Aeromechanics Analysis of a Boundary Layer Ingesting Fan

presented by
Dr. Milind Bakhle
NASA Glenn Research Center

AIAA-2012-3995 co-authors:
Dr. T. S. R. Reddy (NASA GRC / University of Toledo)
Dr. Gregory P. Herrick (NASA Glenn Research Center)
Dr. Aamir Shabbir and Dr. Razvan V. Florea
(United Technologies Research Center)

48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference
Atlanta, Georgia, July 29 – August 1, 2012

Acknowledgements

- This presentation summarizes work performed at NASA Glenn Research Center (GRC) in collaboration with United Technologies Research Center (UTRC)
  - Thanks to Mr. David Arend (Team Lead, Robust Design of Embedded Engine Systems) and Dr. Gregory Tillman (UTRC Team Lead)
- This work was supported by the Subsonic Fixed Wing Project (Dr. Michael Hathaway, Tech Lead for Efficient Propulsion and Power) and by the Environmentally Responsible Aviation Project (Dr. Kenneth Suder, Propulsion Sub-project Manager)
- Thanks to Ms. Rula Coroneos (NASA GRC) for her support of this task with Nastran finite element analysis

Outline

- Background
- Fan CFD Analysis – TURBO-AE Code
- Fan Performance – Clean Inflow, Distorted Inflow
- Structural Dynamics, Aeroelastic Formulation
- Inlet Distortion Forced Response, Dynamic Stress
- Blade Vibrations – Flutter Stability
  - Clean Inflow
  - Distorted Inflow
- Summary and Future Work

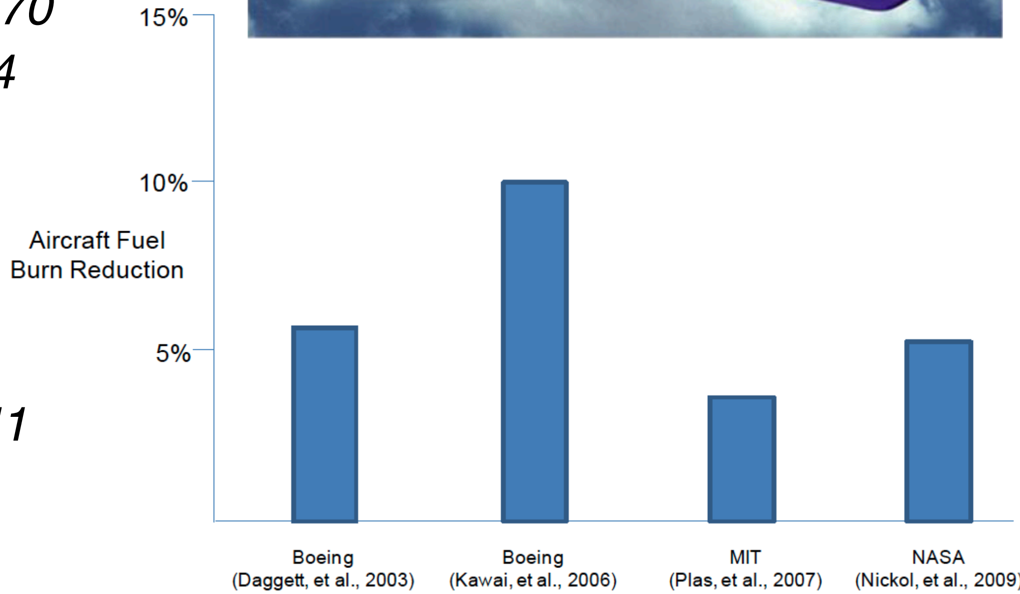
Background

- *"Wake Ingestion Propulsion Benefits," L. H. Smith, AIAA Journal of Propulsion and Power, 1993.*
- Boundary Layer Ingestion (BLI) Propulsion has the potential for significant reduction (5-10%) in Aircraft Fuel Burn
- Previous system studies:

Daggett, et al., NASA-CR-2003-212670
Kawai, et al., NASA-CR-2006-214534
Plas, et al., AIAA 2007-450
Nickol, NASA-TM-2008-215112
Nickol and McCuller, AIAA 2009-931

- Recent system studies:

Tillman, et al., AIAA invited pres., 2011
Hardin, et al., AIAA-2012-3993



Technical Challenges

- The potential benefits of Boundary Layer Ingestion (BLI) Propulsion can be diminished if key parameters do not meet their targets
  - Inlet total pressure loss
  - Fan efficiency reduction
  - Fan stall margin reduction

  - Fan aeromechanics requirements (dynamic stresses and flutter stability)

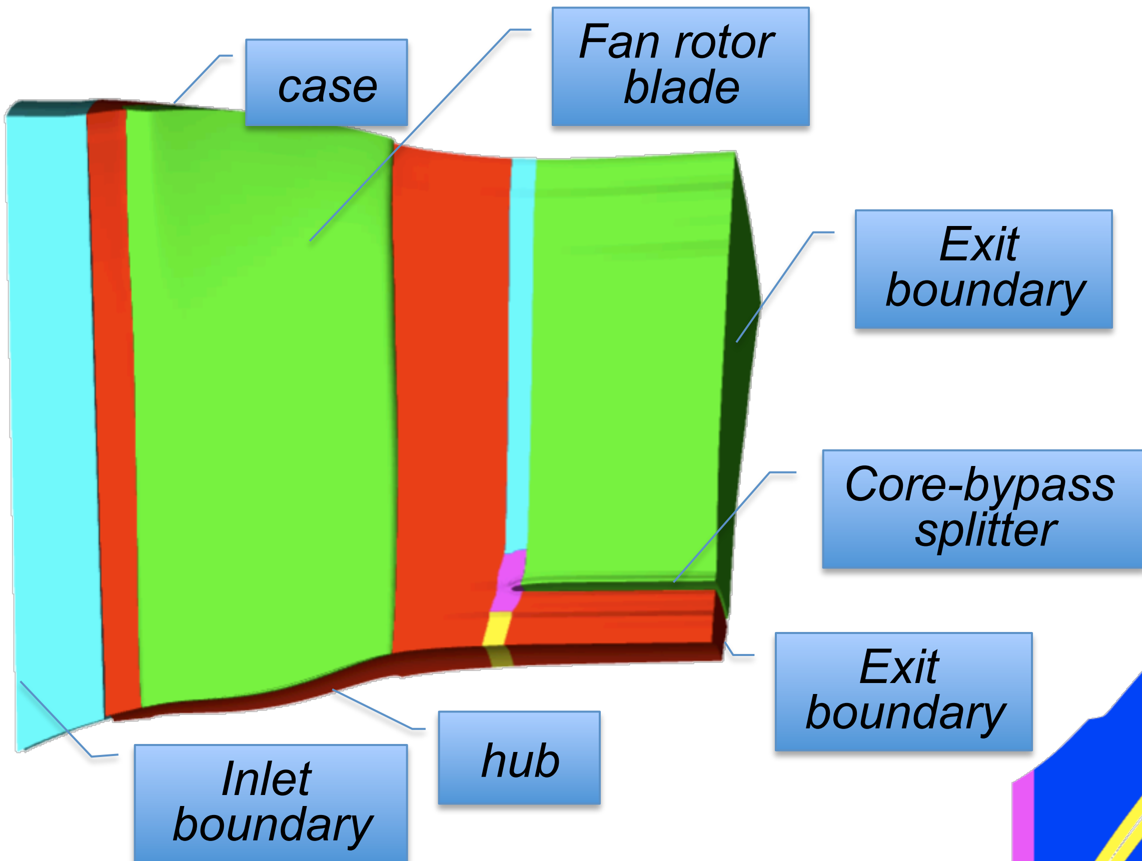
Fan CFD Analysis – TURBO Code

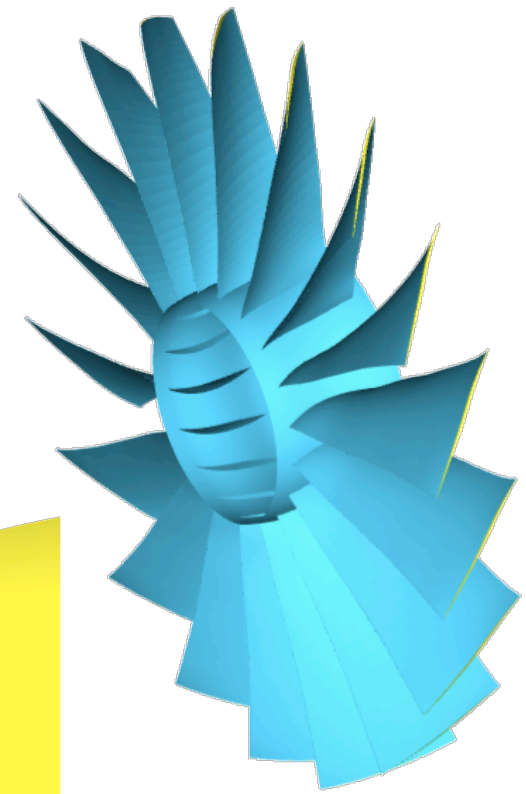
- Implicit, finite-volume solver
- Reynolds-Averaged Navier Stokes equations
- Structured multi-block code
- Multi blade-row code
- k-epsilon turbulence model
- Inlet distortion boundary condition
- Throttle exit boundary condition

- Dynamic grid deformation for blade vibration
- Prescribed harmonic blade vibrations with energy method to evaluate flutter stability

Fan Computational Domain

- Analysis of an Aero Design Iteration (not the Final Design)

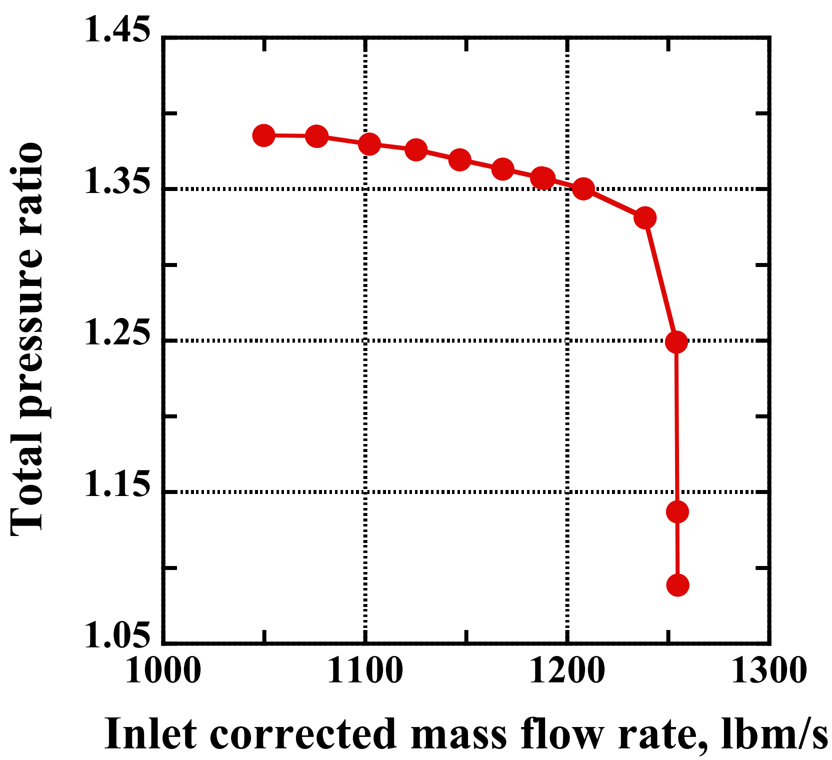


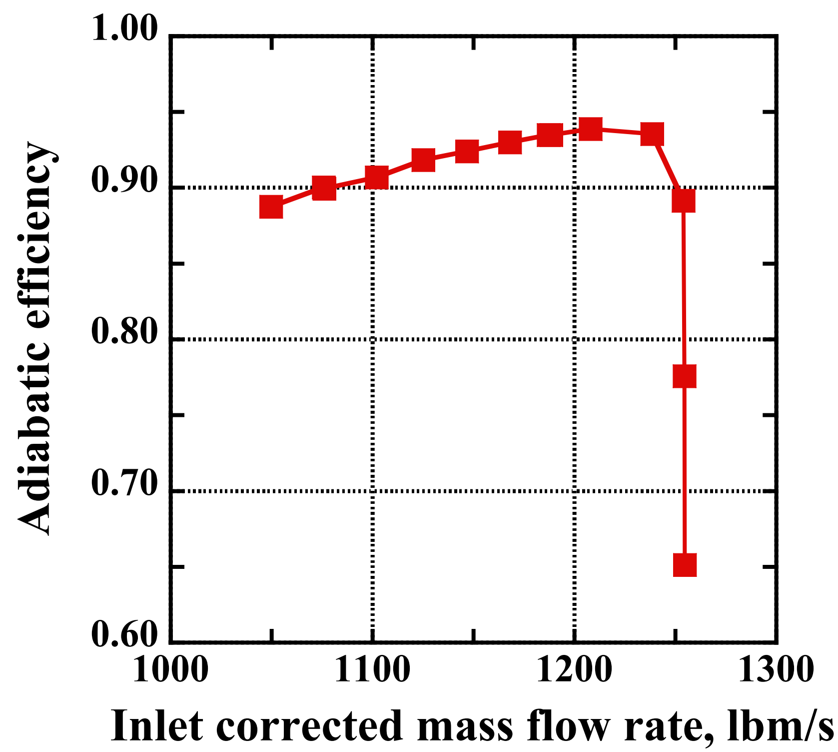


- H, O, and C blocks
  of mesh generated by UTRC

Fan Performance – Clean Inflow

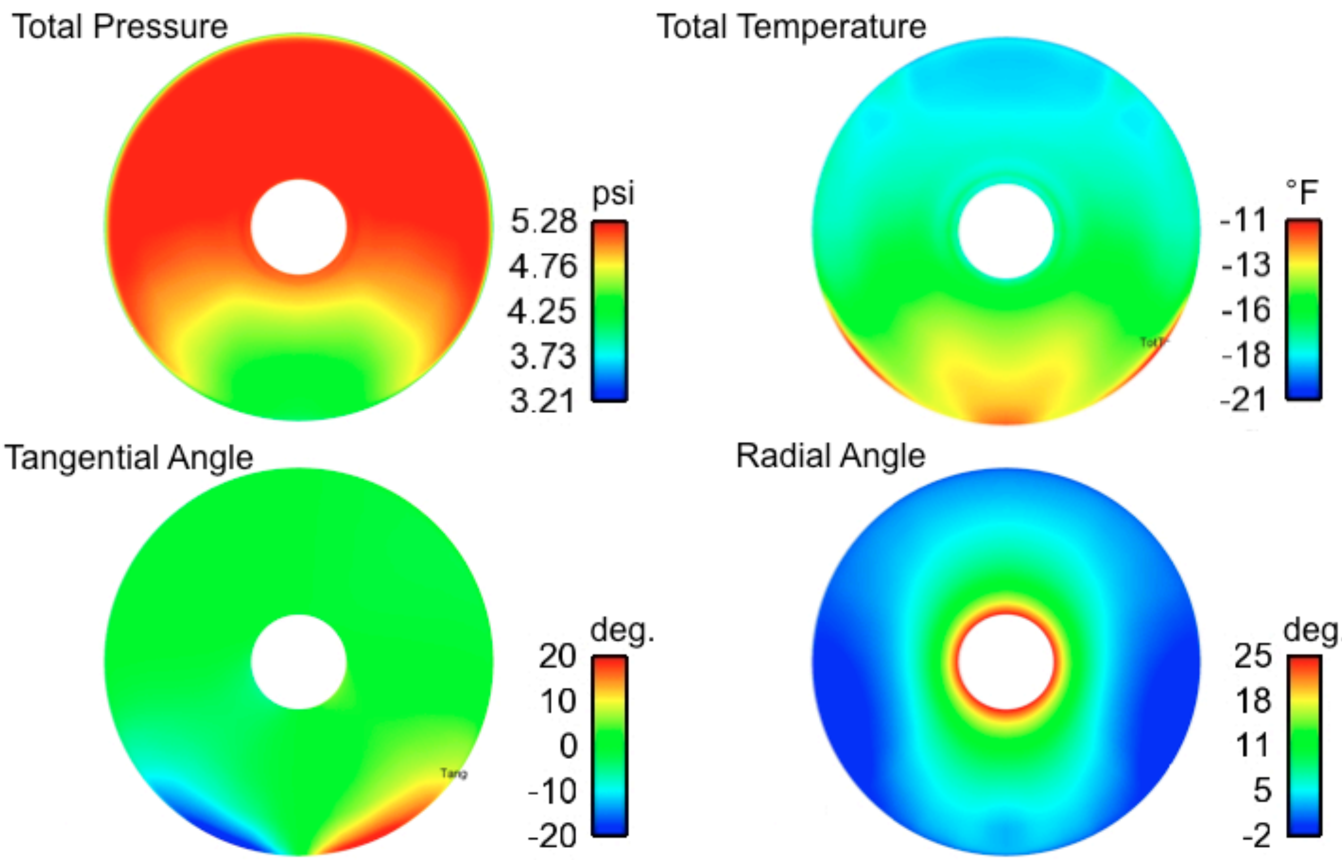
- TURBO code (RANS solver) used with radial inlet profile of total pressure, total temperature, and flow angles
- Speedline traversed by setting exit throttle condition and converging flow solutions





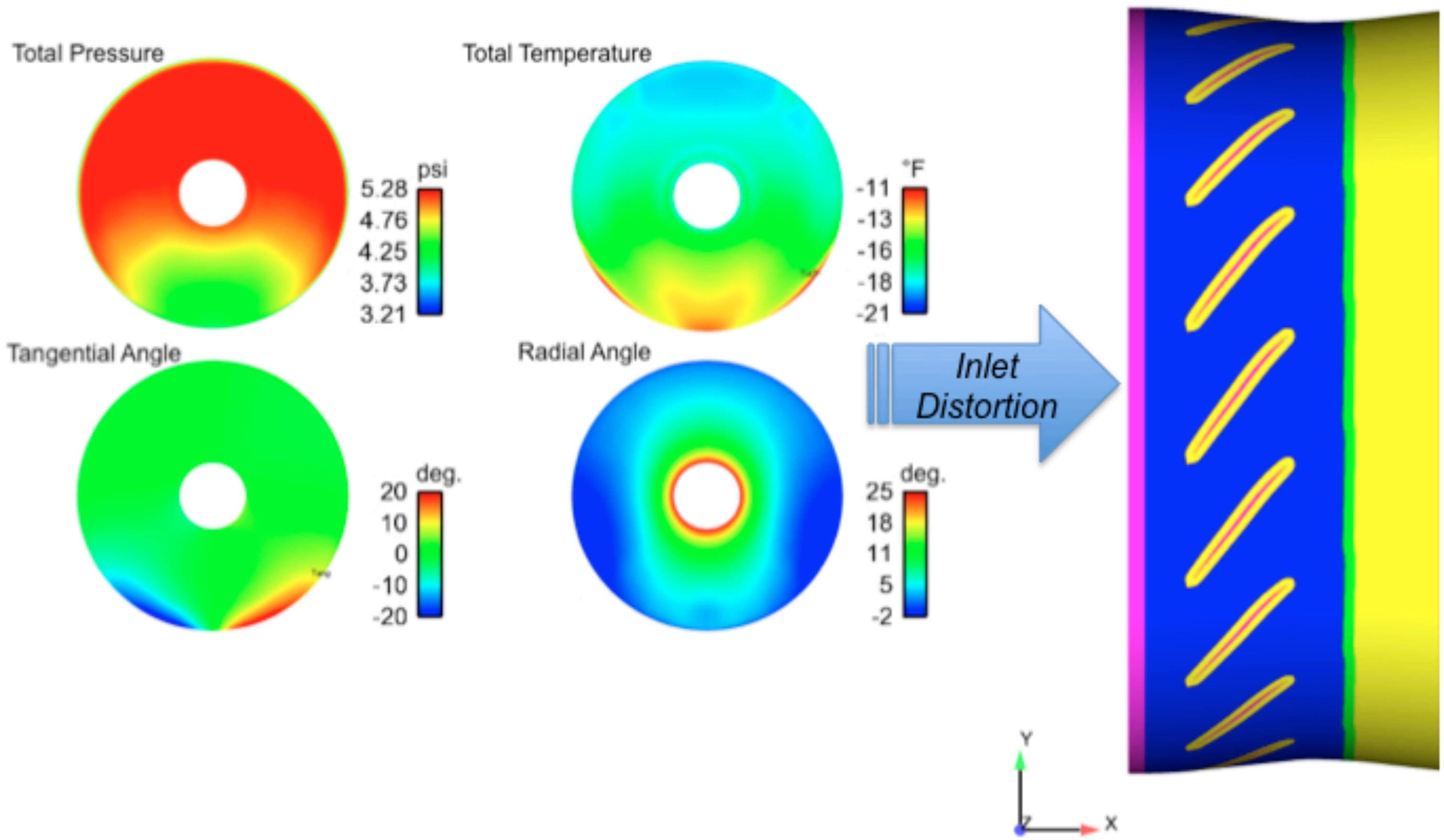
Inlet Flowfield Provides Distortion Pattern

- Inlet flow computations were performed at UTRC for an inlet design iteration (not final design) and the flowfield results were provided to NASA



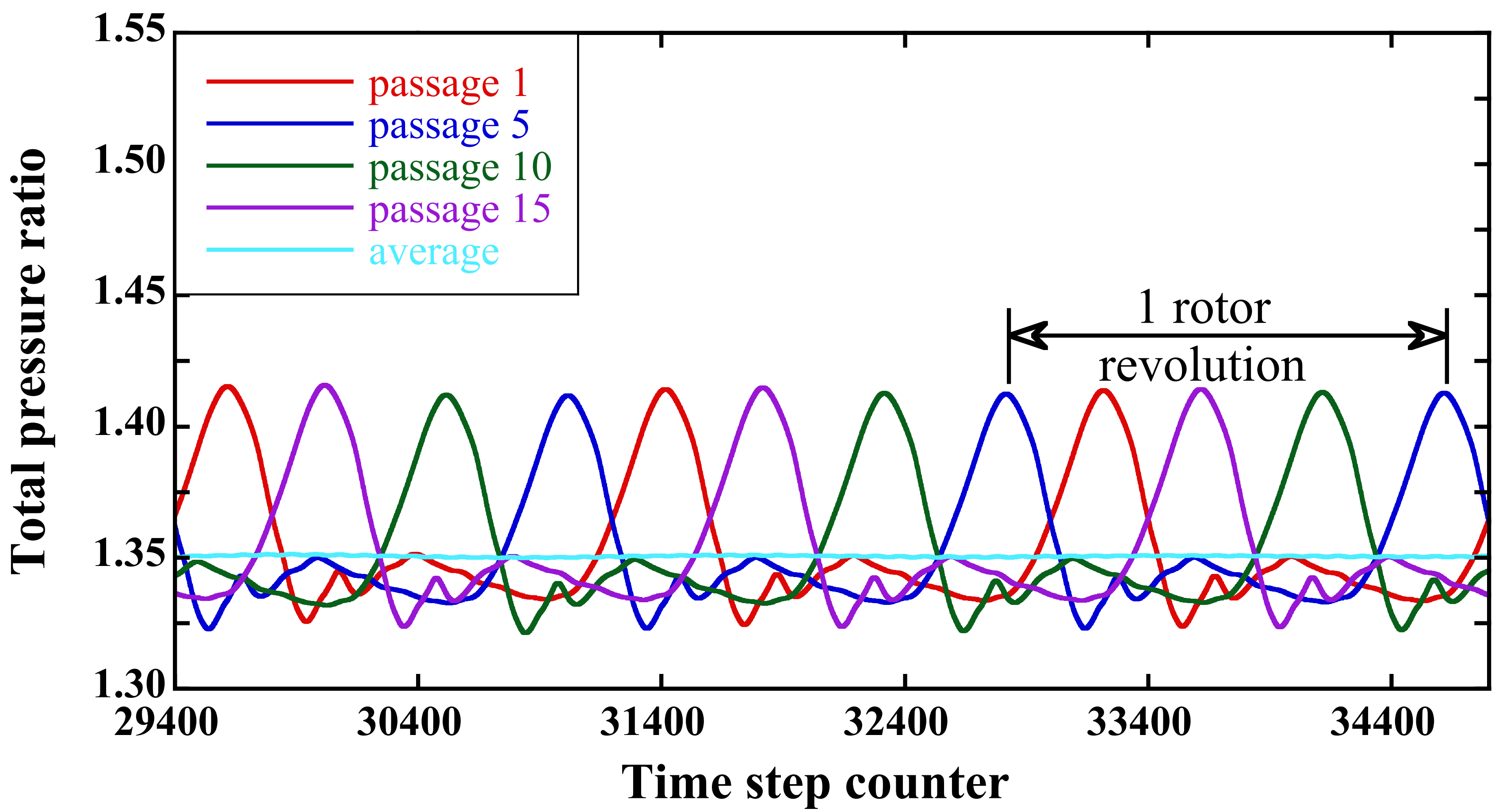
Fan Computation with Inlet Distortion

- Inlet distortion is prescribed as boundary condition at inlet boundary of the fan computational domain (18-blade fan rotor and splitter)



Periodicity of Flowfield Around the Rotor

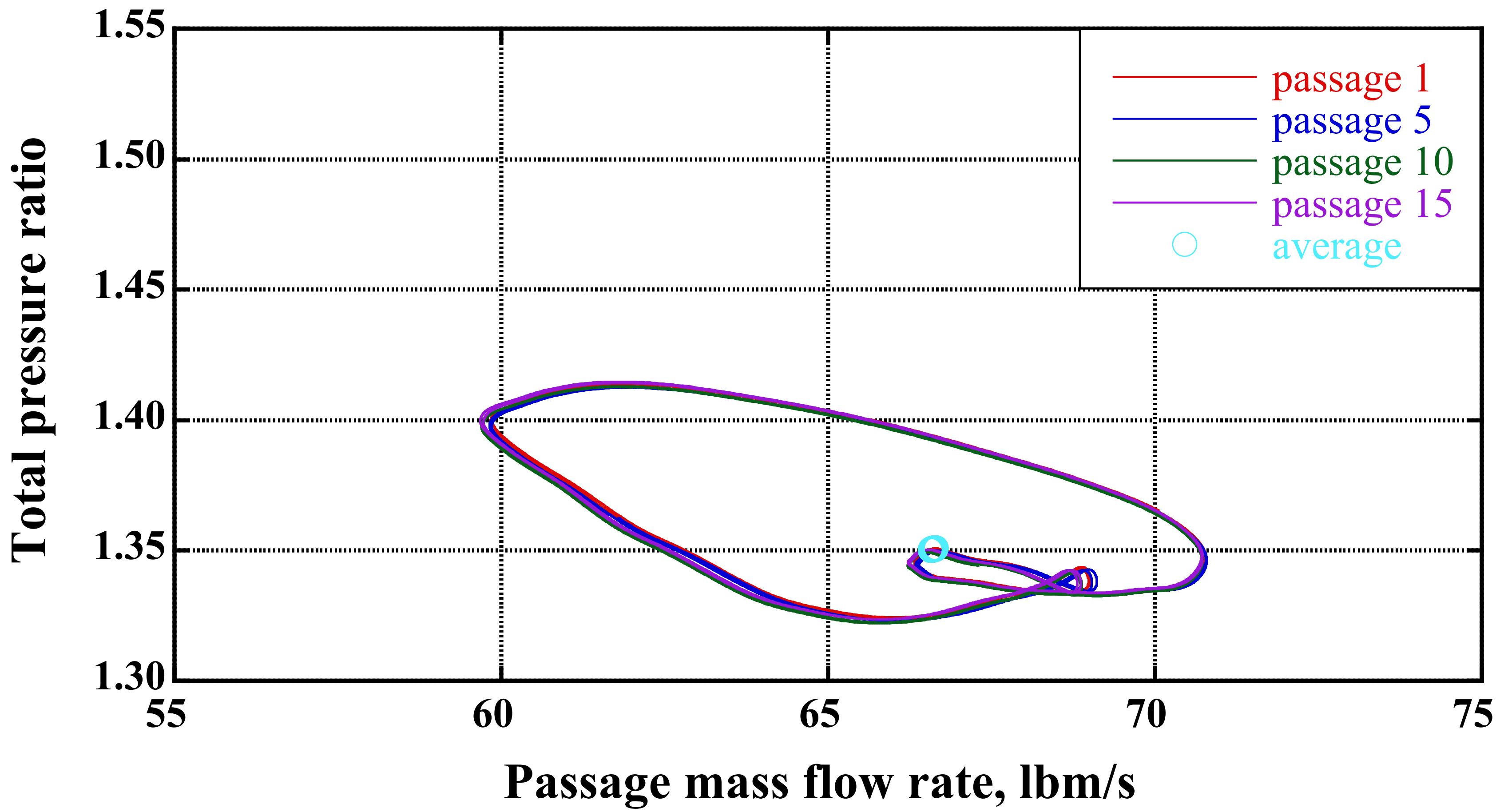
- Total pressure ratio for various blade passages



Variation of total pressure ratio in different blade passages shows flowfield is converged to periodicity

Periodicity of Flowfield Around the Rotor

- Total pressure ratio for various blade passages

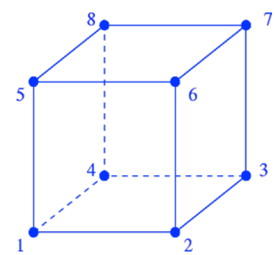


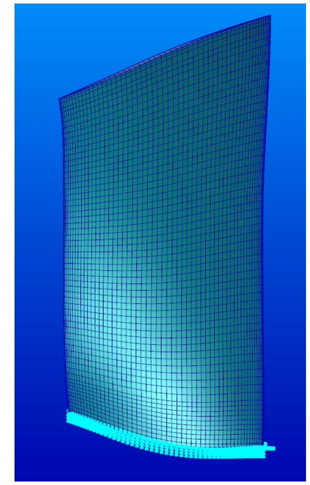
Inlet Distortion causes variations in mass flow rate and pressure ratio around the fan rotor

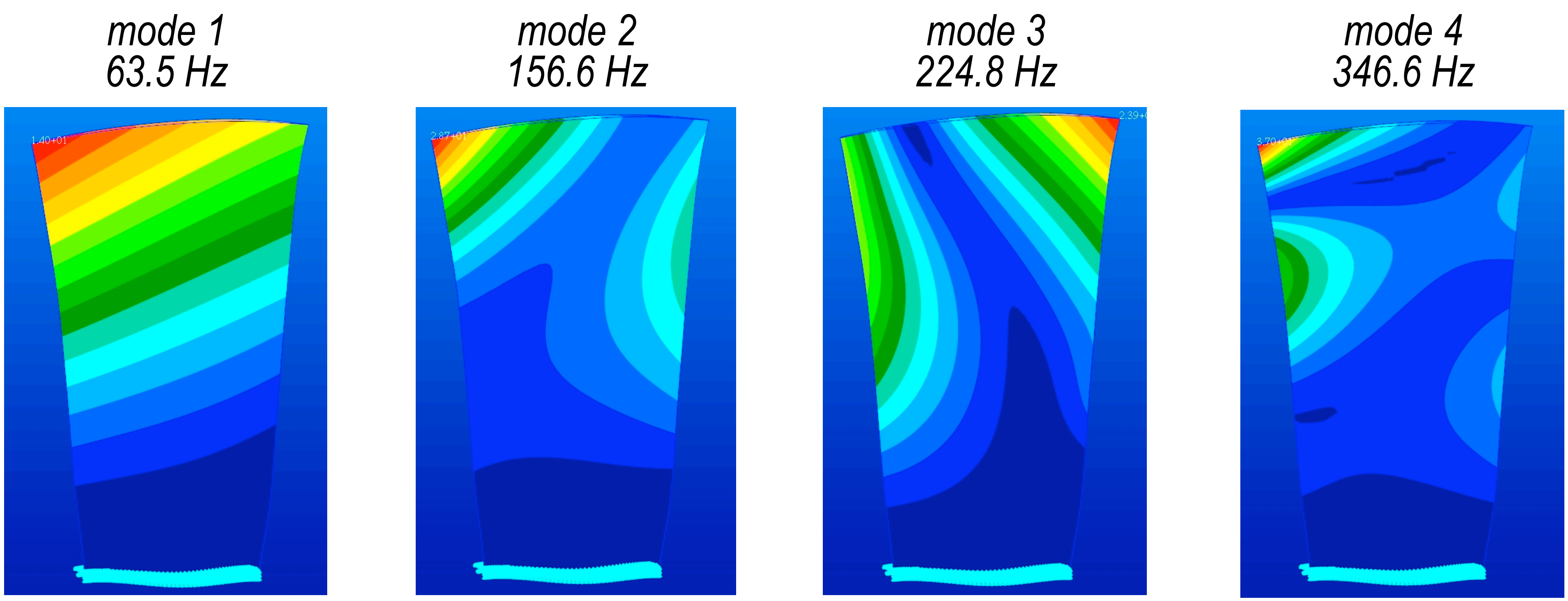
Structural Dynamics Model & Results

Blade structural model created based on aero design iteration (structural design is in progress)

- 8-node brick elements
- 9,782 elements, 15,096 nodes
- 222 nodes at the root constrained







Blade Vibration Modes or Modal Displacements

Aeroelastic Formulation

- Blade structural dynamics modal equations with aerodynamic load

$$[M]\{\ddot{q}\} + [K]\{q\} = \{AD\}$$

$\{AD\}$ is the motion-independent aerodynamic load vector – ***Modal Force***

$$AD_i = \int \vec{\delta}_i \cdot p\,d\vec{A}$$

Modal Force *computation requires* ***unsteady pressure*** *and* ***modal displacements***

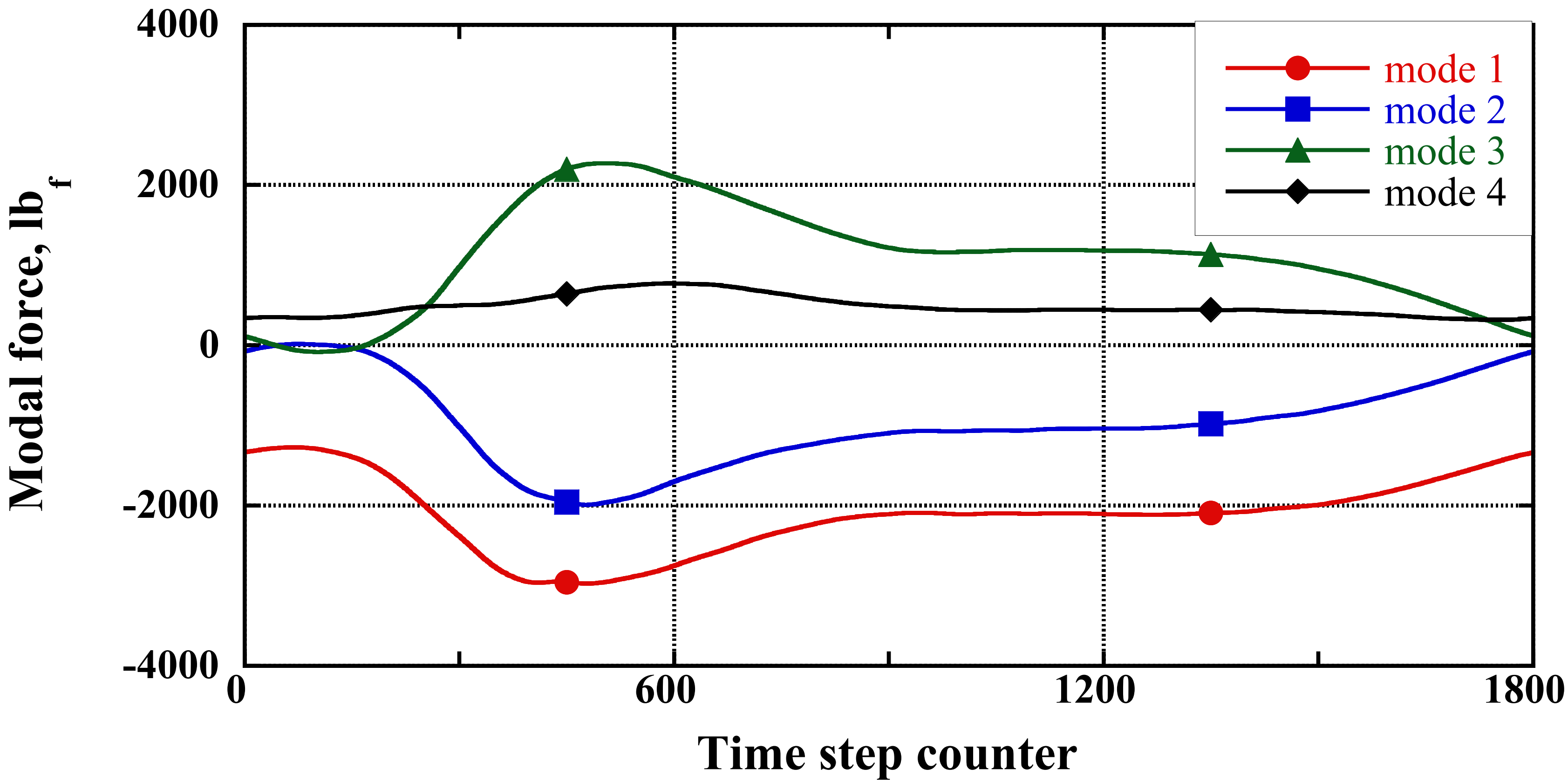
$$\{q\} = \left[[K] - \omega^2[M]\right]^{-1}\{AD\}$$

Forced Response

Modal Force

Time history over one rotor revolution

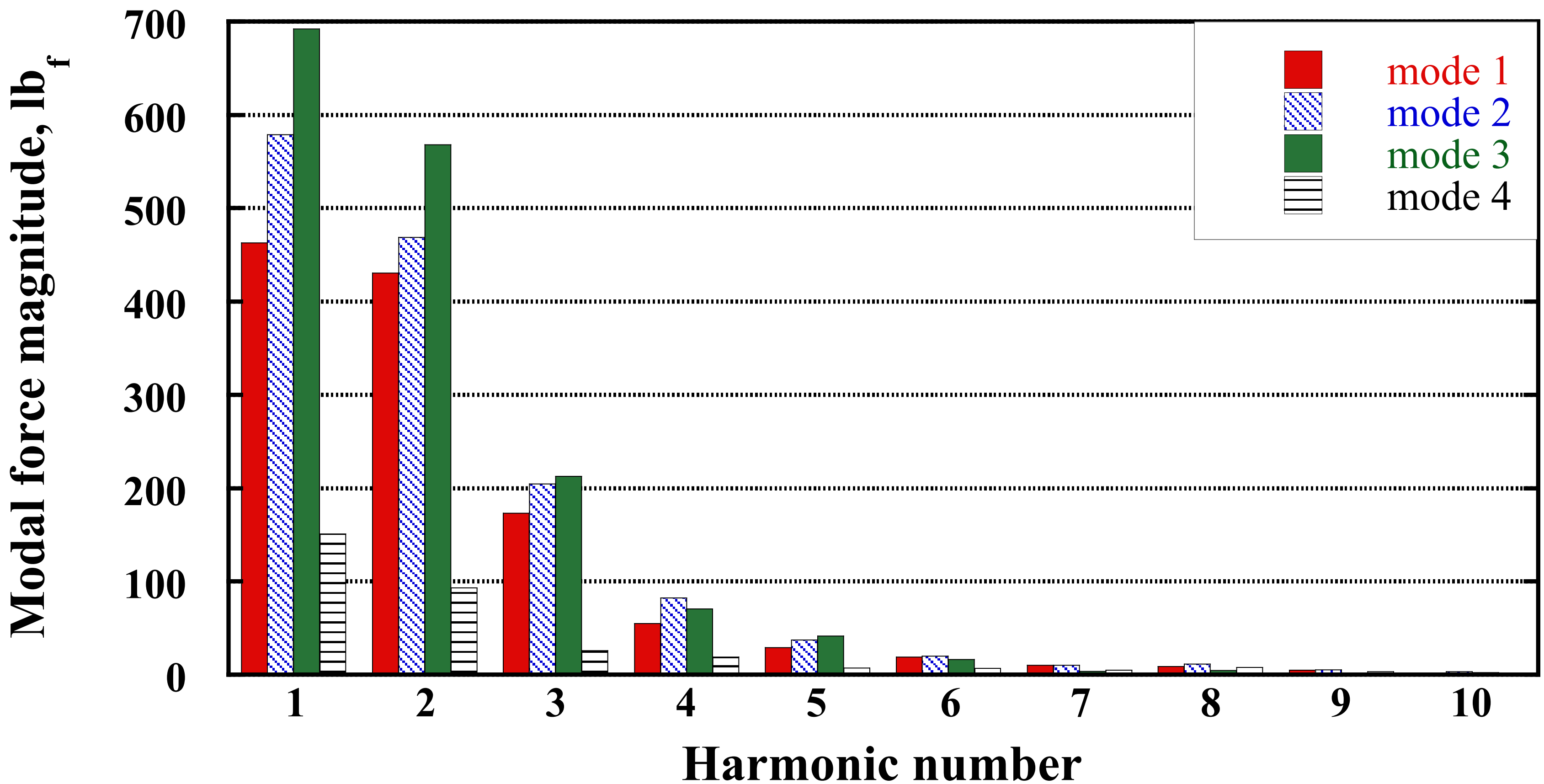
$$AD_i = \int \vec{\delta}_i \cdot p\,d\vec{A}$$



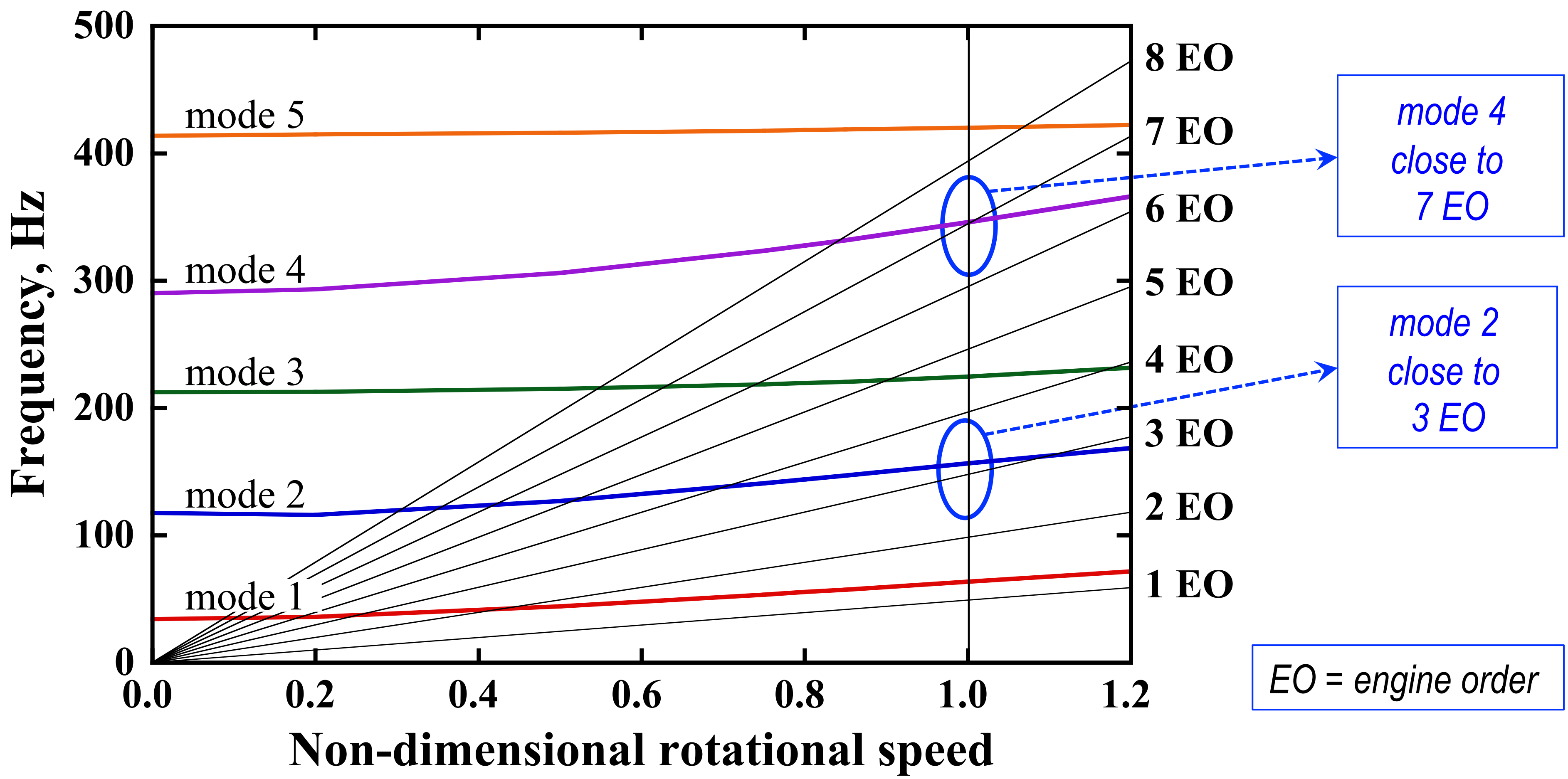
1,800 time steps per revolution

Modal Force

Fourier components

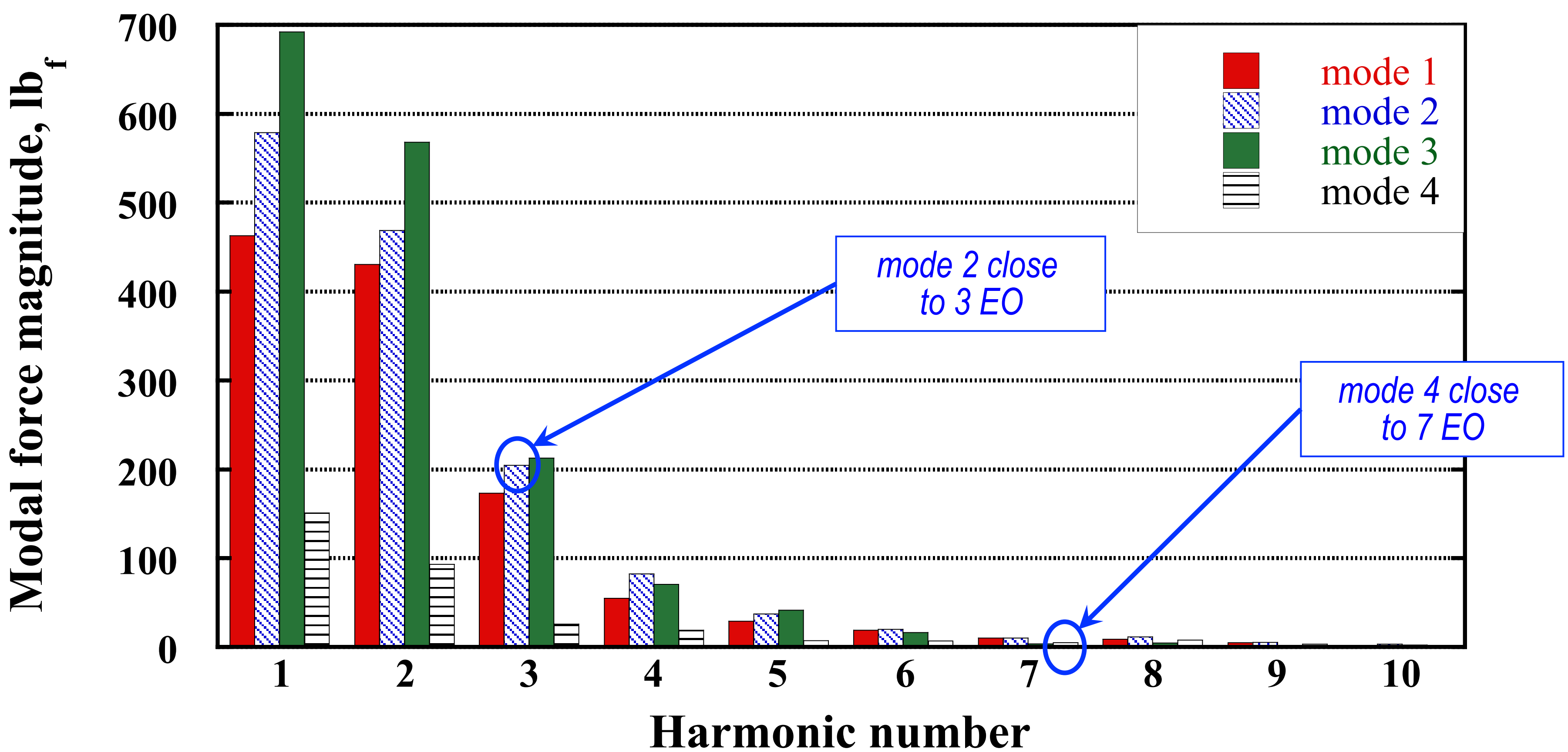


Campbell Diagram



Modal Force

Fourier components

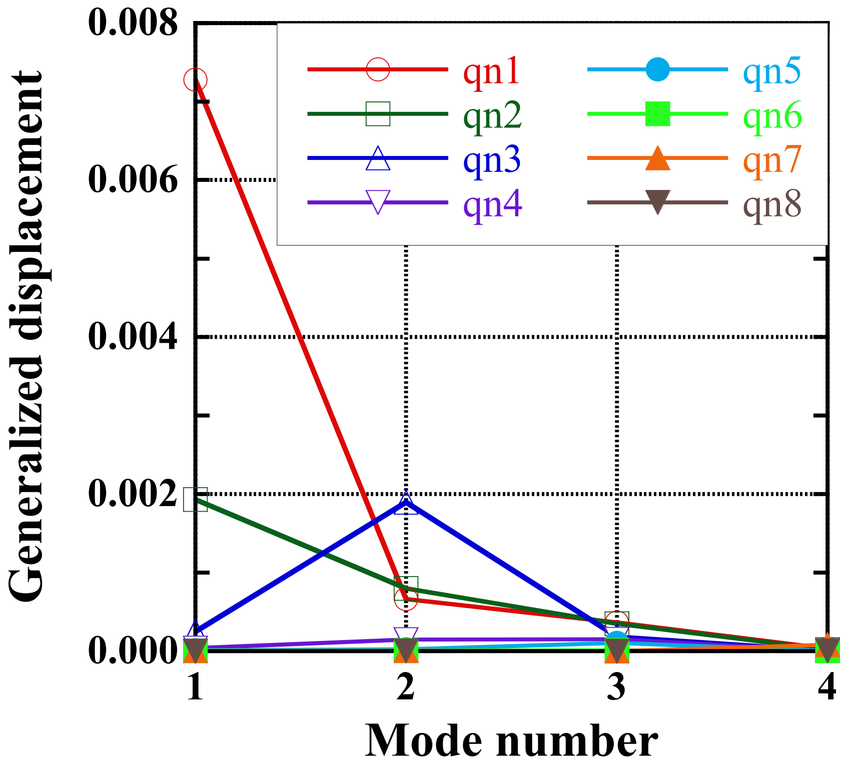


Forced Response – Vibration Amplitude and Dynamic Stresses

- Dynamic stresses are required to determine fatigue characteristics (Goodman diagram)

$$\{q_{nr}\} = \left[[K_n] - \omega_r^2 [M_n]\right]^{-1} \{AD_{nr}\}$$ *for n^{th} mode, r^{th} harmonic*

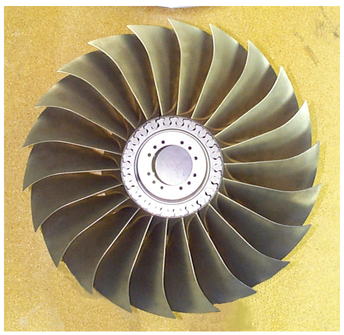
dynamic stress $$\sigma_r = \sum_n s_n q_{nr}$$ *where s_n is the modal stress*



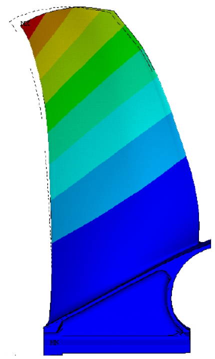
harmonic or engine order	vibration amplitude (inch) at tip t.e.	dynamic stress amplitude (psi)
1	5.5×10^{-2}	273
2	3.0×10^{-2}	290
3	1.9×10^{-2}	666
4	3.1×10^{-3}	308
5	2.6×10^{-3}	169
6	2.7×10^{-4}	33
7	7.0×10^{-4}	427
8	6.0×10^{-5}	19

Flow Chart for Flutter Stability Computation

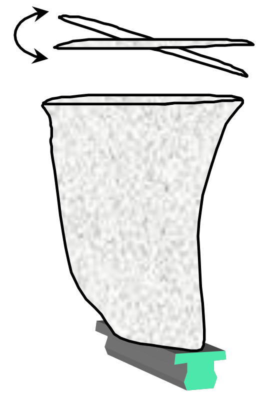
- Aerodynamic damping computation using TURBO-AE



Configuration



Mode Shape



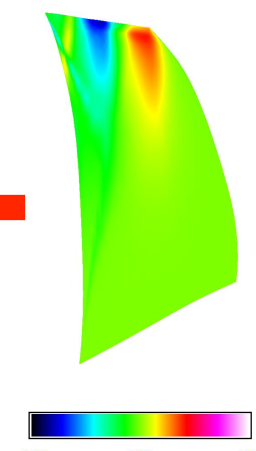
Prescribe Blade Motion

$$\mathbf{X} = \mathbf{X}_0 \mathbf{e}^{i(\omega t + \phi)}$$

Calculate Work

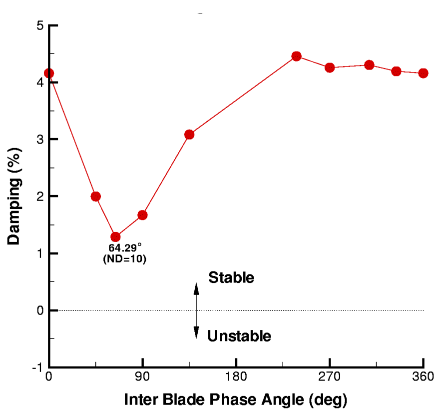
(for all ω and ϕ of interest)

$$W = \oint \int_{surface} -p.d\vec{A} \bullet \left(\frac{\partial \vec{X}}{\partial t}\right) dt$$



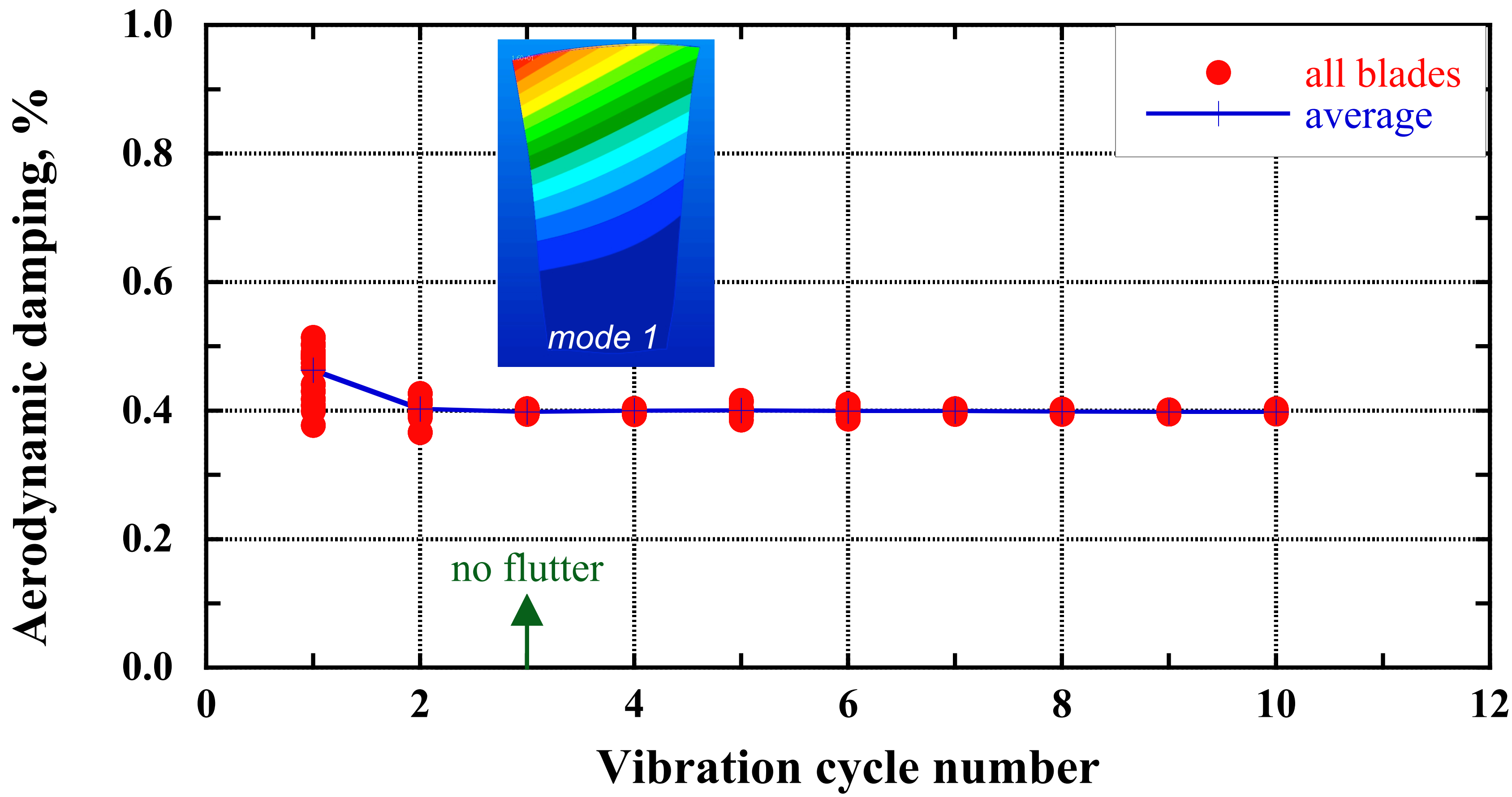
Calculate Aerodynamic Damping

$$\gamma = -\frac{W}{8\pi K_E}$$



Flutter Stability with Clean Inflow

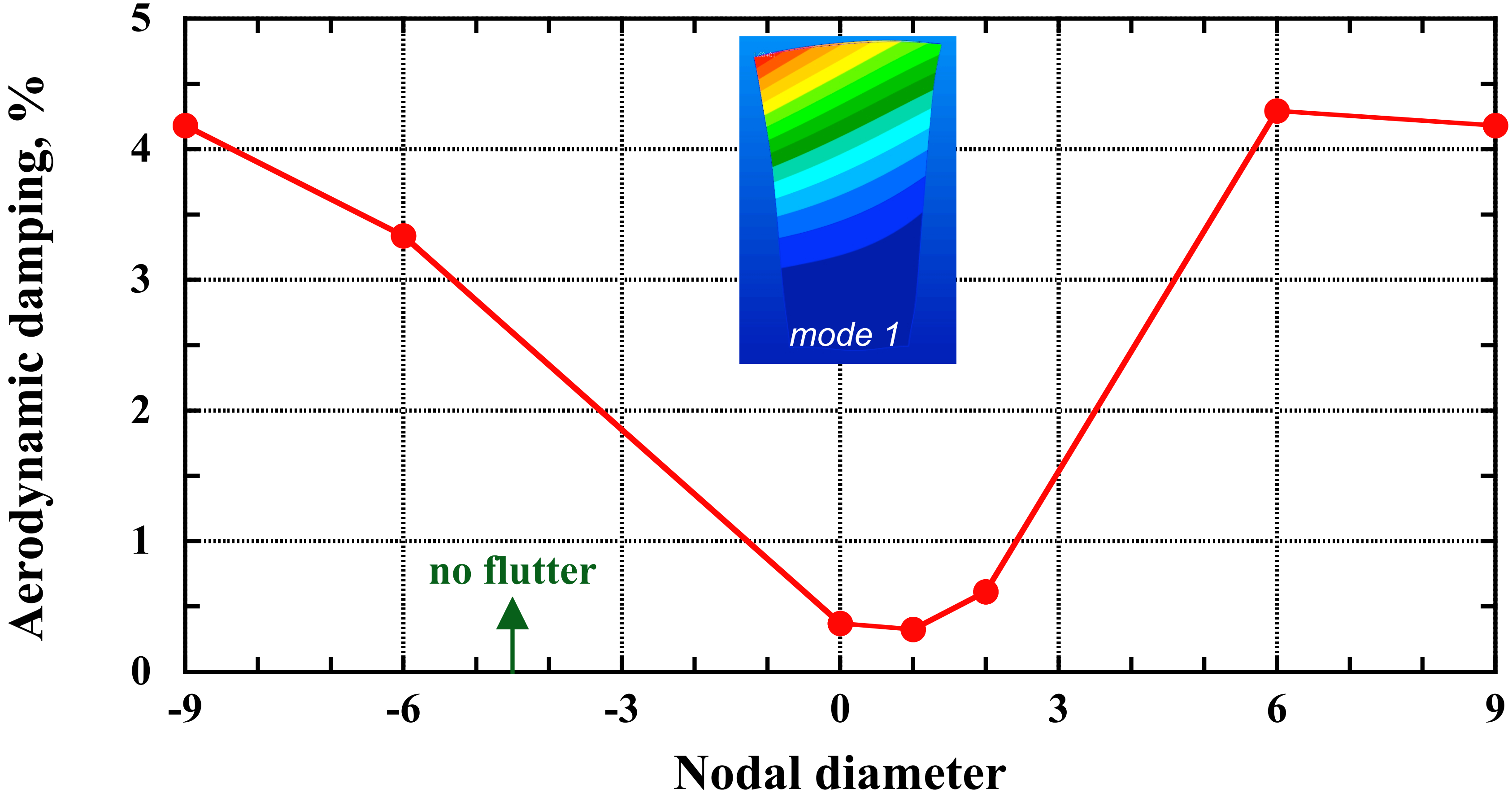
- Design operating speed, mode 1, 0 nodal diameter pattern (all blades in-phase), 18 blade passages (full rotor)



Flutter Stability with Clean Inflow

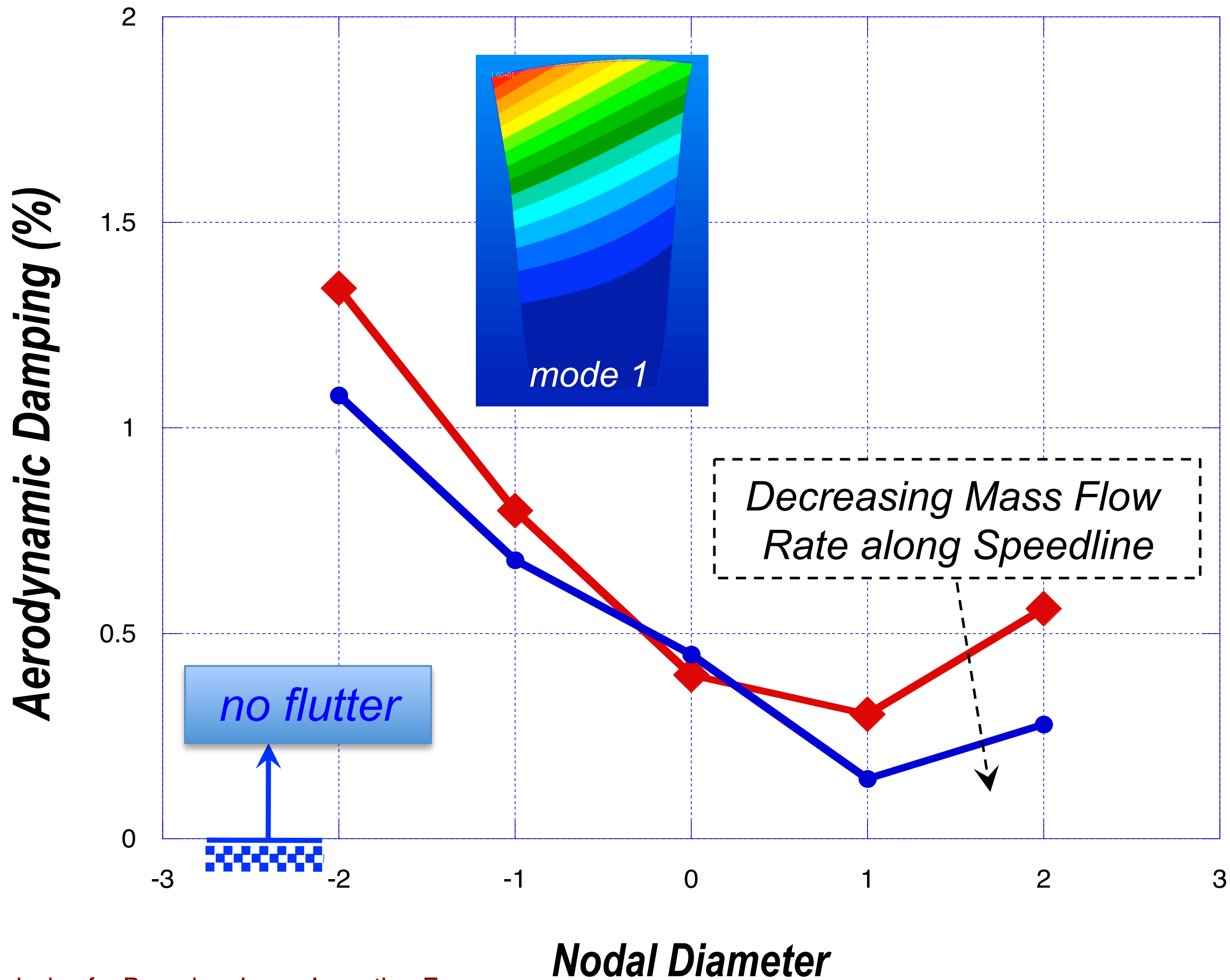
- Design operating speed, 18 blade passages (full rotor)
- Phase angle of vibration = 360 * Nodal Diameter / 18

mode 1



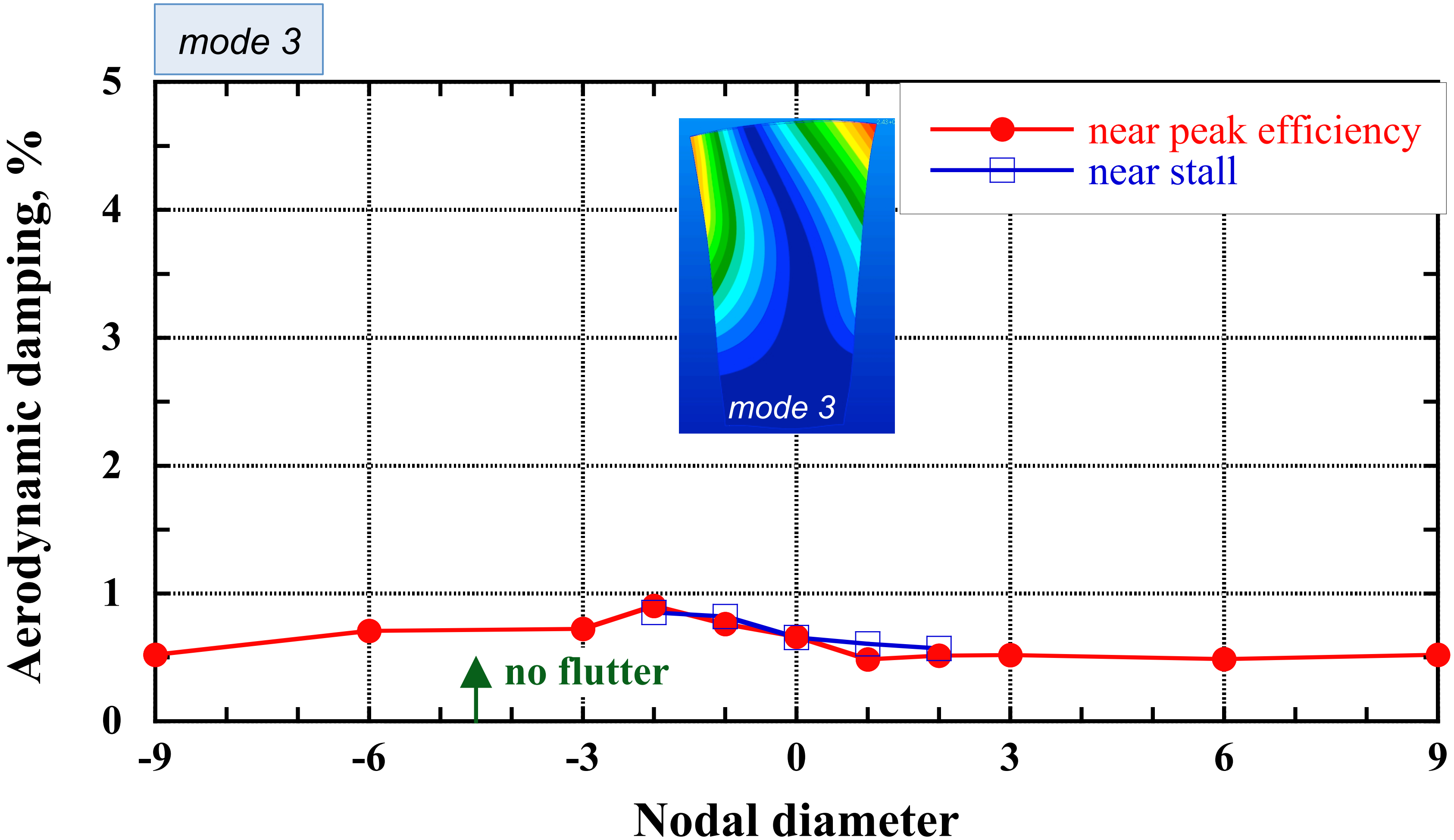
Flutter Stability with Clean Inflow

- Design operating speed, 18 blade passages (full rotor)
- Phase angle of vibration = 360 * Nodal Diameter / 18



Flutter Stability with Clean Inflow

- Design operating speed, 18 blade passages (full rotor)
- Phase angle of vibration = 360 * Nodal Diameter / 18



Flutter Stability with Distorted Inflow

Various Approaches

- Circumferentially average the distorted inflow to obtain an equivalent radial profile; use work-per-cycle analysis
- Select a portion of the inlet distortion to represent a "worst-case" inflow condition that is used at all circumferential locations; use work-per-cycle analysis
- Prescribe blade vibrations and distorted inflow; use work-per-cycle analysis; average the results over all blades, and over multiple blade vibration cycles
- Use tightly-coupled aeroelastic analysis with distorted inflow; blade vibrations are determined as part of the computations; post-process time history to estimate average damping over all blades and multiple vibration cycles

Flutter Stability with Distorted Inflow

Current Preferred Approach

- Prescribe blade vibrations and distorted inflow
- Use work-per-cycle analysis
- Average the results over all blades, and over multiple blade vibration cycles

$$Work = \oint_{cycle} \int_{surface} -p.d\vec{A} \bullet \left(\frac{\partial \vec{X}}{\partial t}\right) dt$$

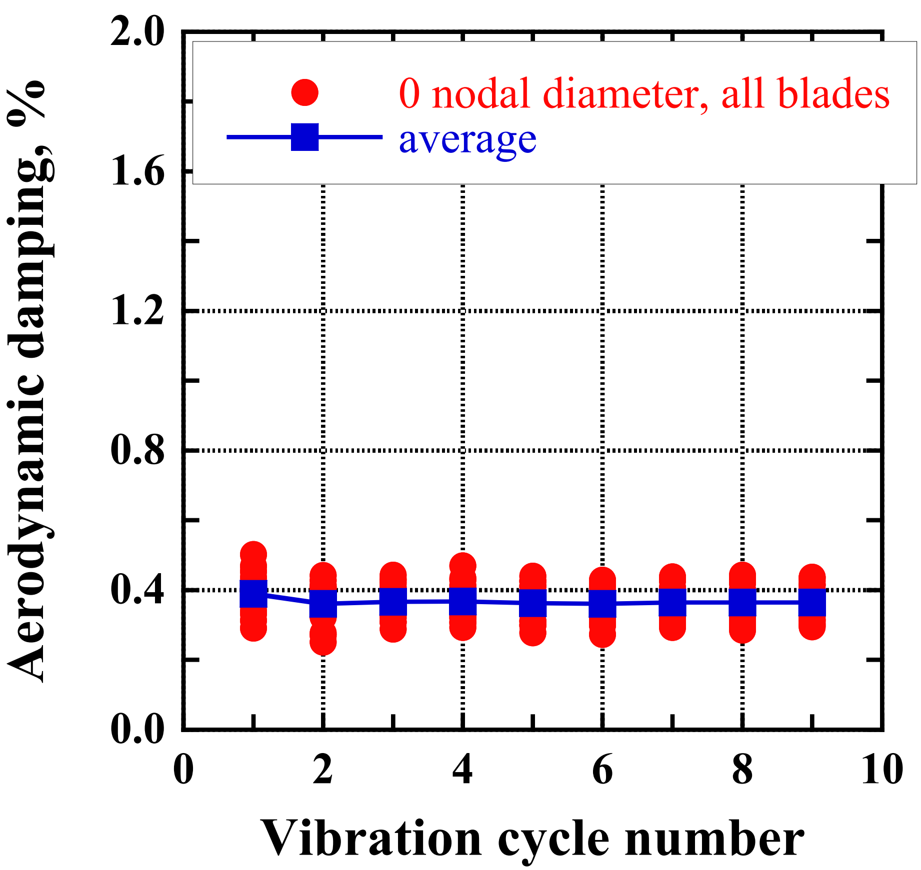
Unsteady pressure includes effect of

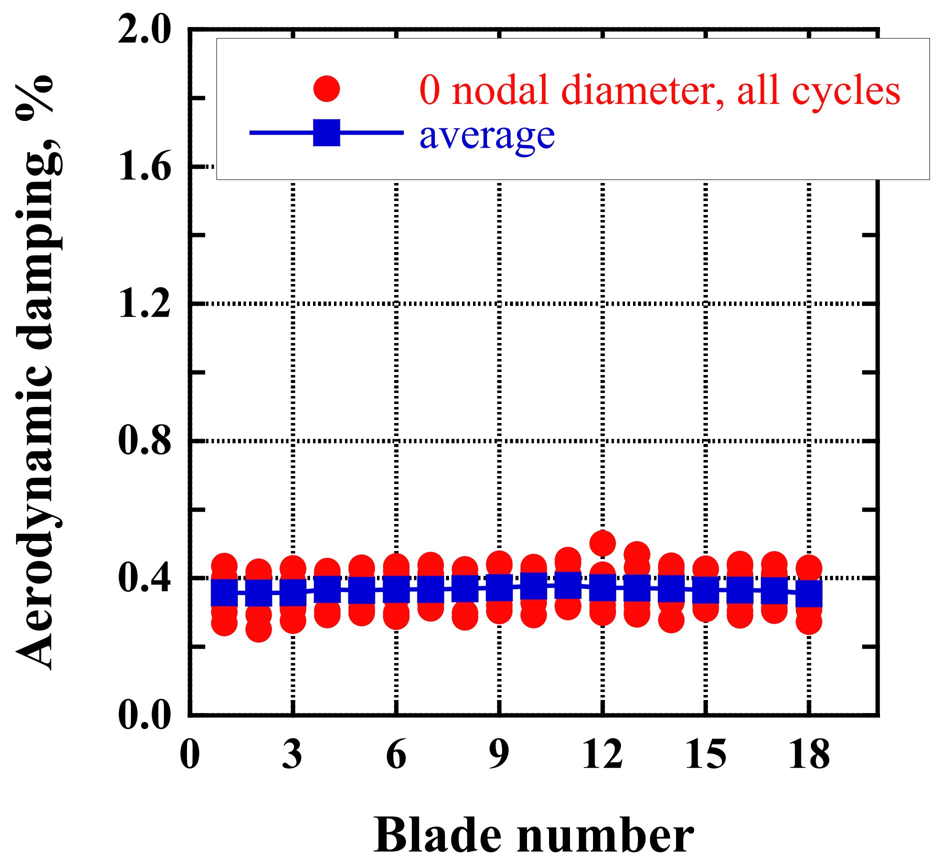
1) inlet distortion

2) blade vibration → *isolate this component to assess flutter stability*

Flutter Stability with Distorted Inflow

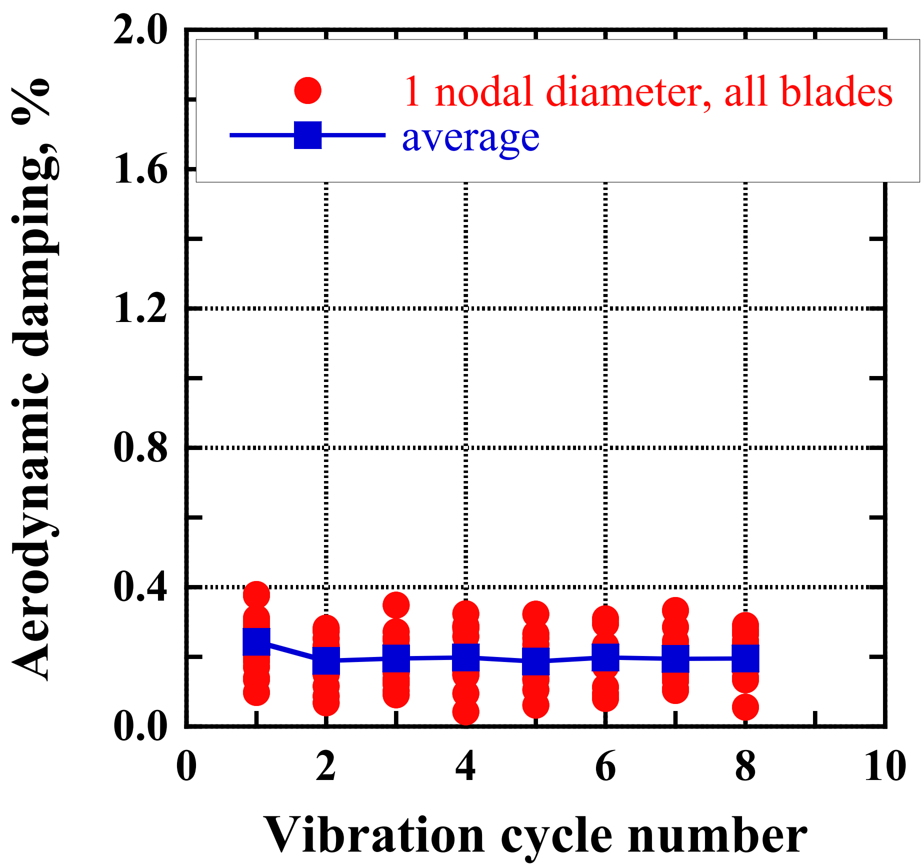
- Design operating speed, mode 1, 0 nodal diameter pattern (all blades in-phase), 18 blade passages (full rotor)

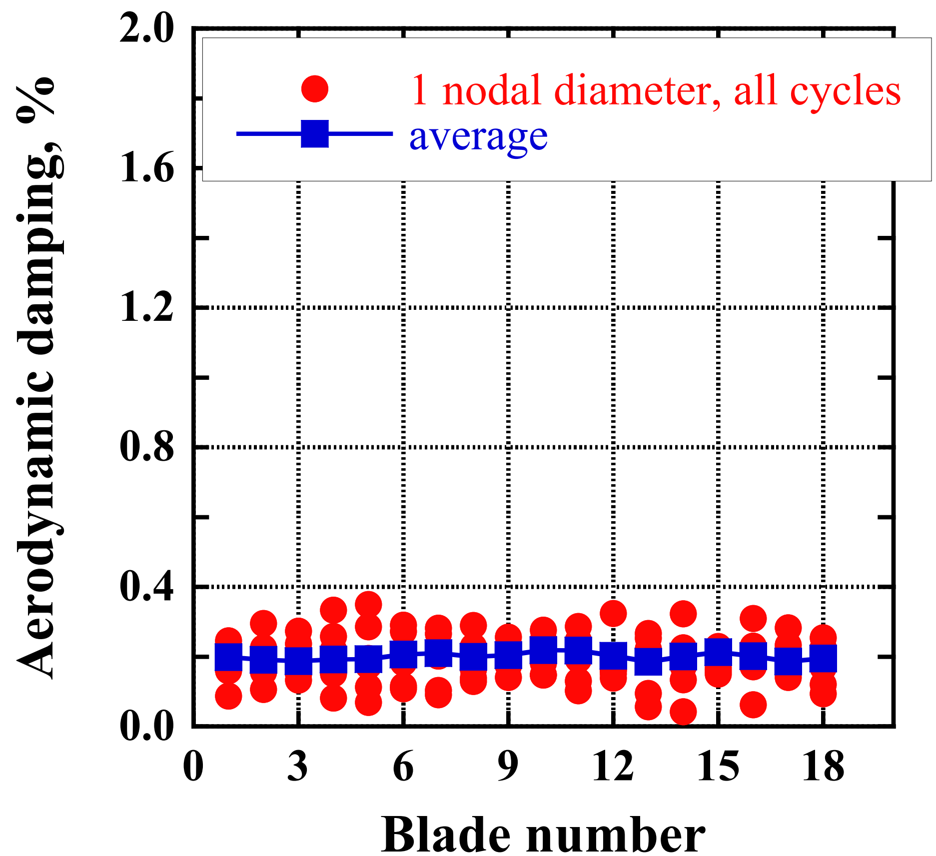




Flutter Stability with Distorted Inflow

- Design operating speed, mode 1, 1 nodal diameter pattern (all blades in-phase), 18 blade passages (full rotor)





Summary

- Created structural model based on aero design iteration and computed structural dynamics characteristics
- Performed aeromechanical analysis of design iteration
- Performed fan flutter analysis with clean inflow at design speed – no flutter encountered at conditions analyzed; additional work needed at part-speed conditions
- Performed distorted inflow analysis for forced response vibrations to determine dynamic stress at design speed – additional work needed at on-resonance conditions near design speed
- Performed initial analysis with blade vibrations and distorted inflow to estimate flutter stability – additional flutter analyses needed for other vibration modes and operating conditions

Future Work

- Perform aeromechanical analysis on final inlet-fan design to ensure safe wind-tunnel test
- Develop tightly-coupled aeroelastic analysis capability in TURBO for more detailed analysis of blade vibrations with distorted inflow
- Perform aeromechanical analysis on updated fan stage design including non-axi-symmetric exit guide vanes
- Develop inlet-fan coupled aeroelastic analysis capability

Questions?