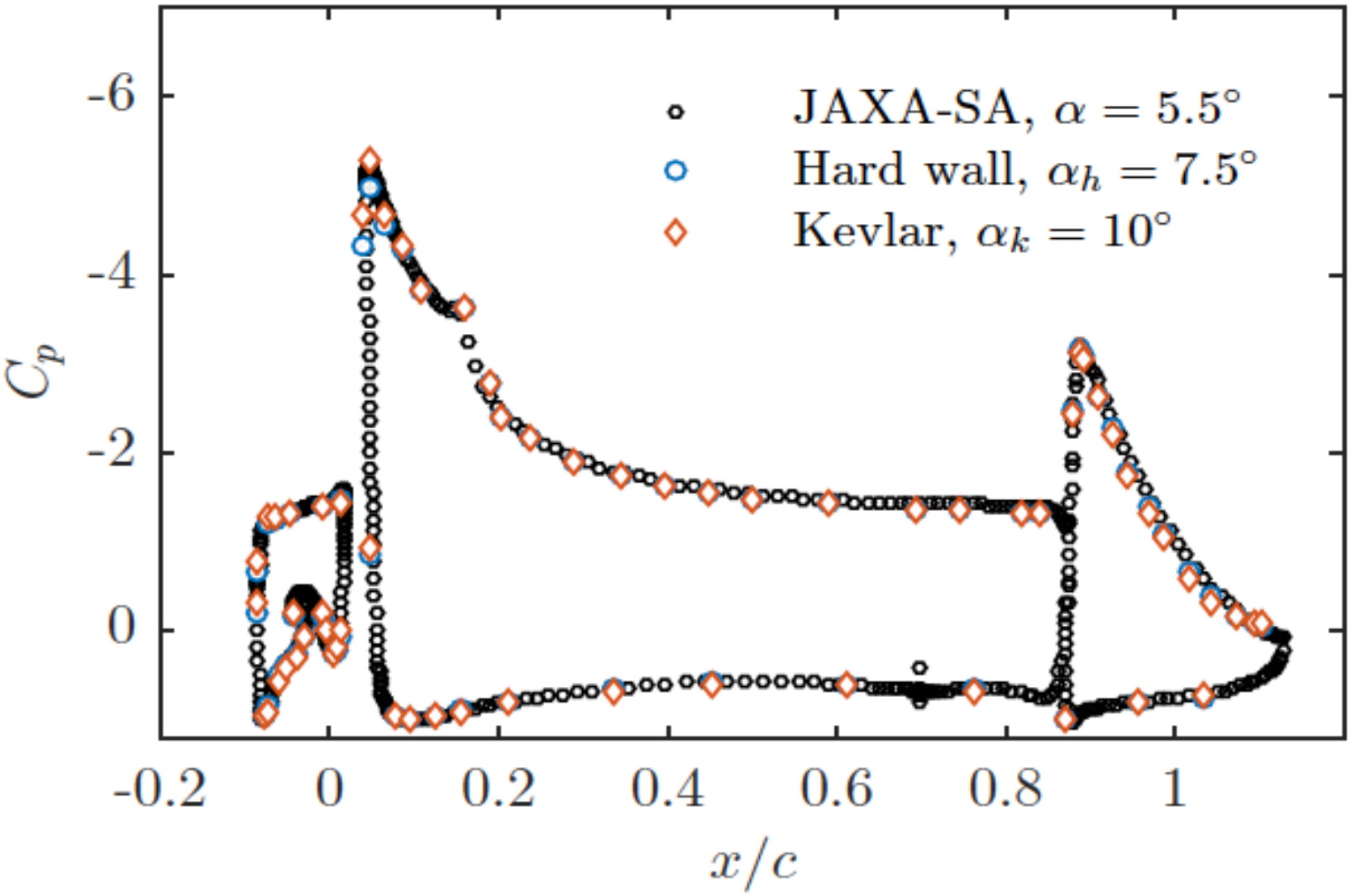
Kevlar™ wall test section (FSU)



+ Embraer facility

Validation Success: CFD to Calibrate AoA in Wind Tunnels

Mean Cp: Measurements vs. Open Air RANS

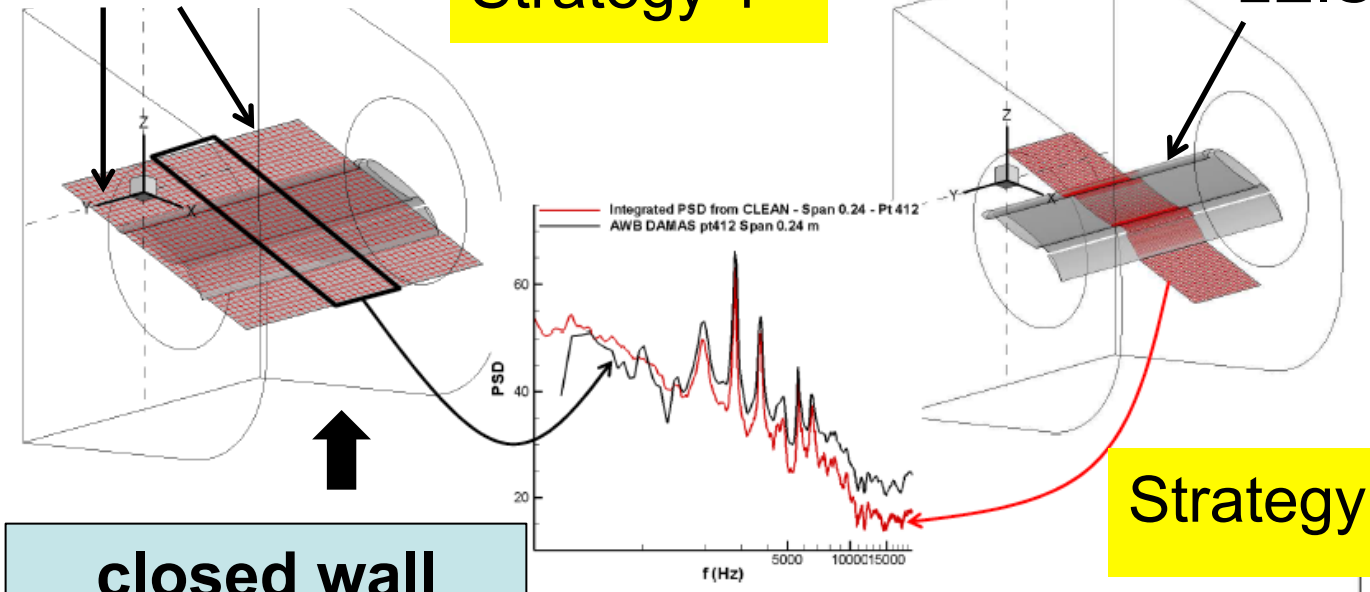


Validation Challenges: Comparison With Microphone Array Measurements

Rejection region

Strategy 1

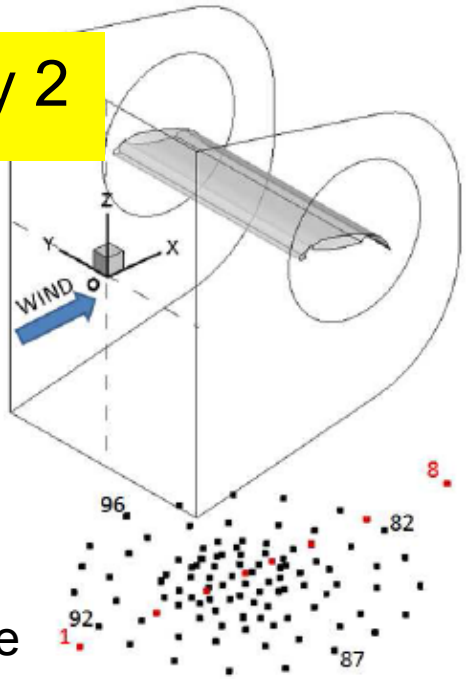
LEISA2



open jet
DLR AWB

closed wall
ONERA F2 CEPRA
FSU
JAXA

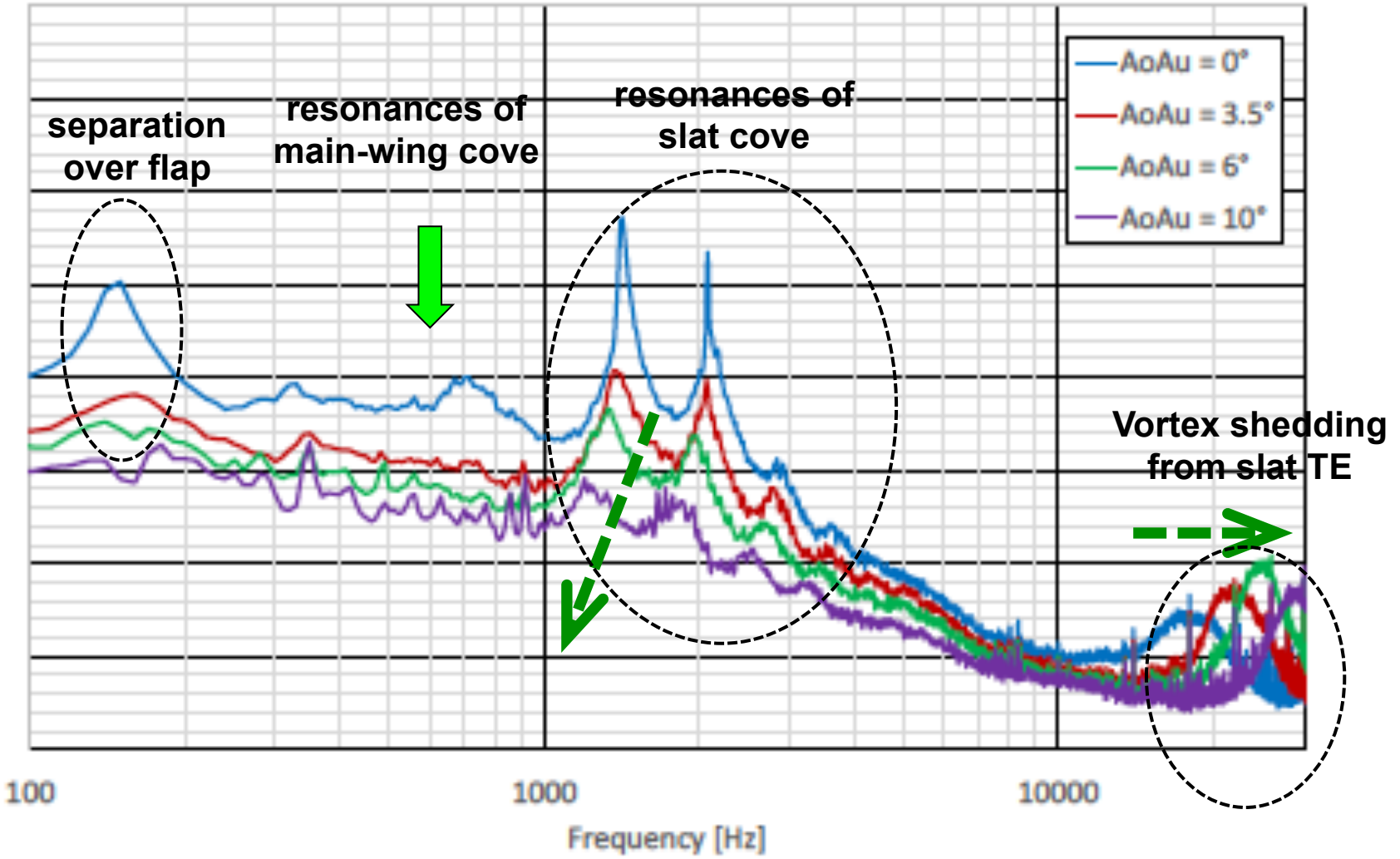
Strategy 2



Microphone array

Origins of Spectral Peaks (Who Dun It) and Associated Acoustic Radiation Patterns

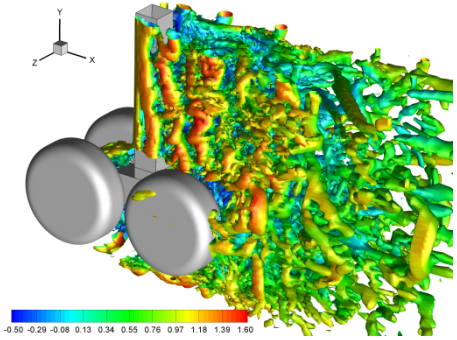
- Surface Pressure Spectra on main wing leading edge JAXA-NASA Measurements (Murayama et al. 2014)

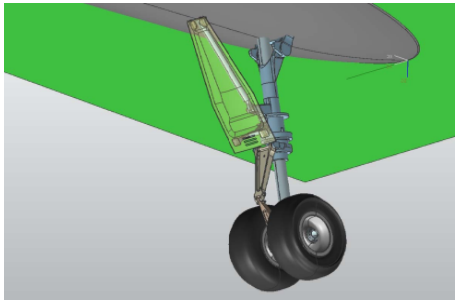


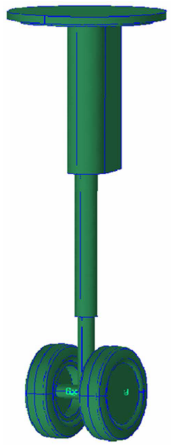
Landing Gear Noise

Cat. 3. Rudimentary Landing Gear (Boeing)

4, 5. PDCC-NLG (NASA, Gulfstream), LAGOON (ONERA, Airbus)





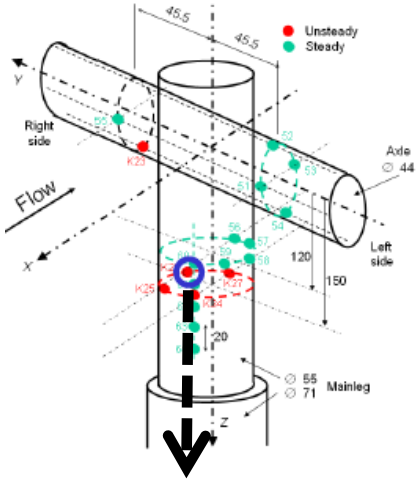


- **Synergistic configurations representing both main and nose landing gears via varying degrees of geometric fidelity**
  - ➢ **All highly complex geometries and fully 3D**

- Mostly broadband spectra with an occasional narrow-band peak (NBP)
- Minimal jet deflection in open jet facilities

Validation Challenges: CFD vs. Acoustics

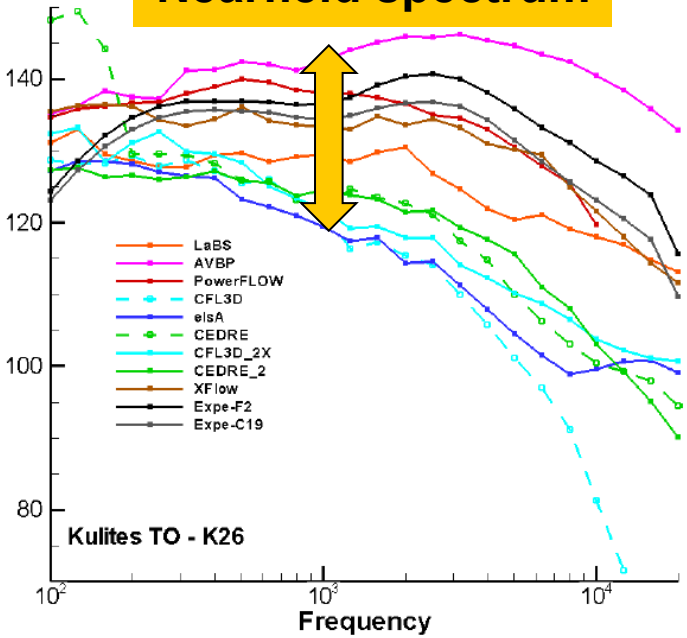
Less Variability in Predicted Acoustics than Unsteady Nearfield?



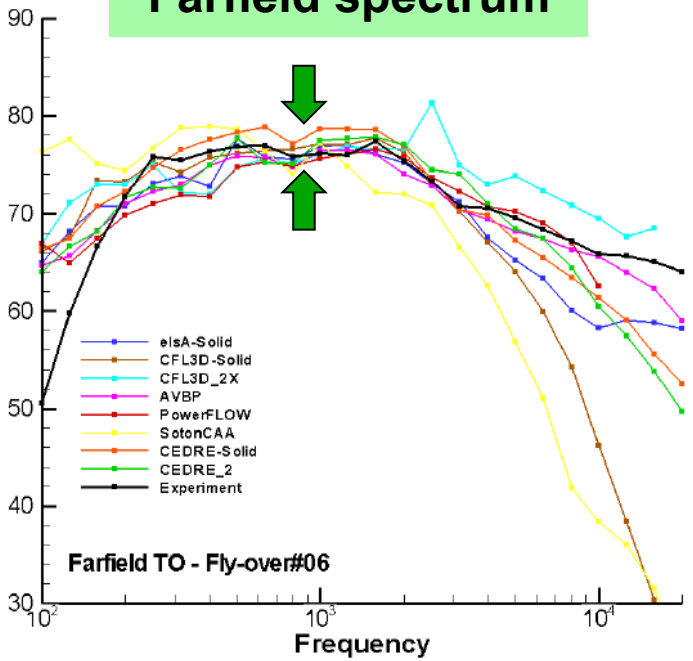
workshop submissions
Category 5



Nearfield spectrum



Farfield spectrum



Summary

- **Model installation effects = critical factor in development of benchmark quality datasets for airframe noise**
  - Cannot be addressed without CFD/CAA/measurement integration
  - Boundary layer tripping an important consideration
- **BANC effort has shown that a thorough integration leads to fuller insights, improved measurement strategies, and broad advances in computational modeling**
  - **Integration is optimally achieved via focused collaborative effort among multiple stakeholders (strong stewardship by NASA/ JAXA/ONERA/DLR and industry partners)**
  - **Remarkable success in case of 3D landing gear configurations**
- **BANC data continues to be used beyond the workshops**
  - Substantial return on moderate NASA investment
- **BANC-V Workshop currently in (early) planning stage**
  - **New noise sources (slat tracks) + realistic semi-span configuration (HL-CRM)**