Aeromechanics Analysis of a Boundary Layer Ingesting Fan

presented by
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Outline

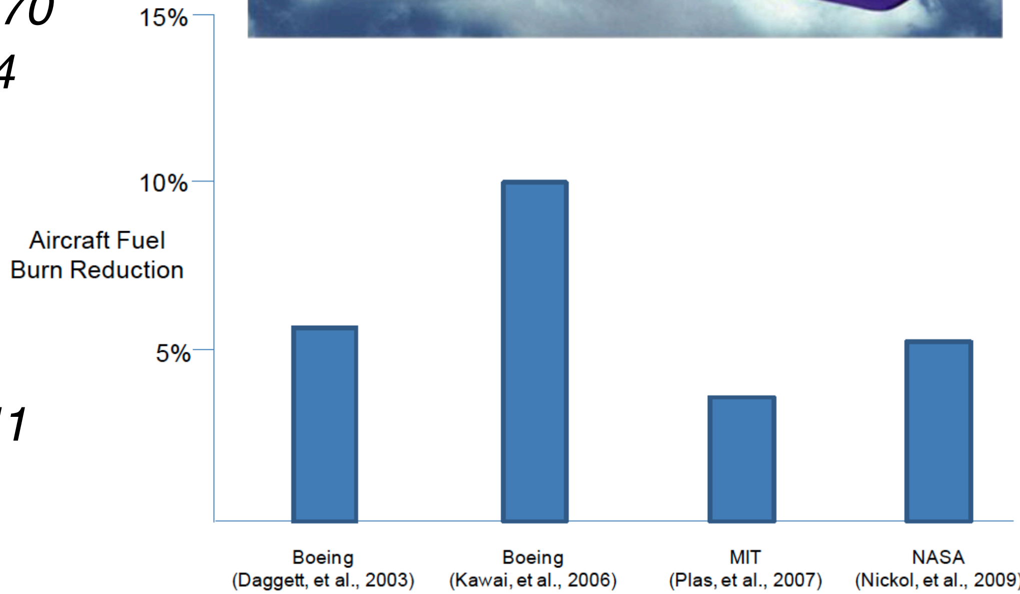
- Background
- Fan CFD Analysis – TURBO-AE Code
- Fan Performance – Clean Inflow, Distorted Inflow
- Structural Dynamics, Aeroelastic Formulation
- Inlet Distortion Forced Response, Dynamic Stress
- Blade Vibrations – Flutter Stability
  - Clean Inflow
  - Distorted Inflow
- Summary and Future Work

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)

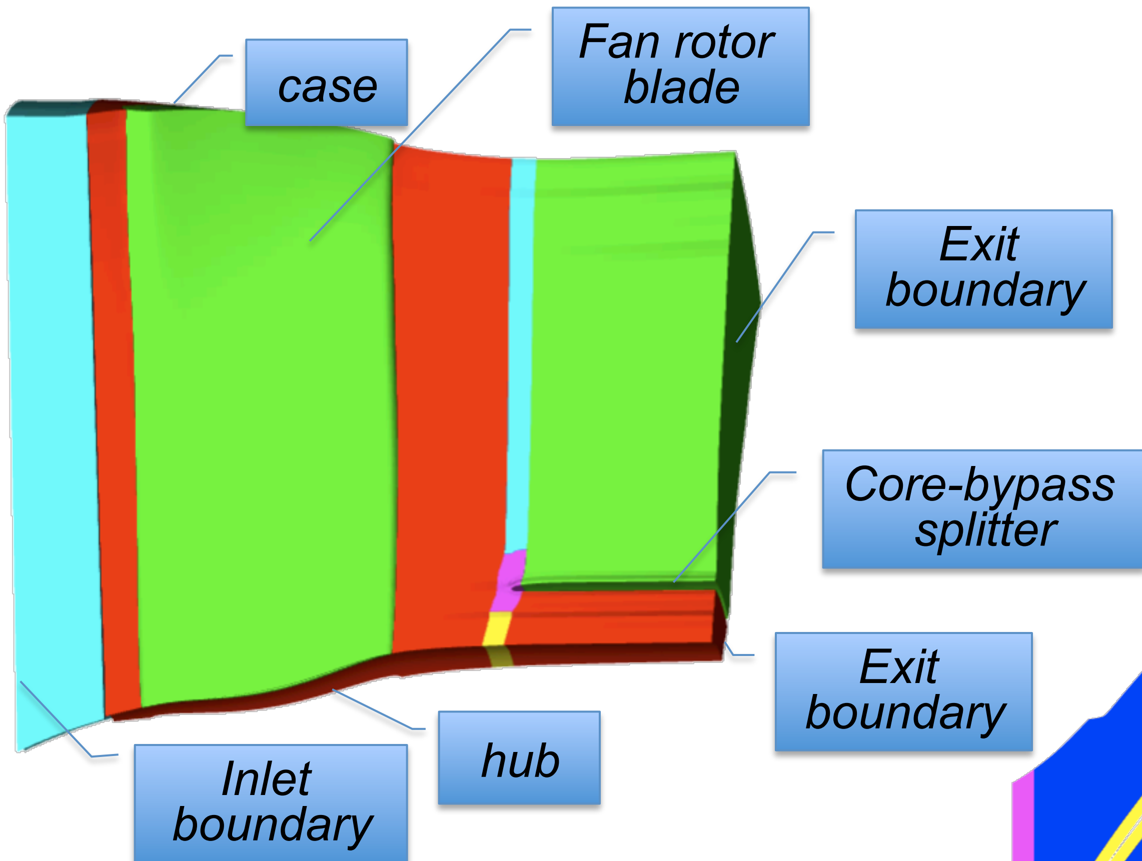
Fan CFD Analysis – TURBO Code

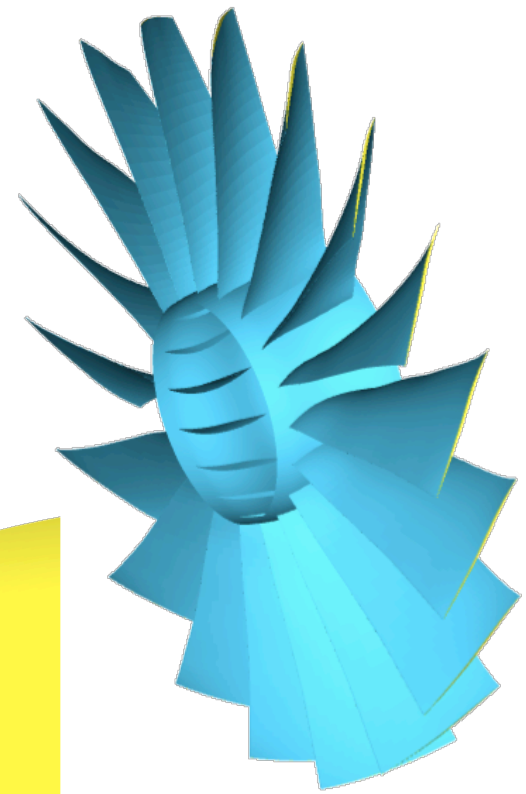
- Implicit, finite-volume solver
- Reynolds-Averaged Navier Stokes equations
- Structured multi-block code
- Multi blade-row code
- k-epsilon turbulence model
- Inlet distortion boundary condition
- Throttle exit boundary condition

- 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)

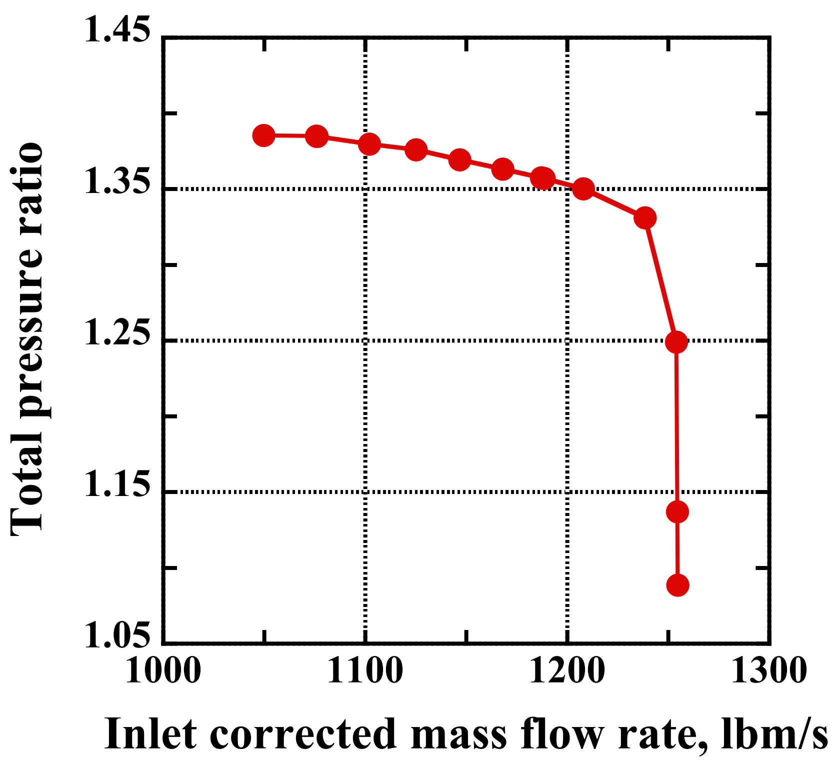


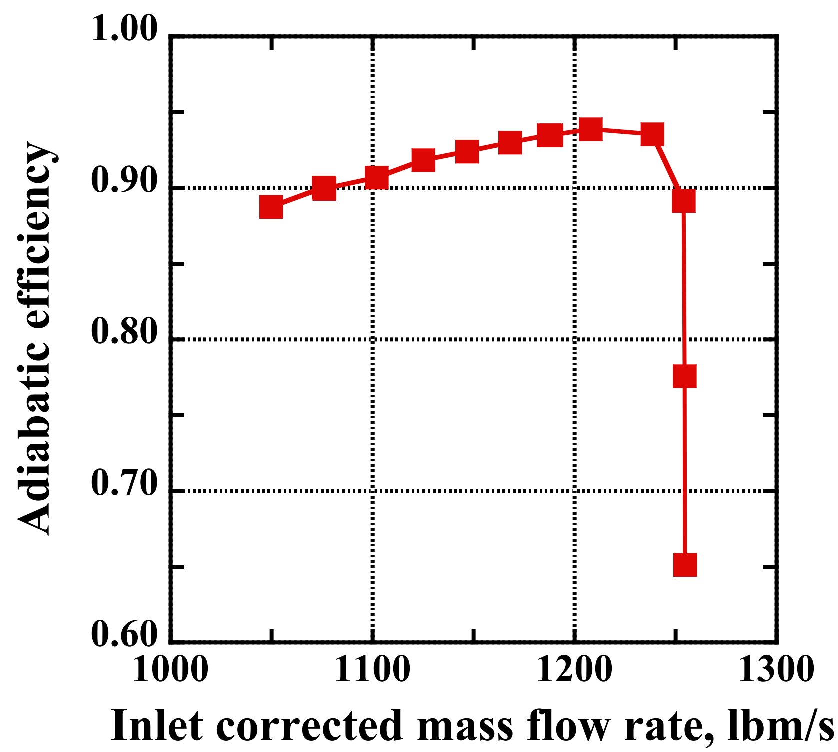


- H, O, and C blocks of mesh generated by UTRC

Fan Performance – Clean Inflow

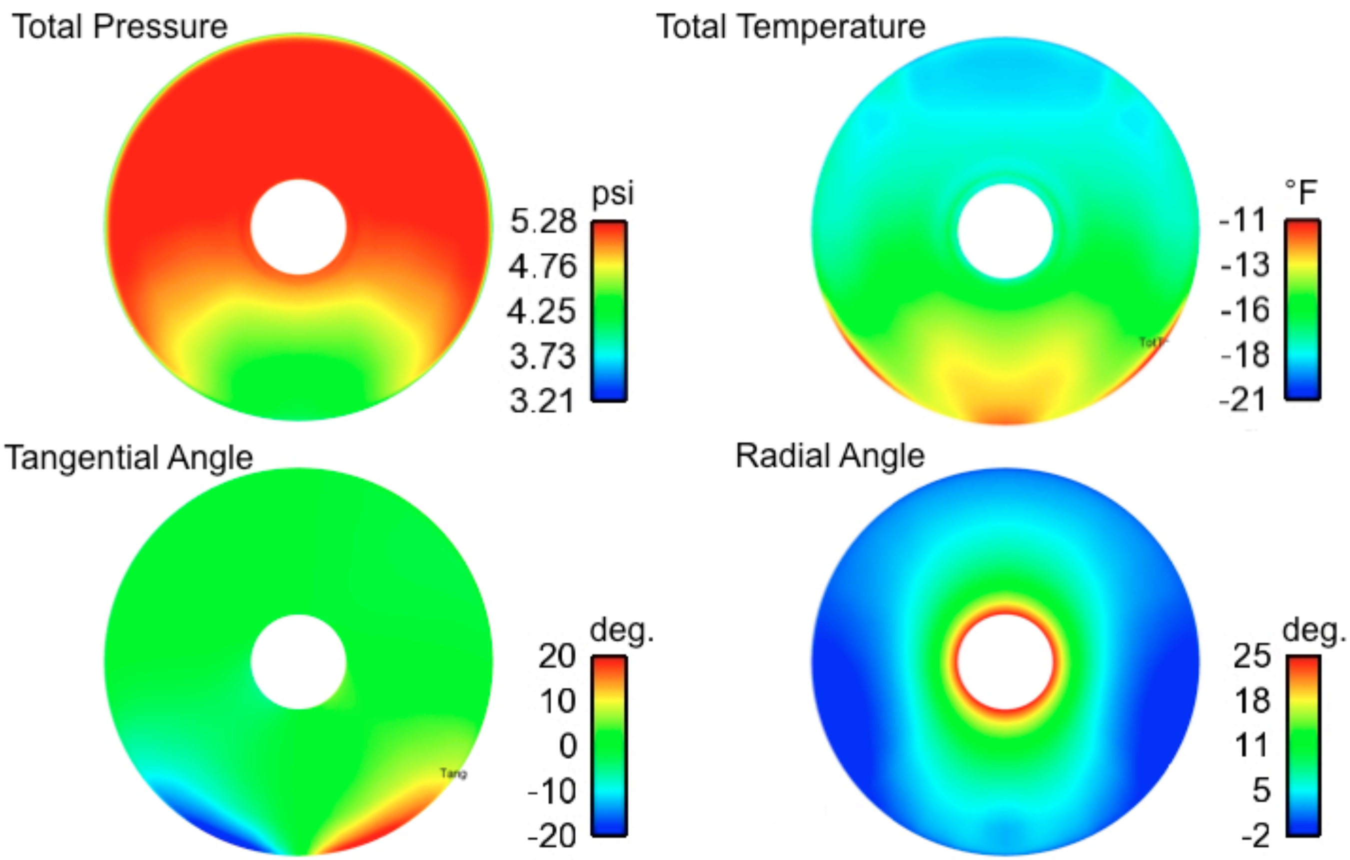
- TURBO code (RANS solver) used with radial inlet profile of total pressure, total temperature, and flow angles
- Speedline traversed by setting exit throttle condition and converging flow solutions





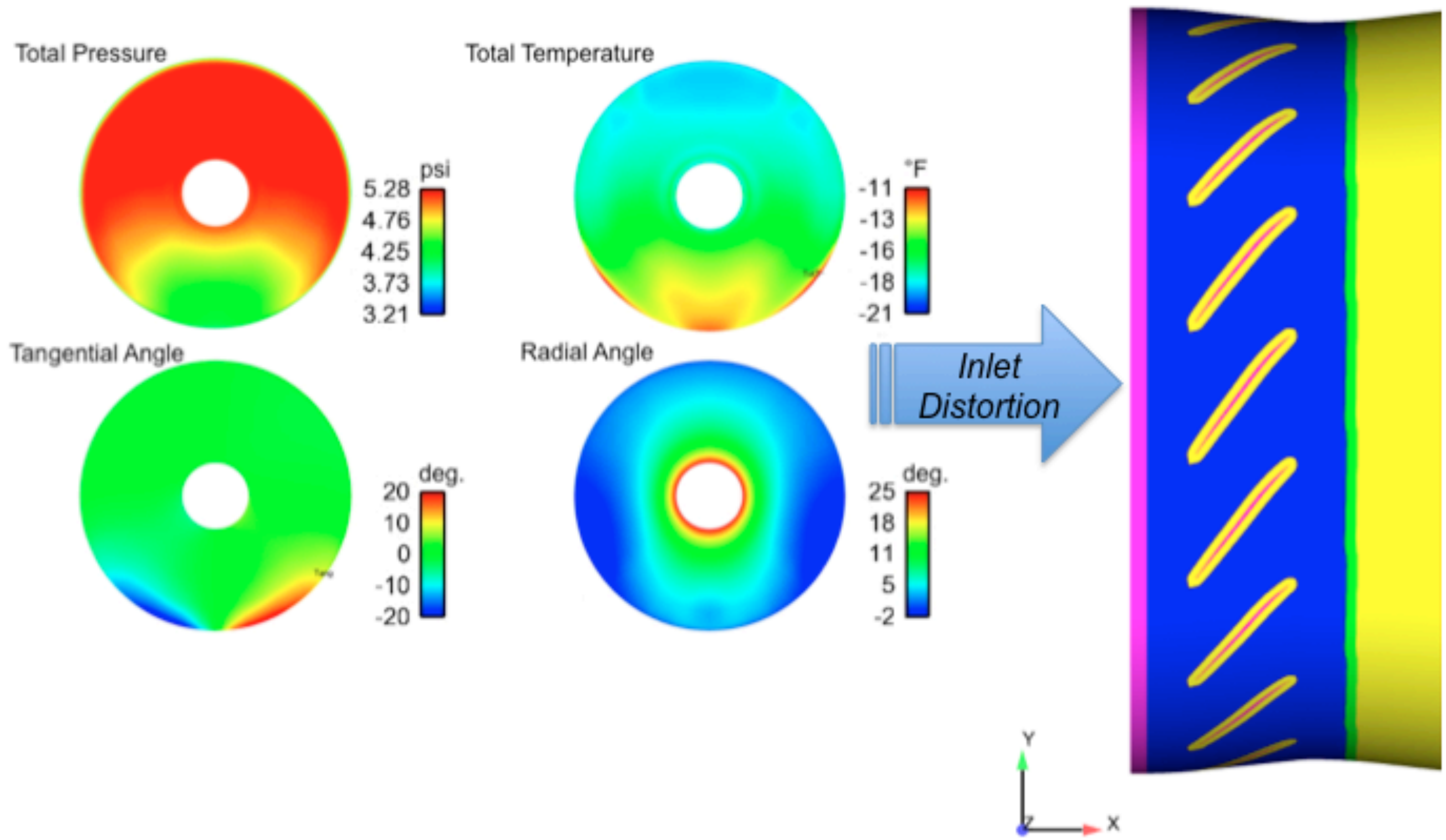
Inlet Flowfield Provides Distortion Pattern

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



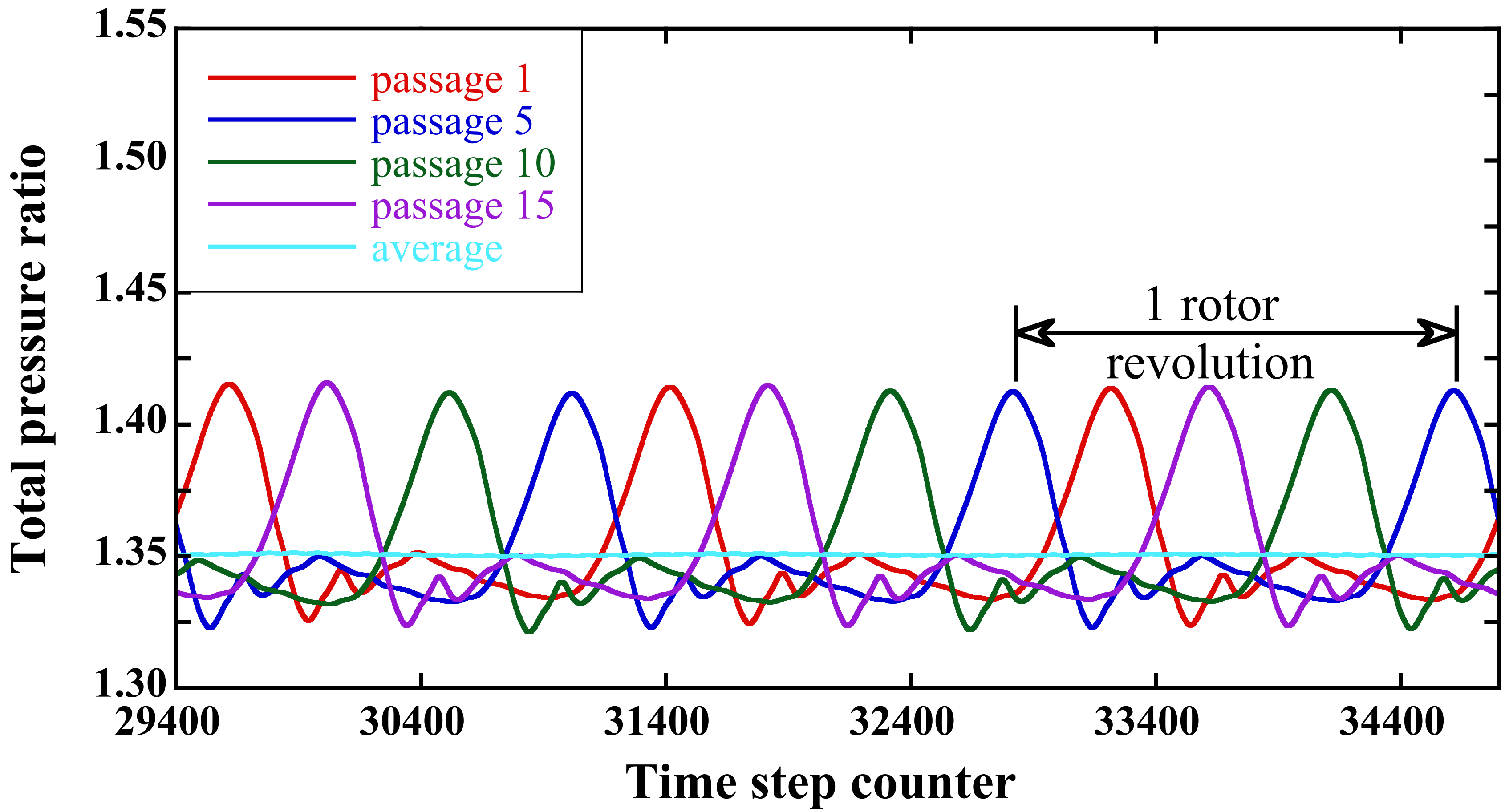
Fan Computation with Inlet Distortion

- 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

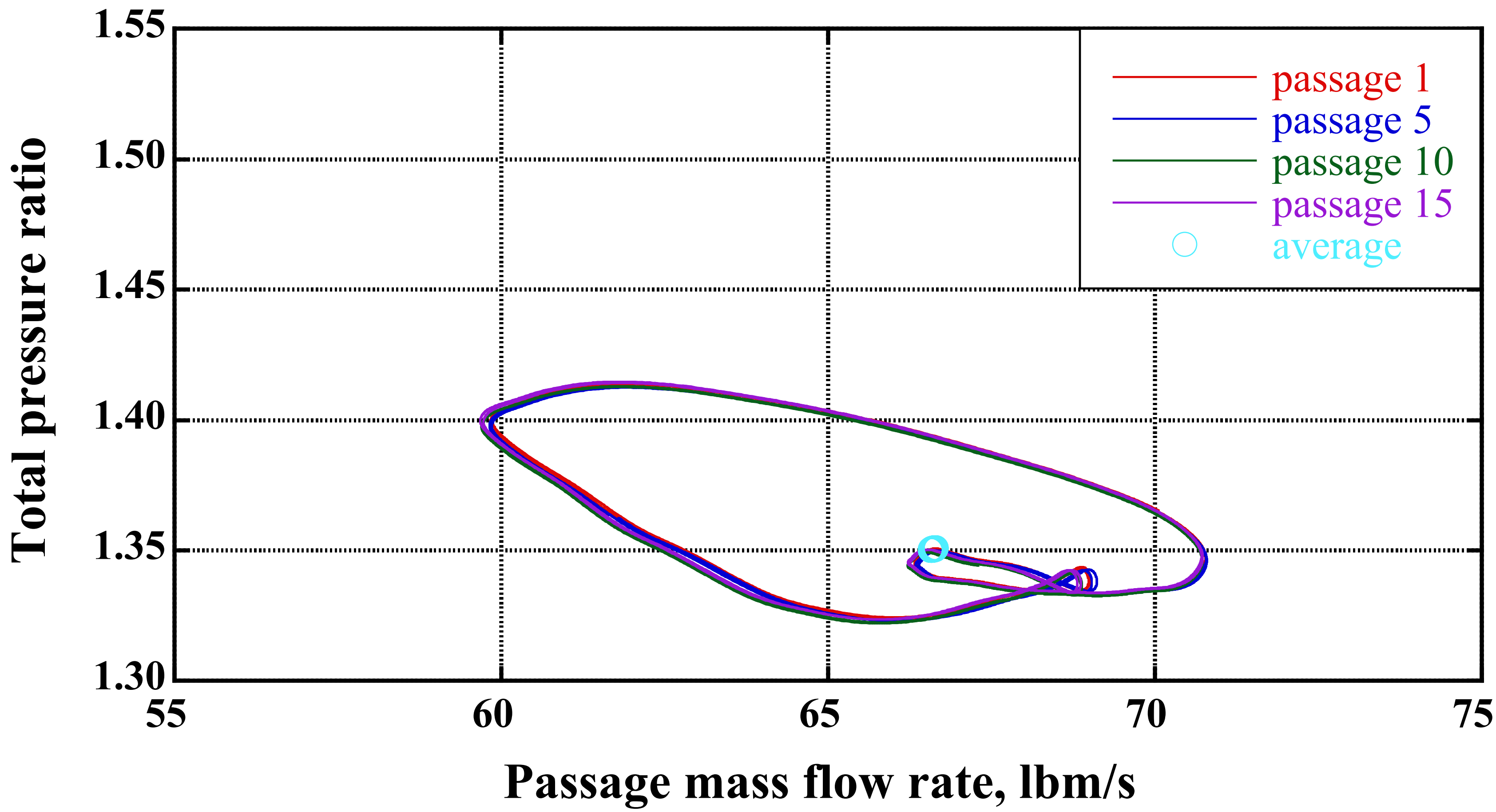
- Total pressure ratio for various blade passages



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

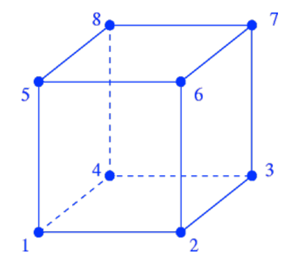


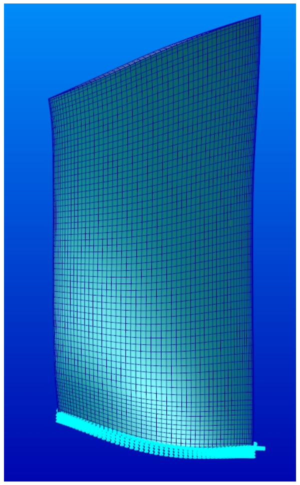
Inlet Distortion causes variations in mass flow rate and pressure ratio around the fan rotor

Structural Dynamics Model & Results

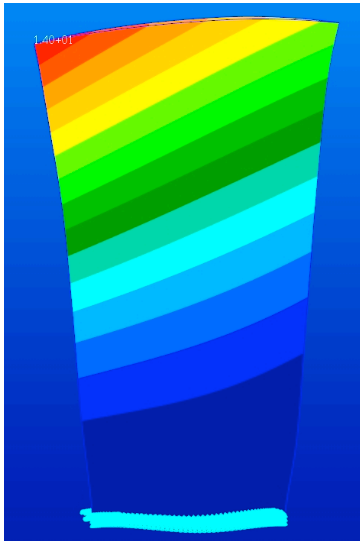
Blade structural model created based on aero design iteration (structural design is in progress)

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

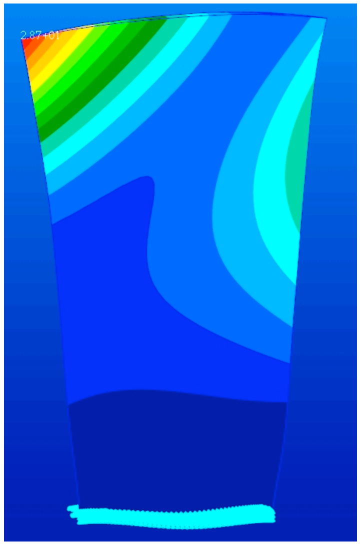




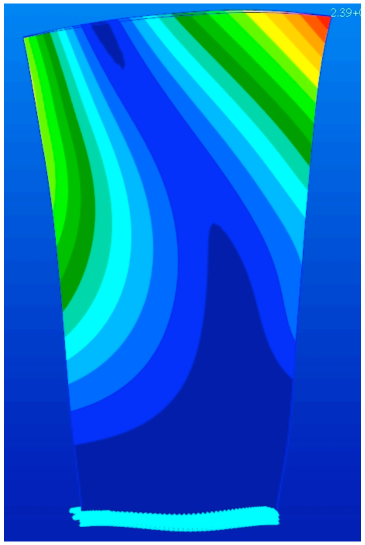
mode 1
63.5 Hz



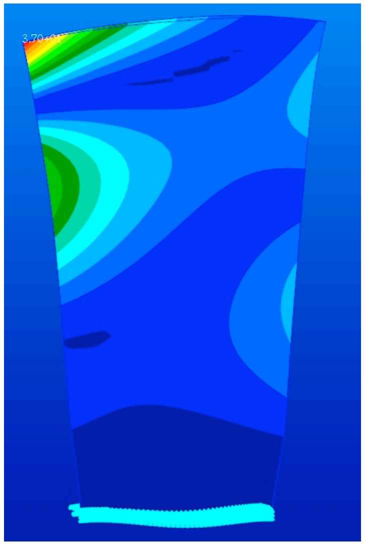
mode 2
156.6 Hz



mode 3
224.8 Hz



mode 4
346.6 Hz



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***

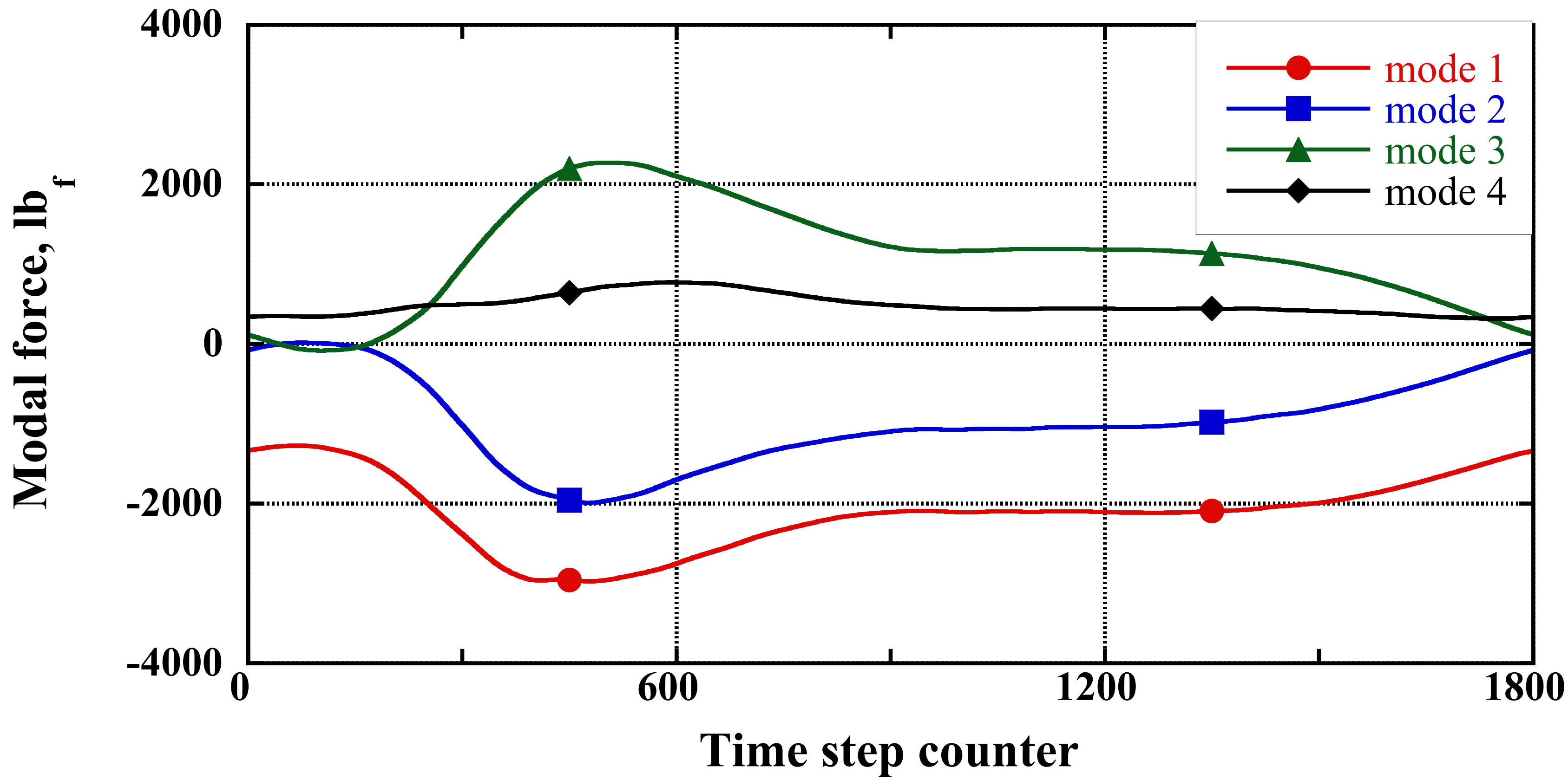
$$\{q\} = \left[[K] - \omega^2[M]\right]^{-1}\{AD\}$$

Forced Response

Modal Force

Time history over one rotor revolution

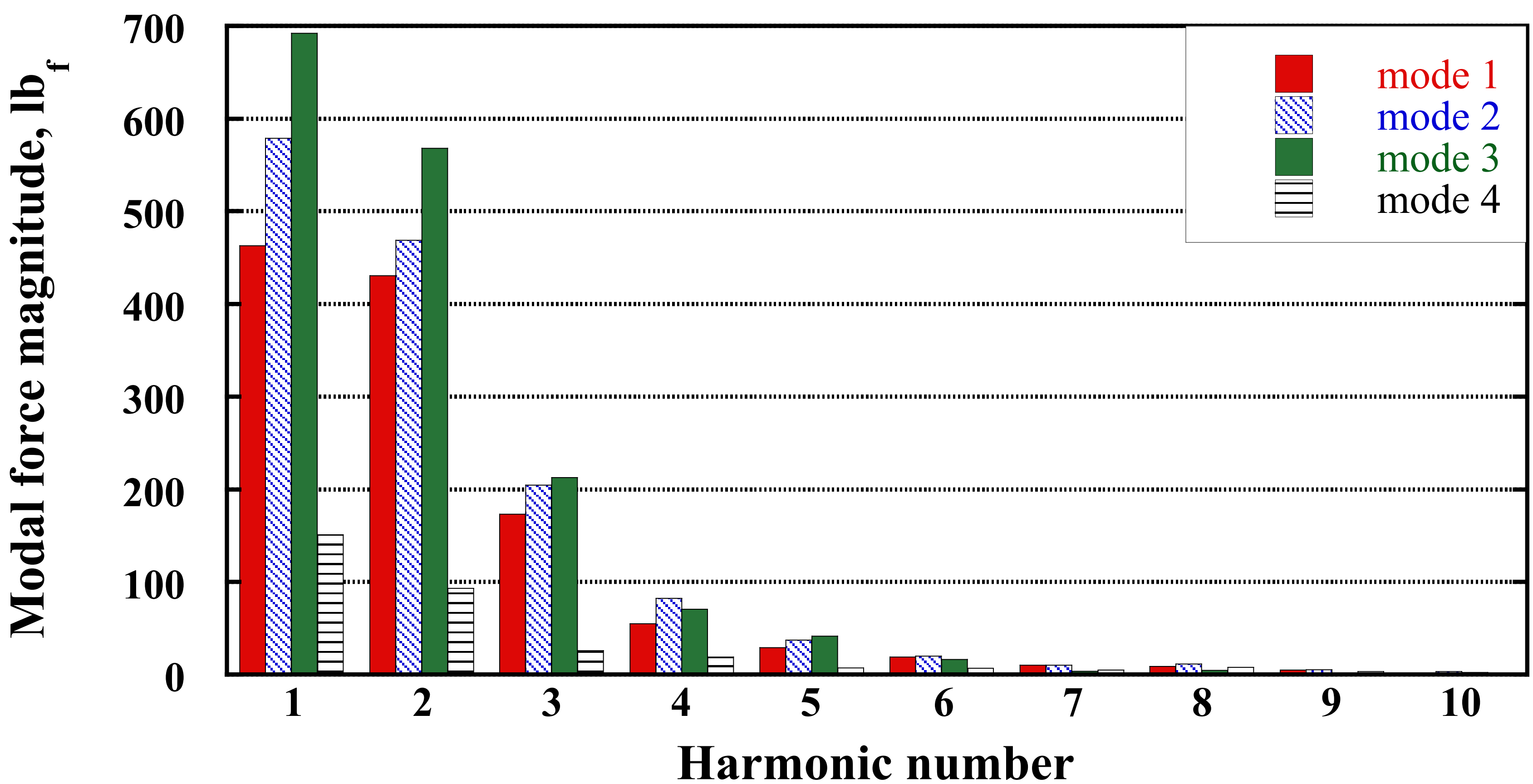
$$AD_i = \int \vec{\delta}_i \cdot p\,d\vec{A}$$



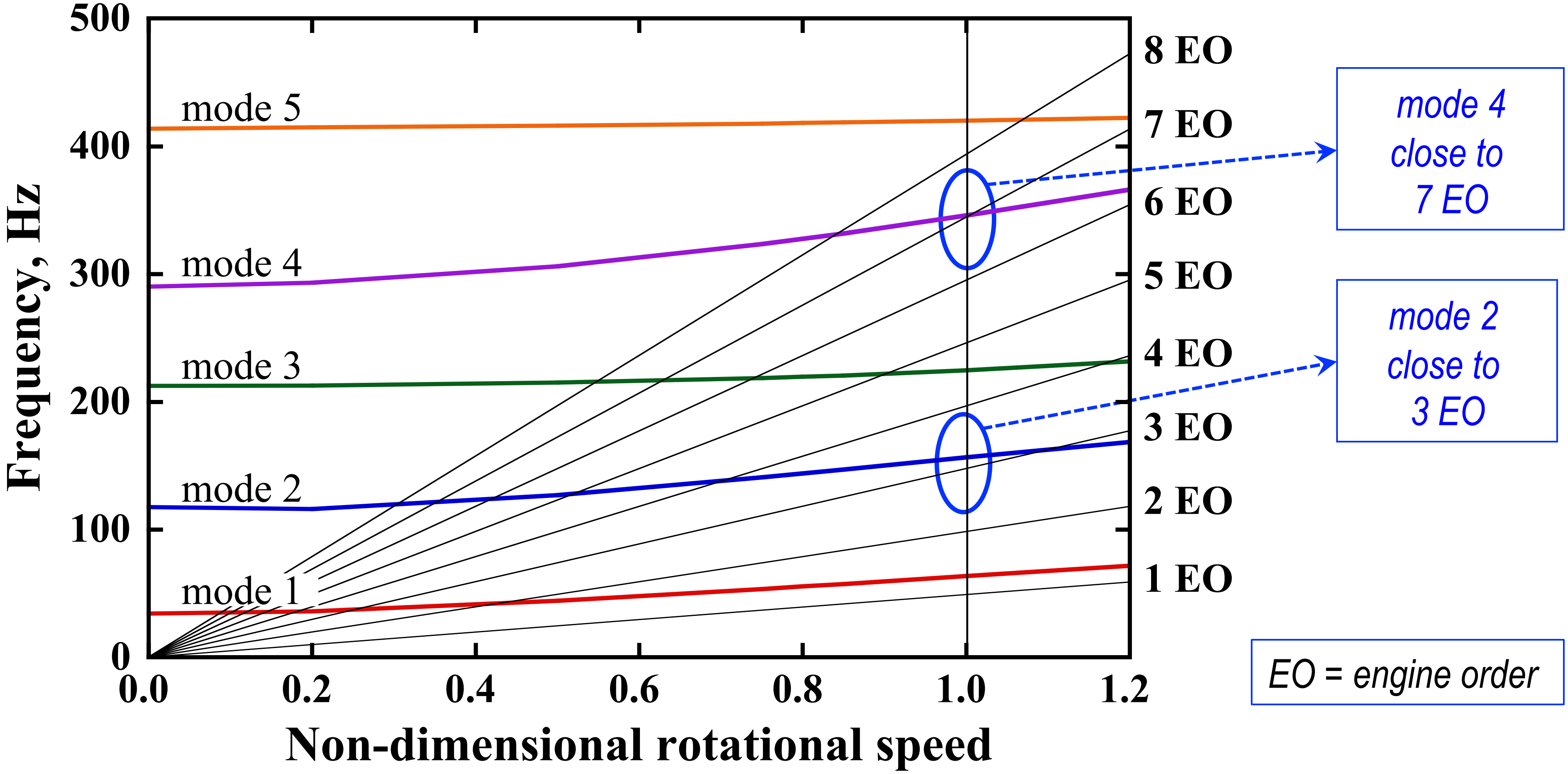
1,800 time steps per revolution

Modal Force

Fourier components

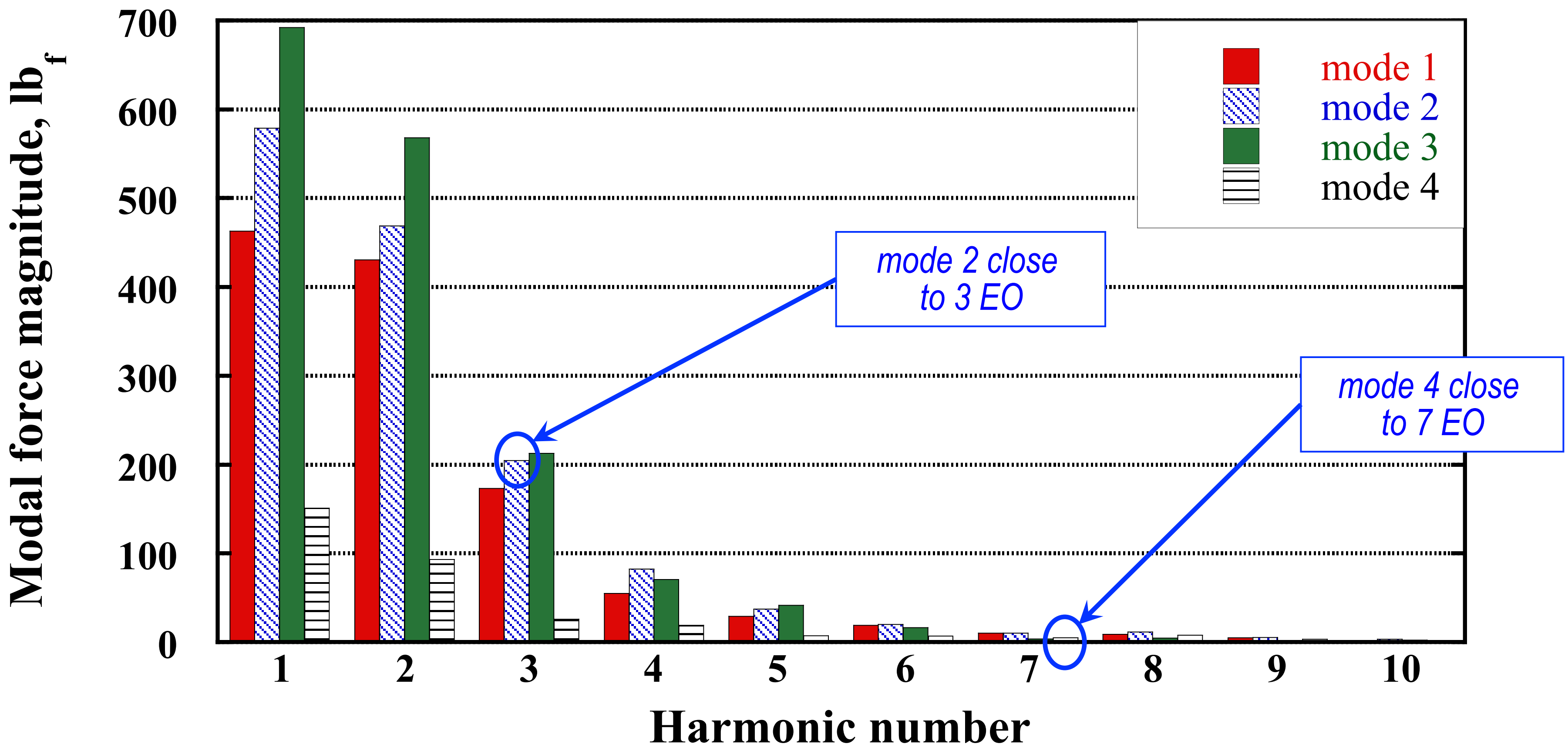


Campbell Diagram



Modal Force

Fourier components

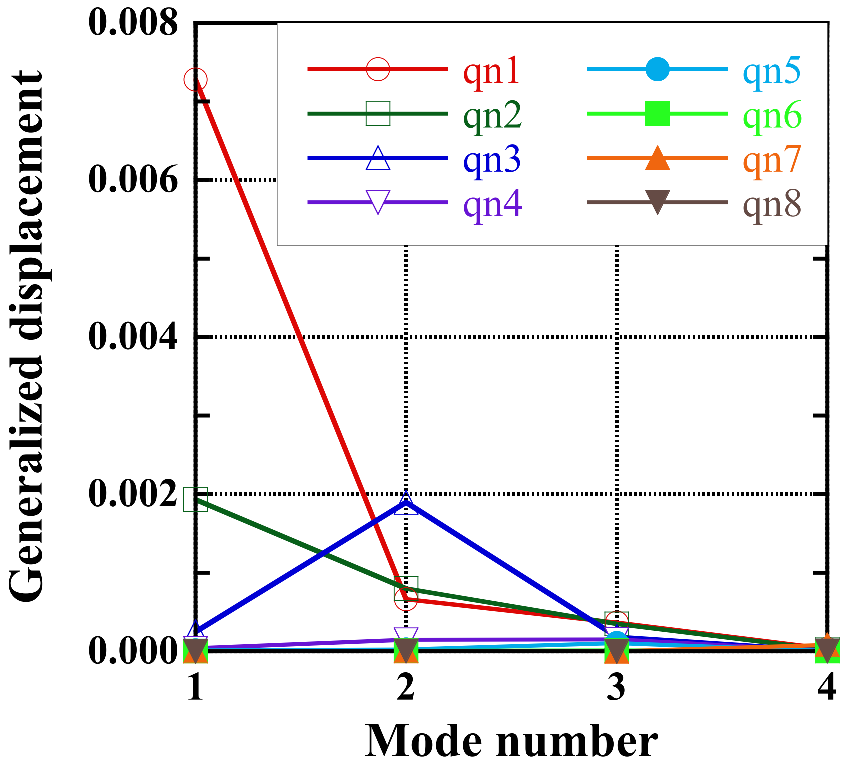


Forced Response – Vibration Amplitude and Dynamic Stresses

- 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*

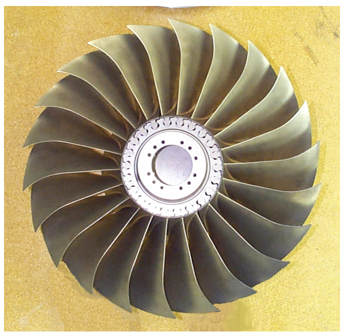
dynamic stress $\sigma_r = \sum_n s_n q_{nr}$ *where s_n is the modal stress*



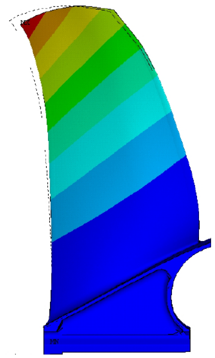
harmonic or engine order	vibration amplitude (inch) at tip t.e.	dynamic stress amplitude (psi)
1	5.5×10^{-2}	273
2	3.0×10^{-2}	290
3	1.9×10^{-2}	666
4	3.1×10^{-3}	308
5	2.6×10^{-3}	169
6	2.7×10^{-4}	33
7	7.0×10^{-4}	427
8	6.0×10^{-5}	19

Flow Chart for Flutter Stability Computation

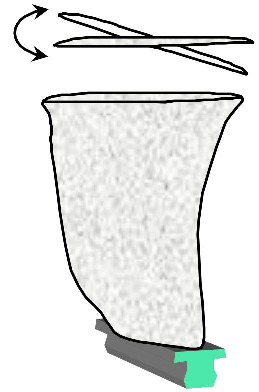
- Aerodynamic damping computation using TURBO-AE



Configuration



Mode Shape



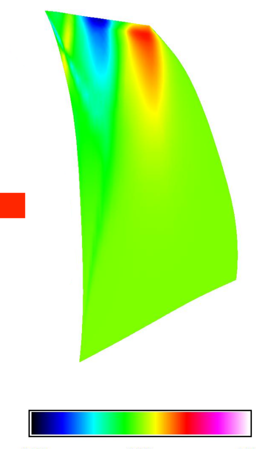
Prescribe Blade Motion

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

Calculate Work

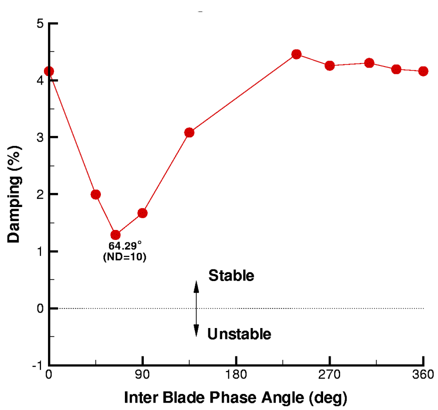
(for all ω and ϕ of interest)

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



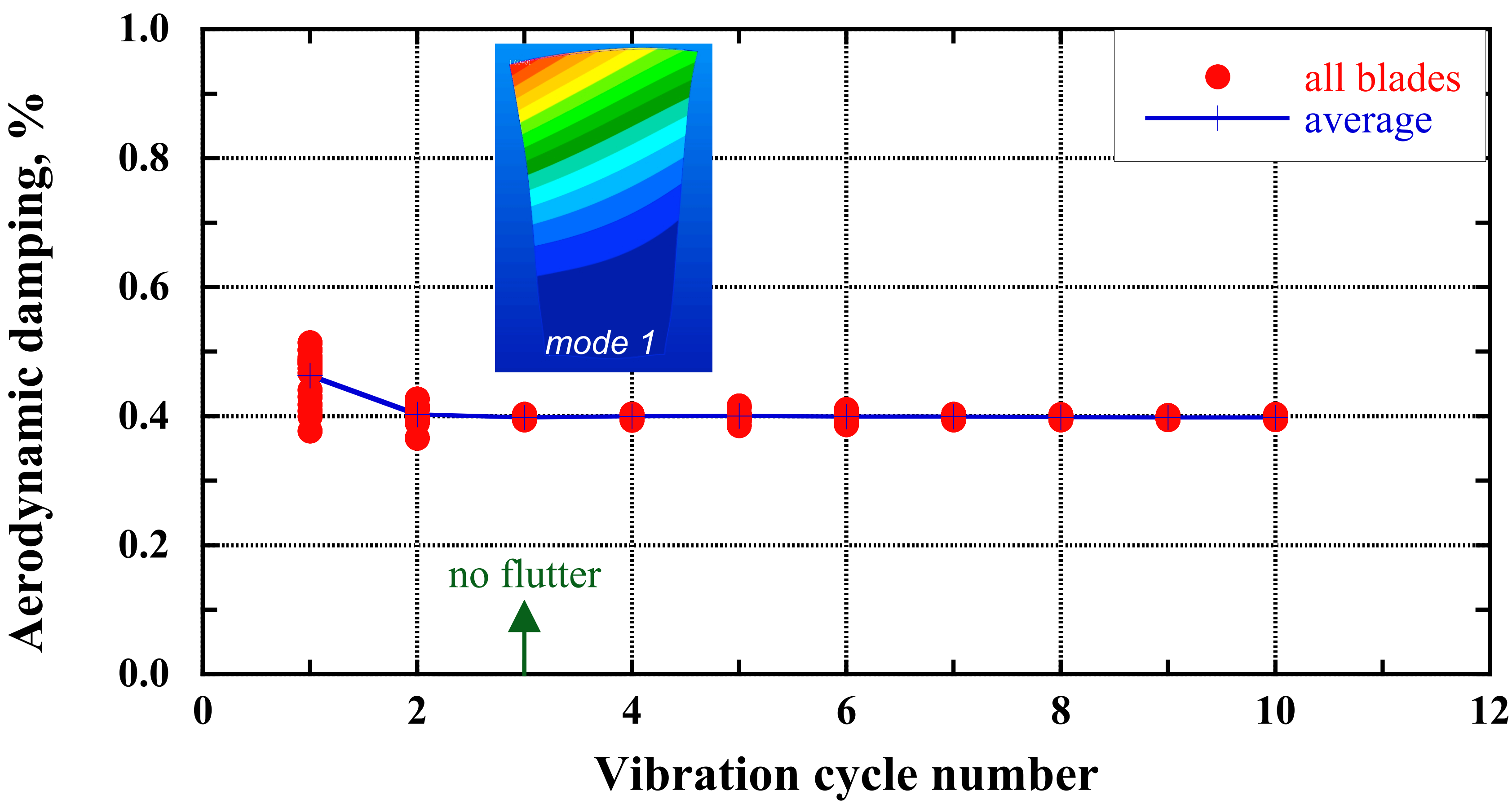
Calculate Aerodynamic Damping

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



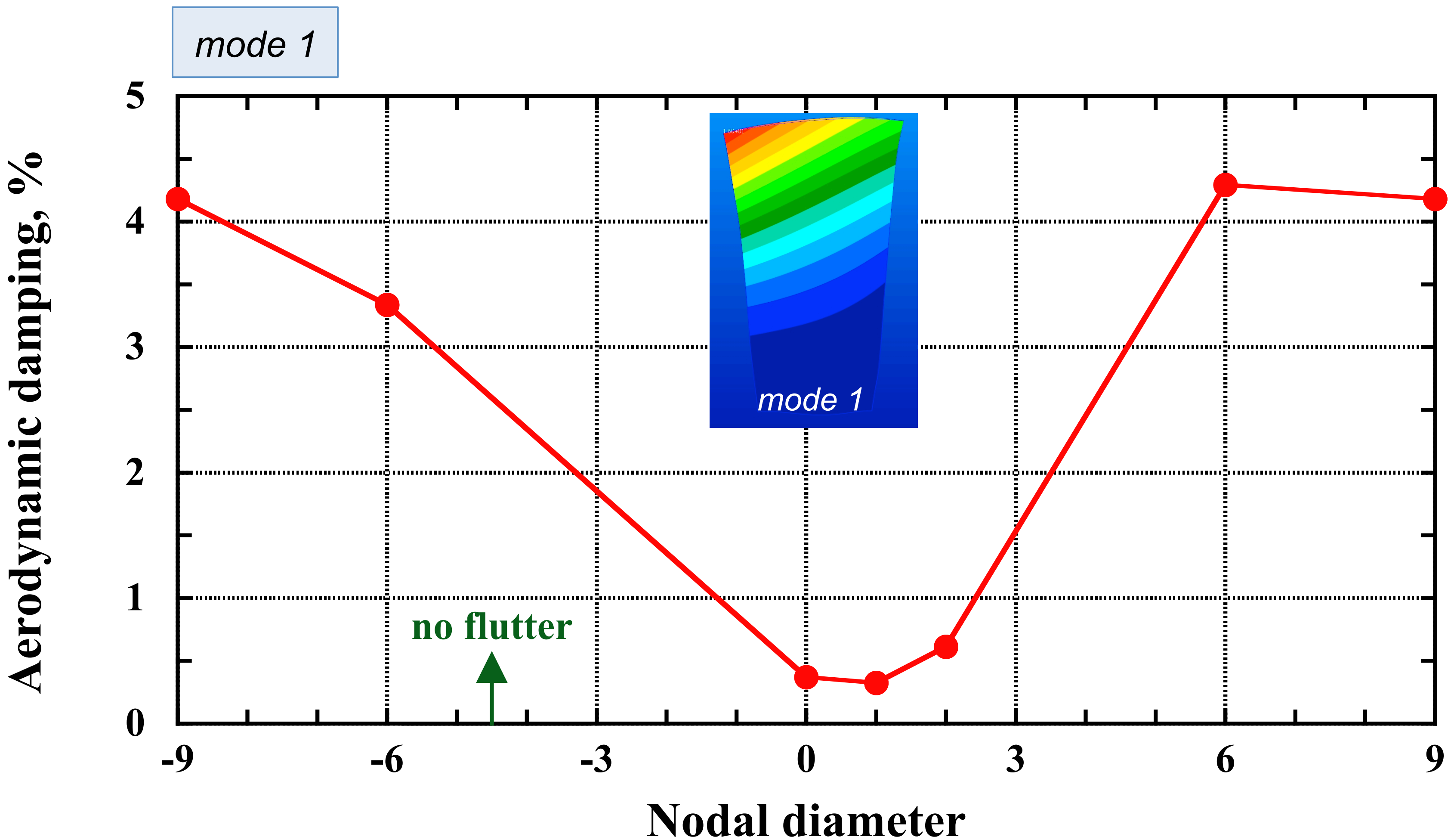
Flutter Stability with Clean Inflow

- 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



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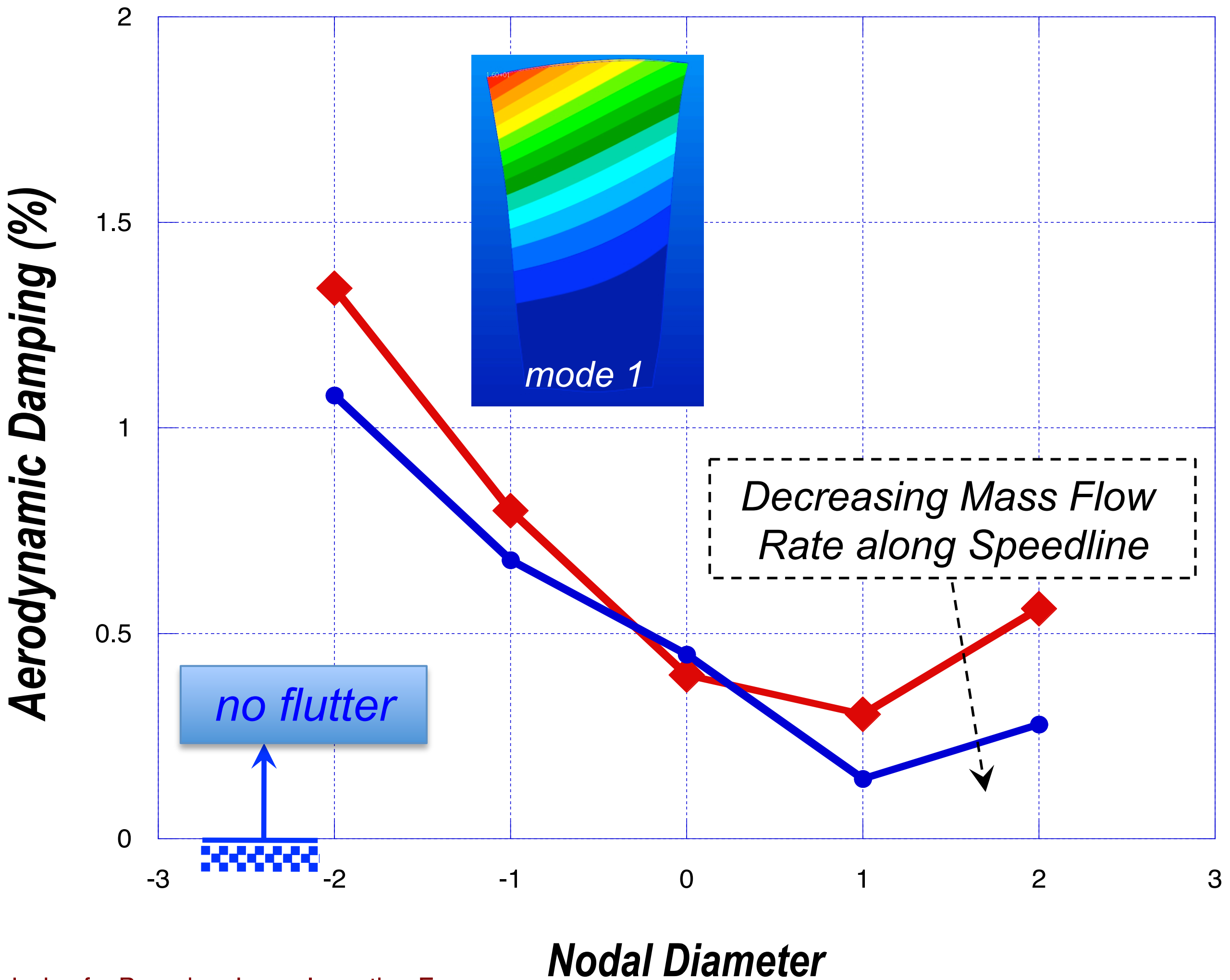

Flutter Stability with Clean Inflow

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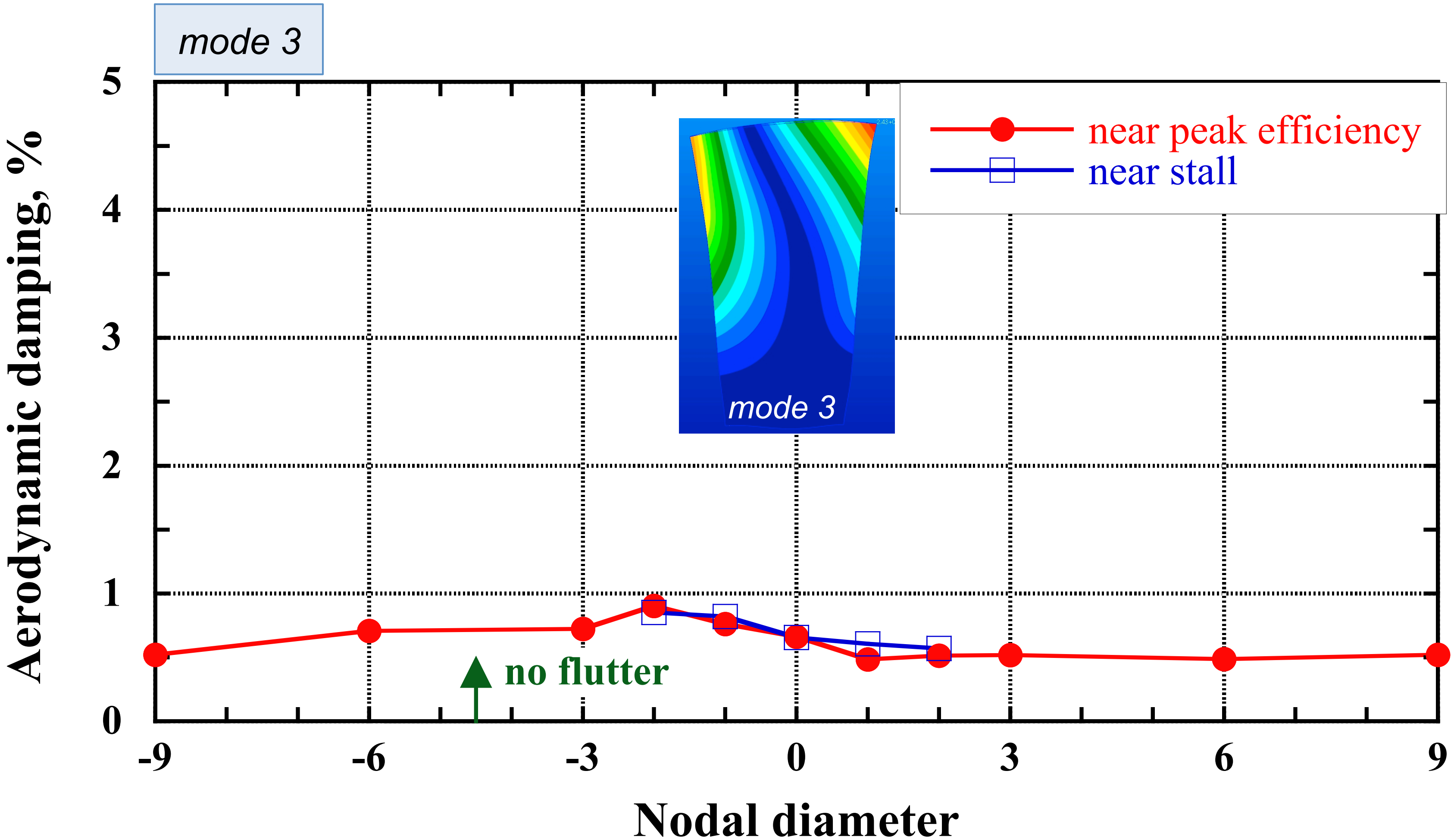


Flutter Stability with Distorted Inflow

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

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

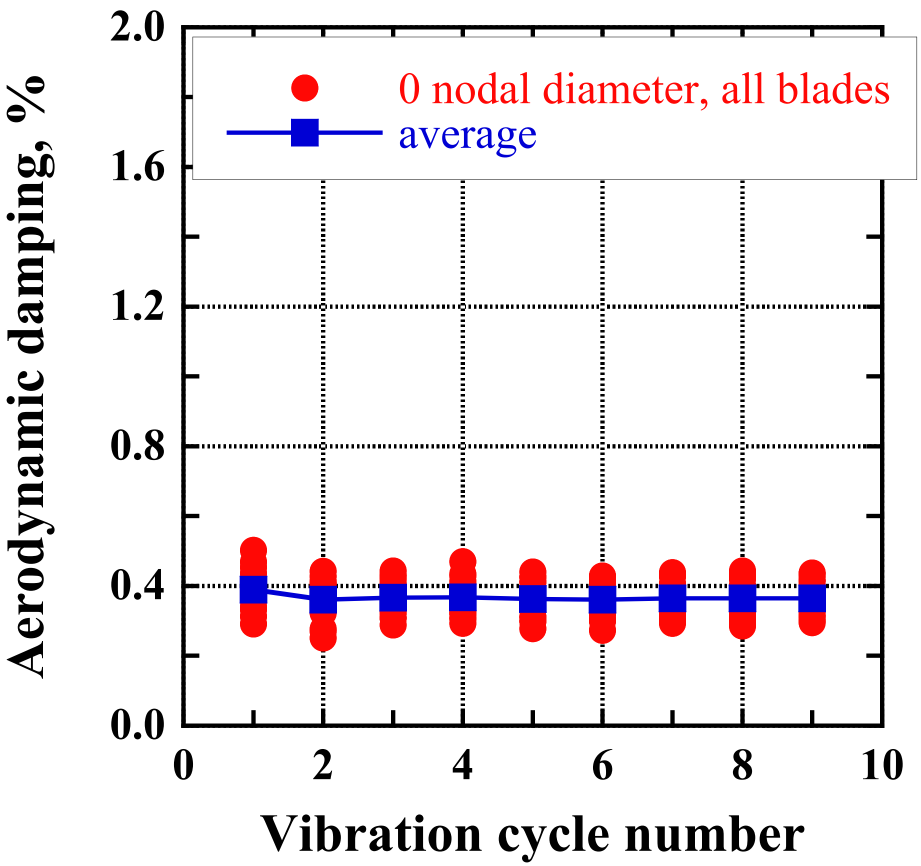
Unsteady pressure includes effect of

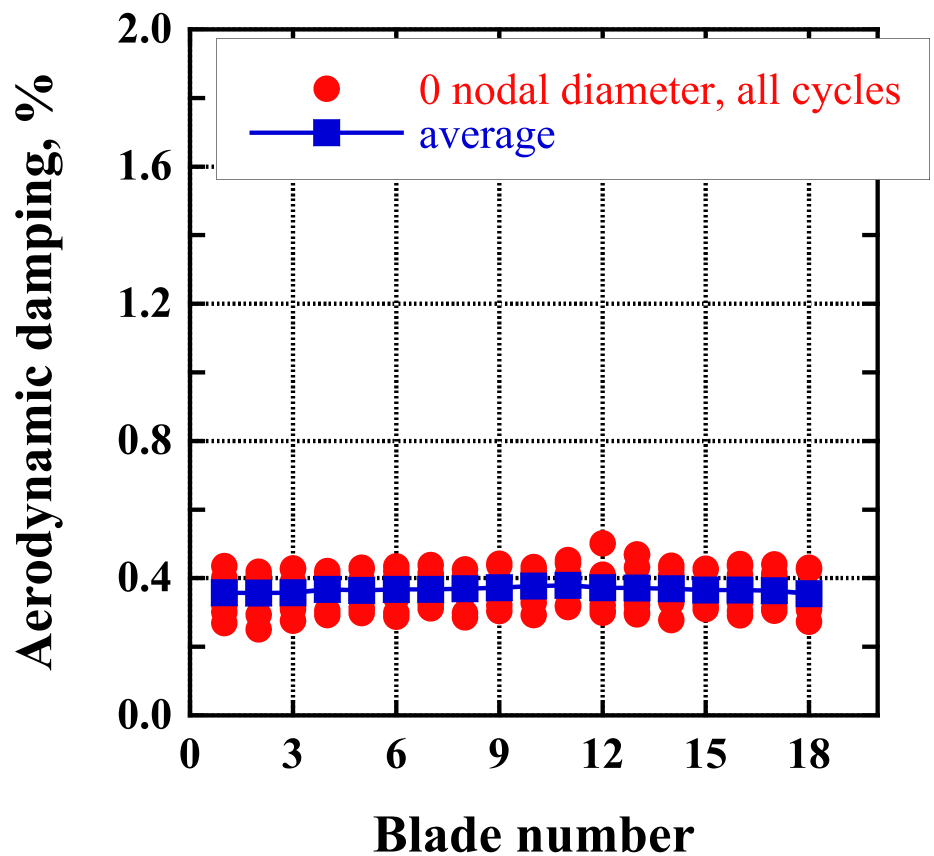
1) inlet distortion

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

Flutter Stability with Distorted Inflow

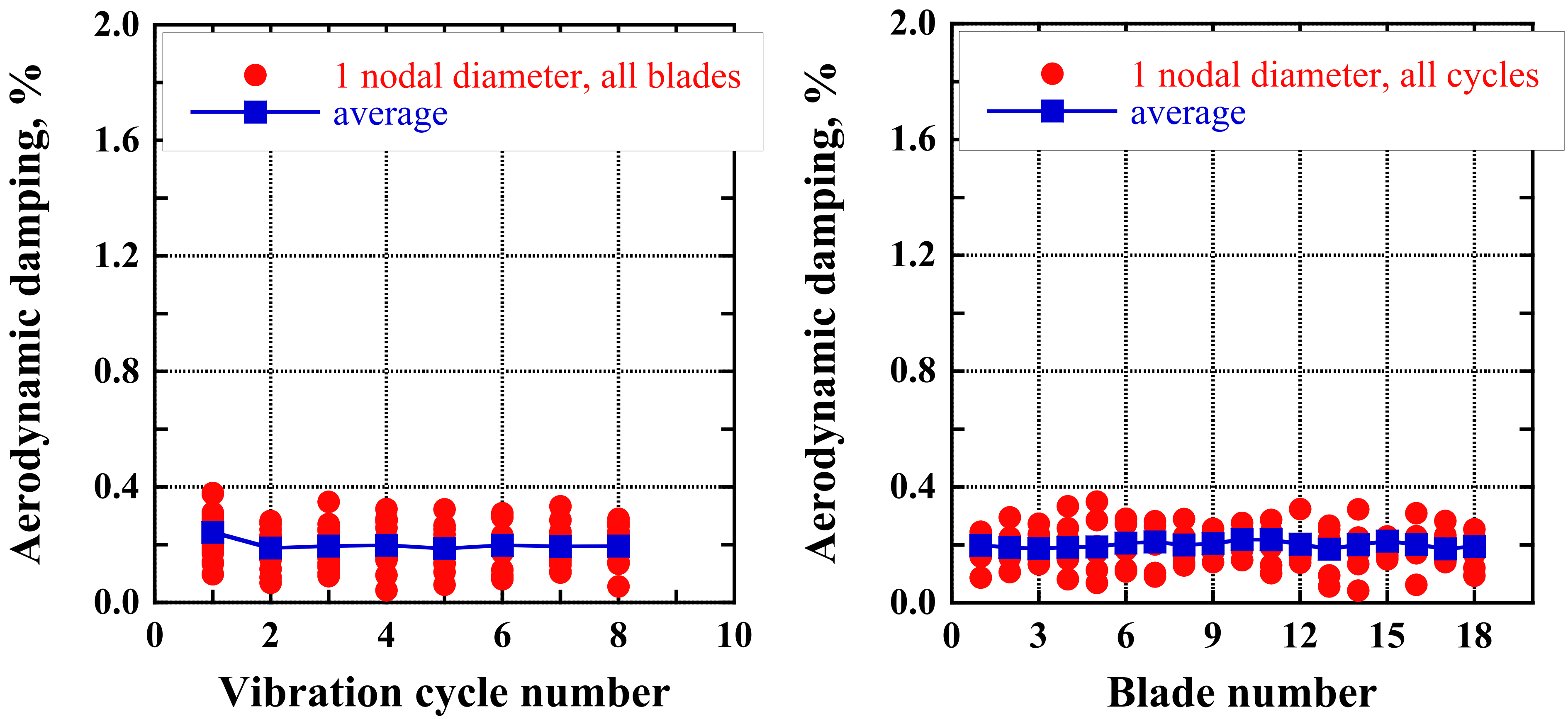
- Design operating speed, mode 1, 0 nodal diameter pattern (all blades in-phase), 18 blade passages (full rotor)





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?