Fan and Compressor Performance Scaling with Inlet Distortions

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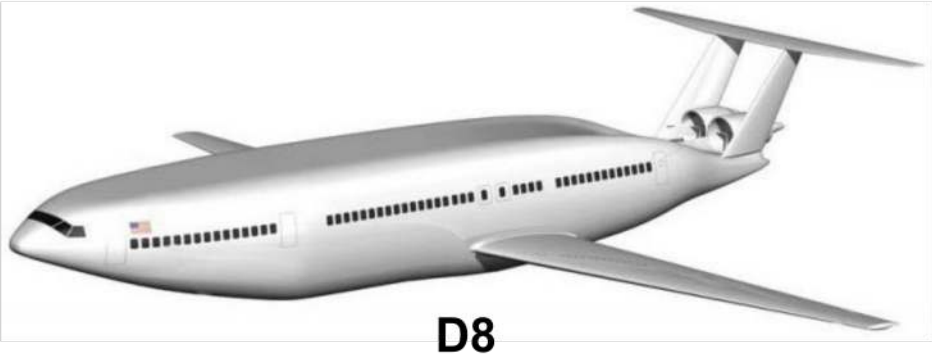
Aerospace Propulsion Research at University of Windsor

- Simplified computational modelling of fans and compressors
- Investigation into design and performance of turbomachines in non-uniform flow
- Aeroacoustics of turbomachinery and unsteady internal flows

Future Aircraft May Utilize Embedded Propulsion

SAX-40

from <http://silentaircraft.org/>



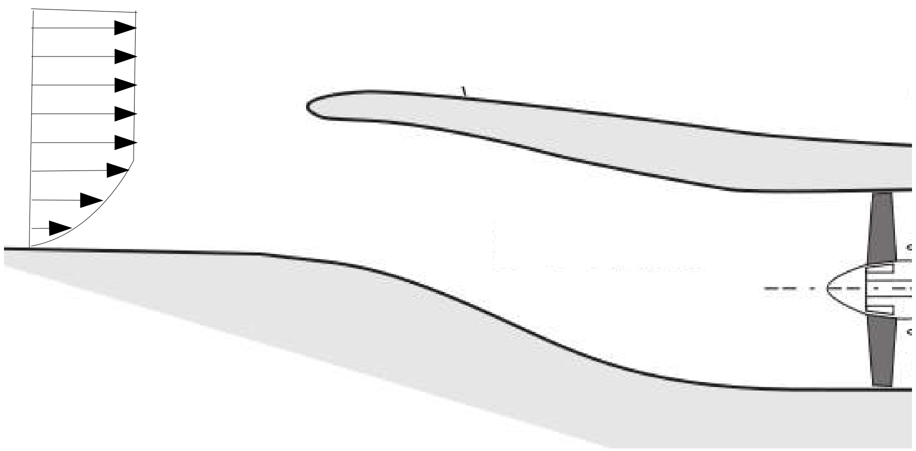
D8

from <http://wordlesstech.com/nasas-double-bubble/>

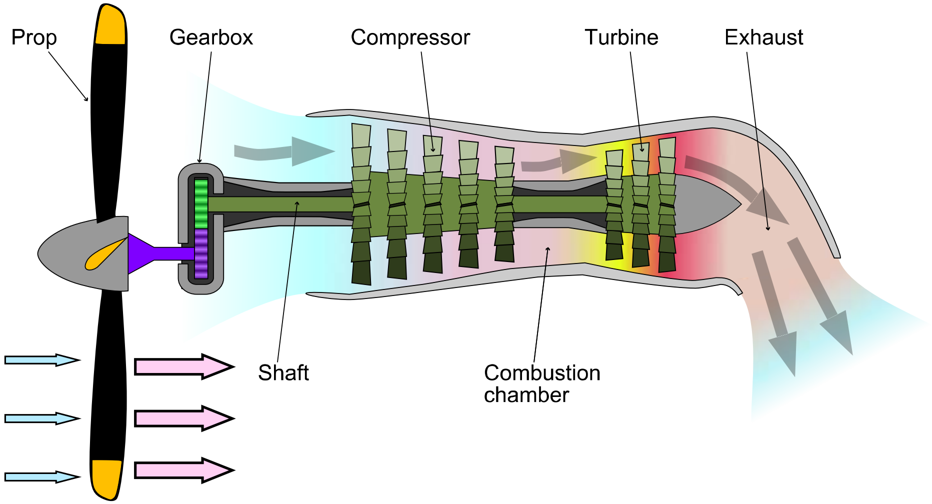
Inlet Distortions Affect Fan/Compressor Performance

- Many fans/compressors must operate continuously with inlet flow distortion

From Wikimedia Commons/Emoscopes

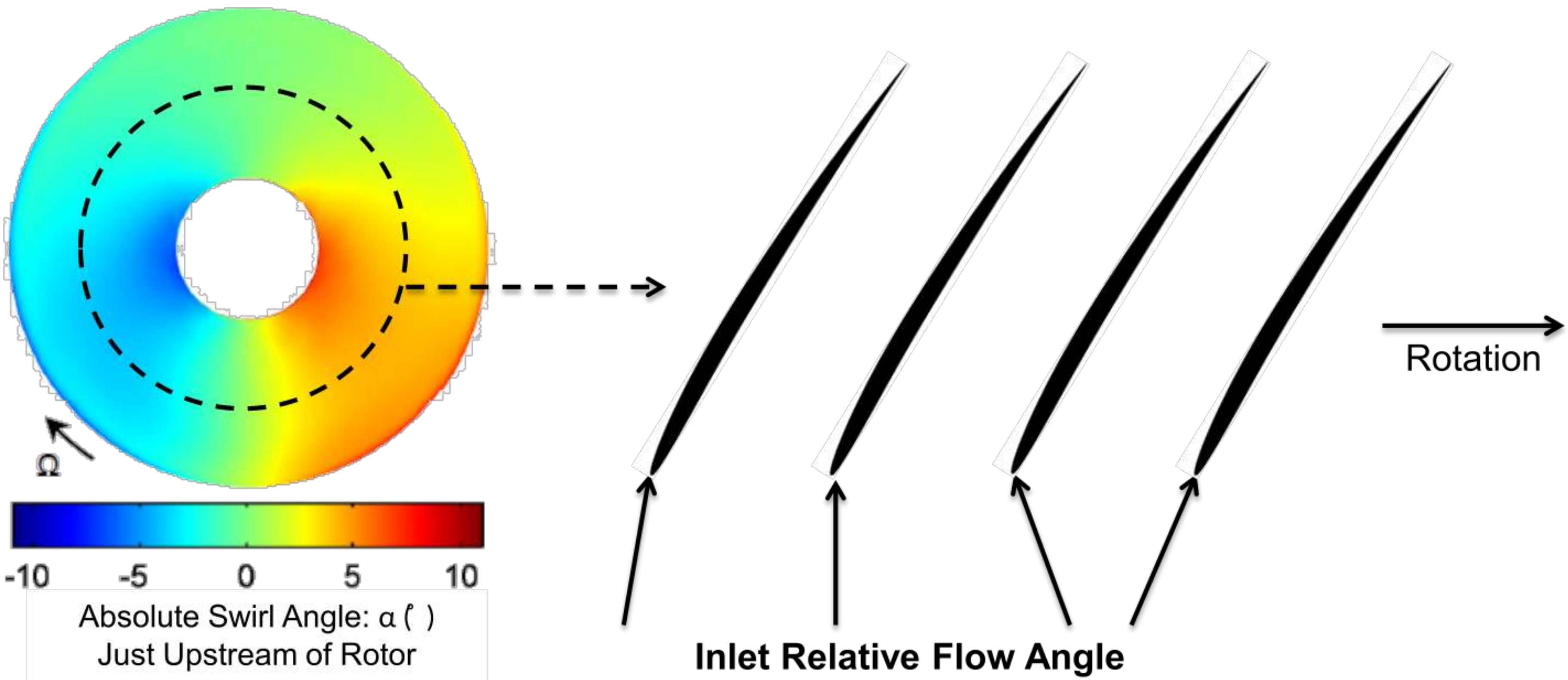


Boundary Layer Ingesting (BLI) Turbofan Engine



Turboprop Engine Compressor

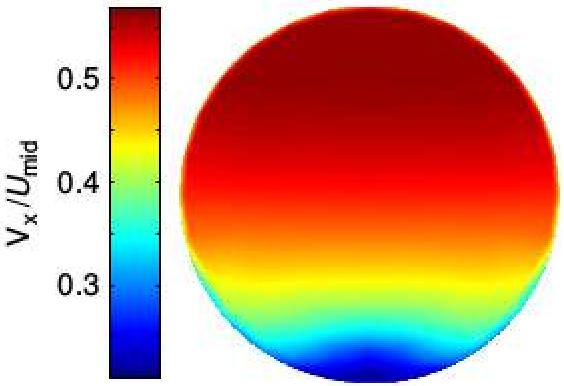
No Frame Of Reference In Which Flow Is Steady



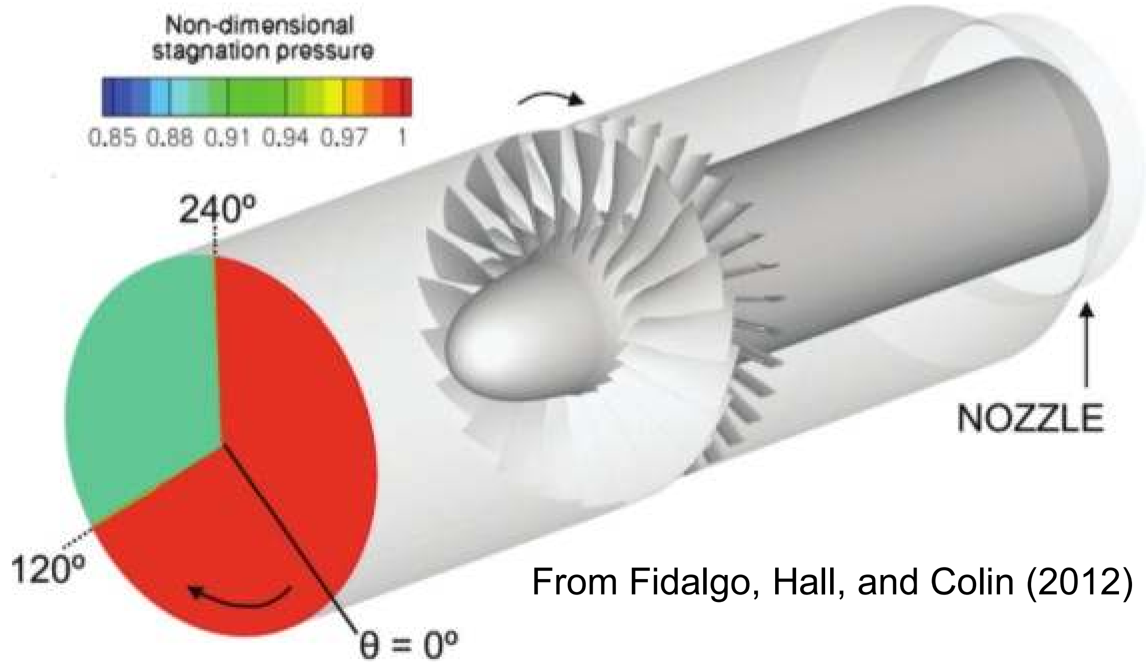
from Gunn & Hall (2014)

Past Studies Focus on One or Few Distortions

- Effects of distortion studied extensively, but normally time-consuming
  - Experimental rig development
  - Computation of full-wheel, unsteady flow solutions



From Gunn and Hall (2014)



From Fidalgo, Hall, and Colin (2012)

Scaling of Fan Performance as Distortion Altered Not Well Known

Objectives

Identify mechanisms by which fans/compressors interact with flow distortions

Numerically assess how performance of axial fan/compressor stages are affected by various types and severity of inlet distortion

- At design flow coefficient and corrected speed

Key Messages – Mechanisms

- Stagnation temperature and pressure distortions fundamentally interact with fans/compressors in same way
  - Flow redistributed to alleviate upstream velocity distortion
- Result:
  - Attenuation of mass flux distortion for varying stagnation pressure
  - Amplification for varying stagnation temperature

Key Messages – Performance Scaling

- At low speed, changes in performance are approximately additive for distortions of:
  - Different inlet flow properties
  - Different severity for a single inlet stagnation quantity

- At high speed, increases in distortion severity lead to *more than additive* increases in performance changes

- Changes in performance for swirl distortion do not scale linearly with severity

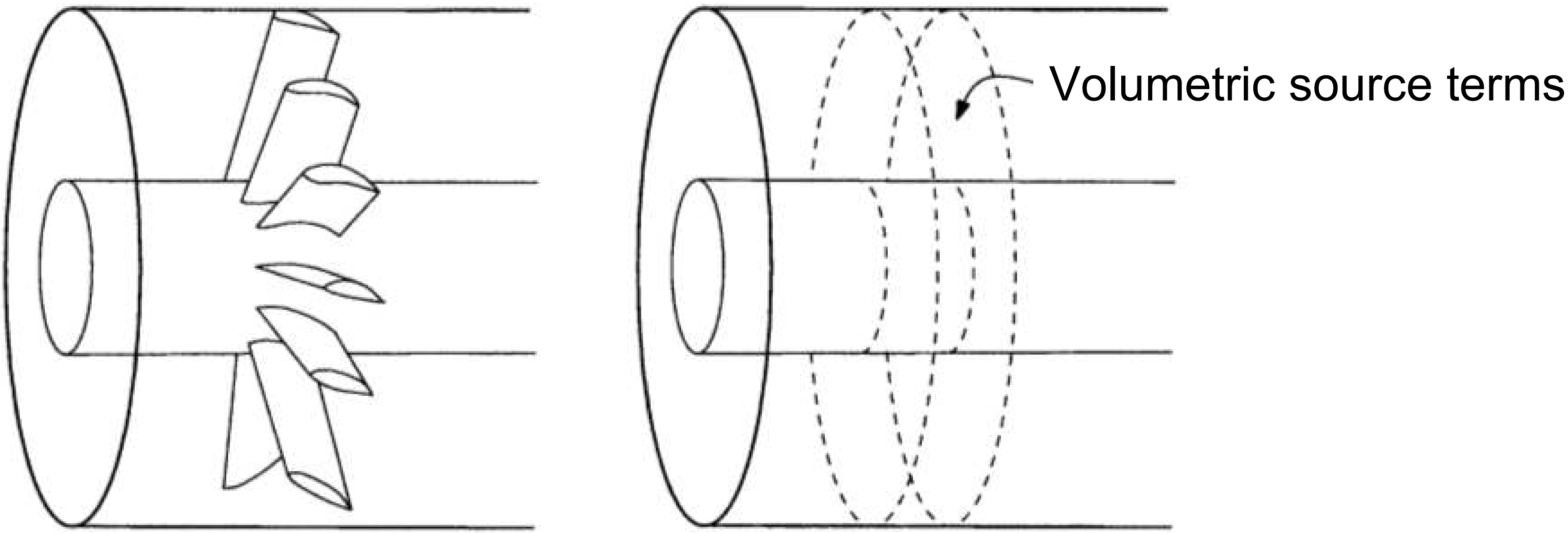
Approach Uses Source-Term-Based Fan Model

- Non-axisymmetric throughflow model of turbomachinery blade rows
  - Steady flow model
- Loss modelling a work in progress – so no discussion of efficiency
- Momentum and energy source terms added to governing equations

Steady flow model + reduced grid resolution reduces computational cost by 2-3 orders of magnitude

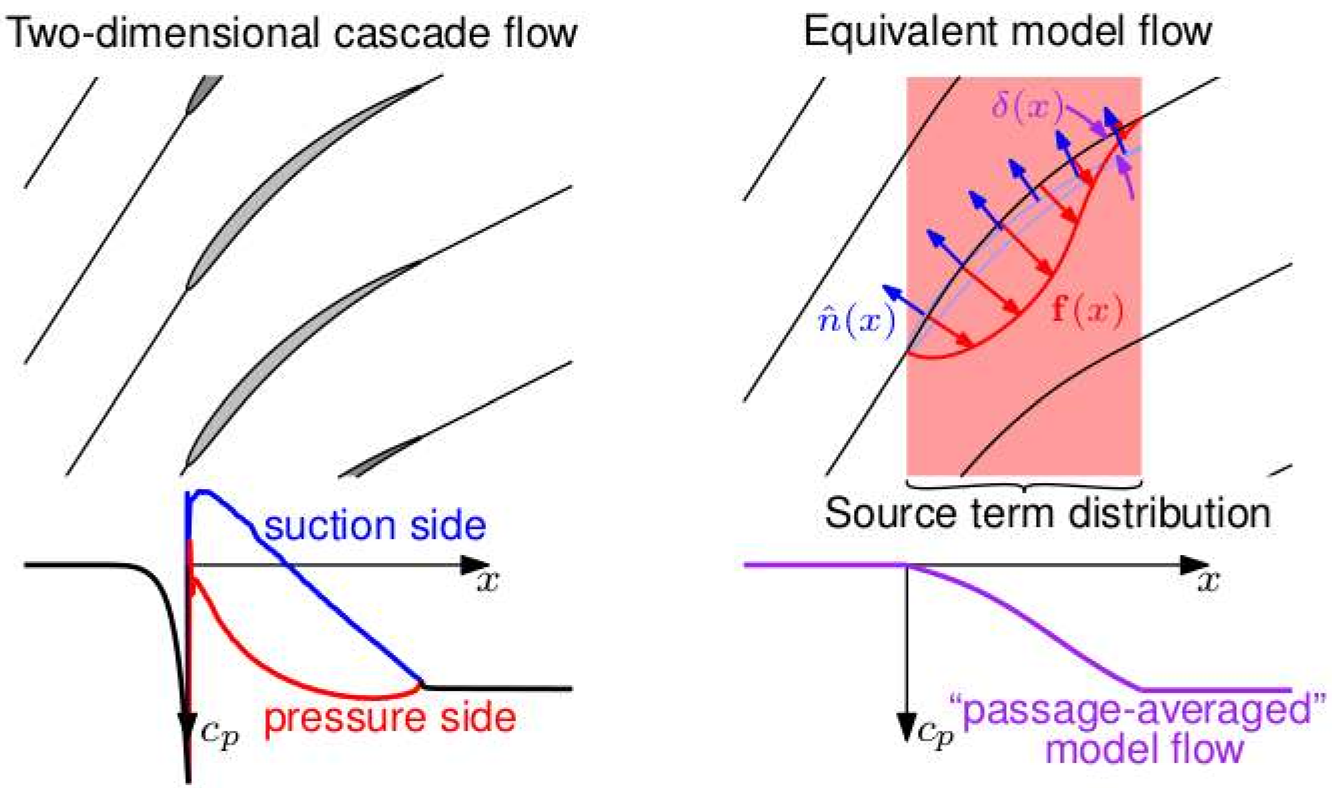
Throughflow Model Generates Turning and Pressure Rise

- Turbomachinery blades replaced with momentum/energy terms



Adapted from Brand (2013)

Blade Loading Force Scales with Local Deviation



$$f_n = \frac{(2\pi\delta)\left(\frac{1}{2}W^2/|\hat{n}_\theta|\right)}{2\pi r/B}$$

Model by David Hall (MIT)

Normal Force Model Modified for use in Compressible Flow

Adjusted to yield correct relative flow angles (captures incidence effects)

Adjusted to yield correct outlet tangential velocity (captures work input)

$$f_n = \frac{(2\pi\delta)\left(\frac{1}{2}W^2/|\hat{n}_\theta|\right)}{2\pi r/B}$$

Approach Captures Distortion Transfer for f_{red} << 1

- Local rotor reduced frequency

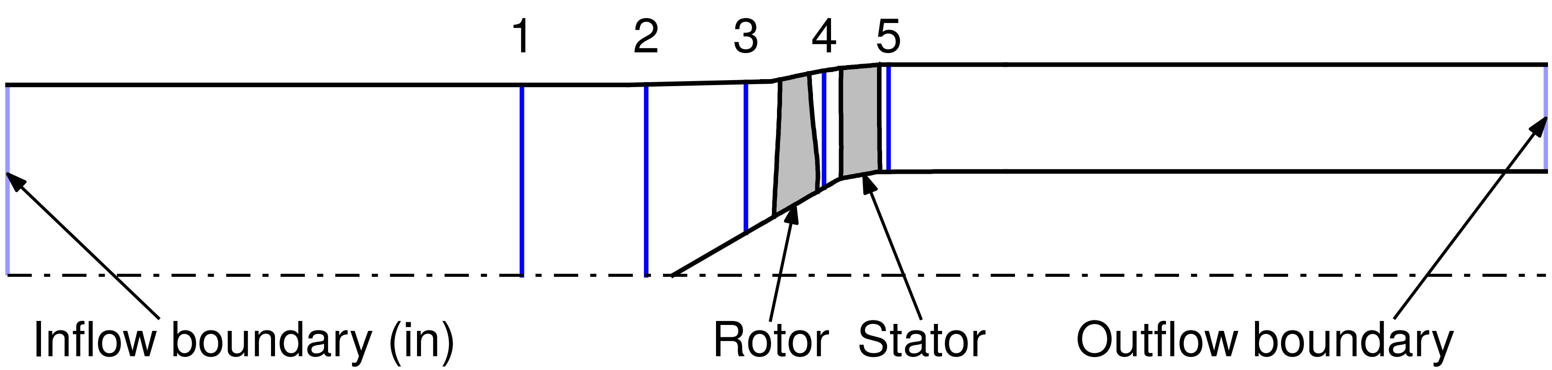
$$f_{red} = \frac{c_x/V_x}{2\pi/\Omega} \approx \frac{\cos\xi\,(1 - R_{hub}/R_{tip})}{2\pi\phi AR}$$

  < 0.1 for all distortions considered

- Additionally require that distortion wavelength is large compared to blade pitch

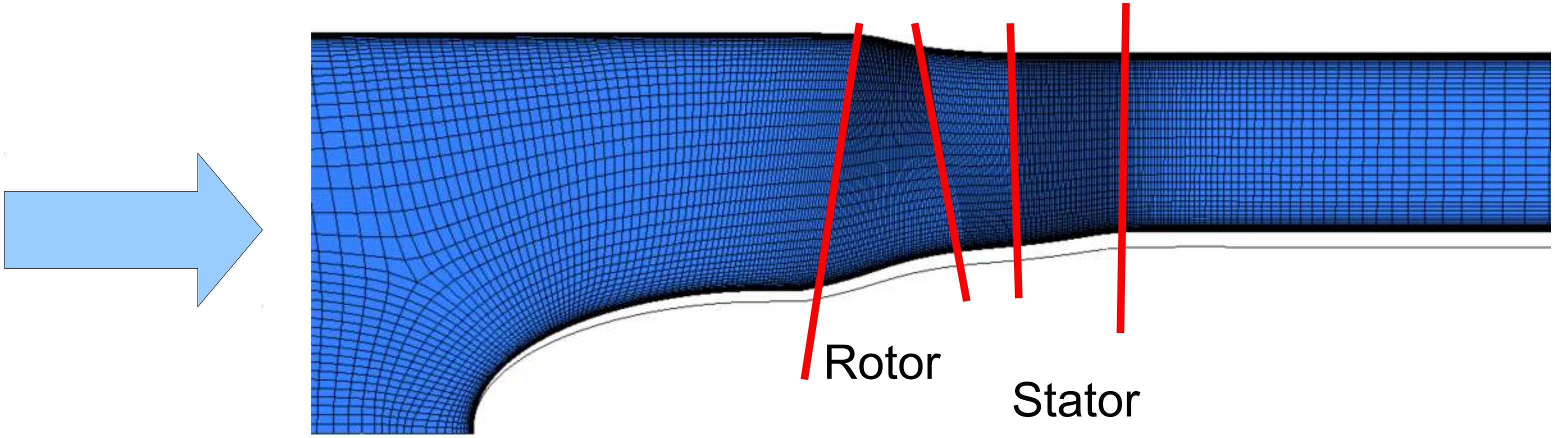
Low Speed Fan Stage Studied

- Model of stage used in experimental work at Whittle Laboratory
  - Gunn, Tooze, Hall, and Colin (2013)
  - Gunn and Hall (2014)
  - Perovic, Hall, and Gunn (2015)
- Rotor and stator camber distributions estimated based on radial distributions of leading/trailing edge metal angles



High Speed Compressor Stage Studied

- NASA rotor 67 + stator
- Blade camber surfaces extracted from detailed blade geometry
- Both models: design work coefficient predicted to within 2% of experiment



Vertical and Radial Distortions Considered

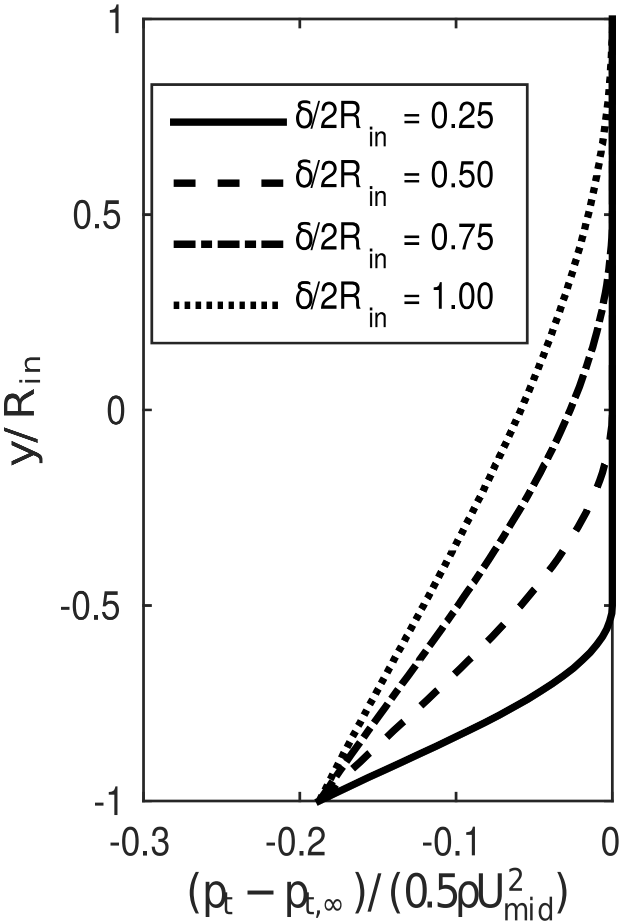
- Vertically stratified (BLI fan)
  - Stagnation pressure variations

- Radially stratified (turboprop 1st compressor stage)
  - Stagnation temperature, stagnation pressure, and swirl variations

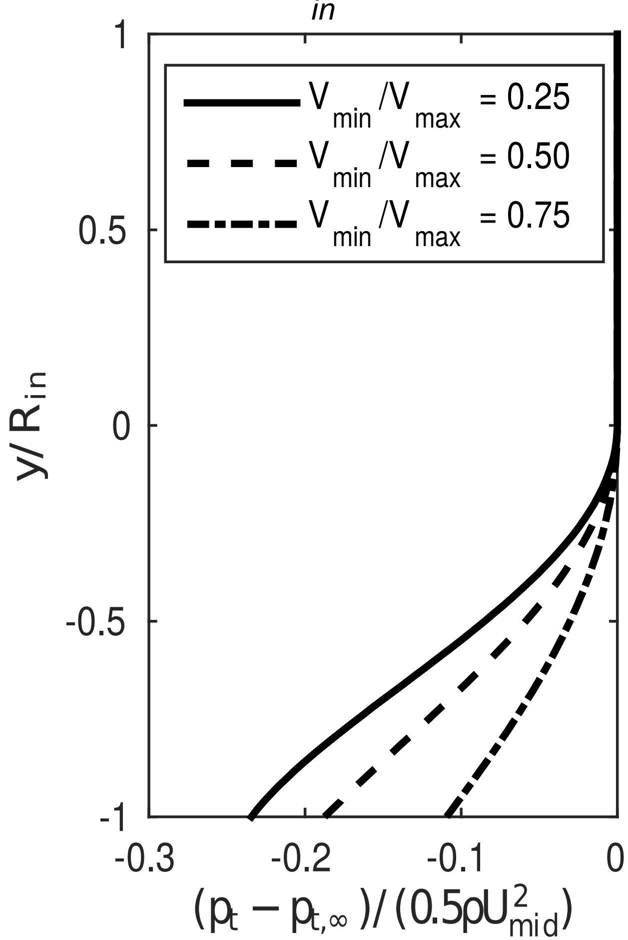
Vertically Stratified Stagnation Pressure Distortions

- Quadratic velocity profile in “boundary layer”

V_{min}/V_{max}=0.5

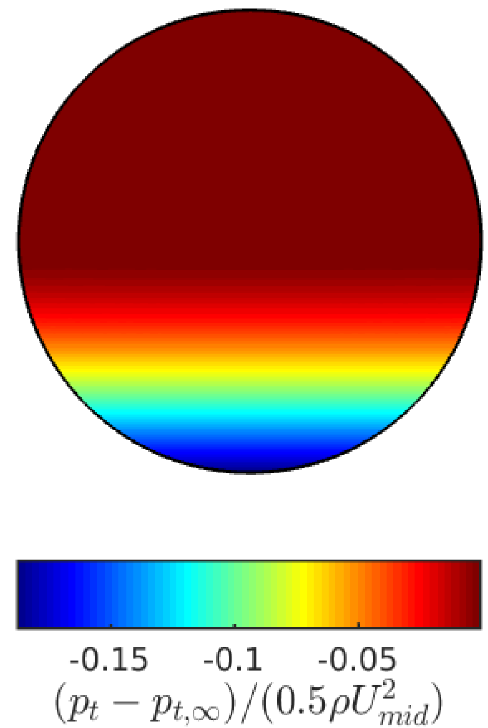


$\delta/2R_{in}$=0.5



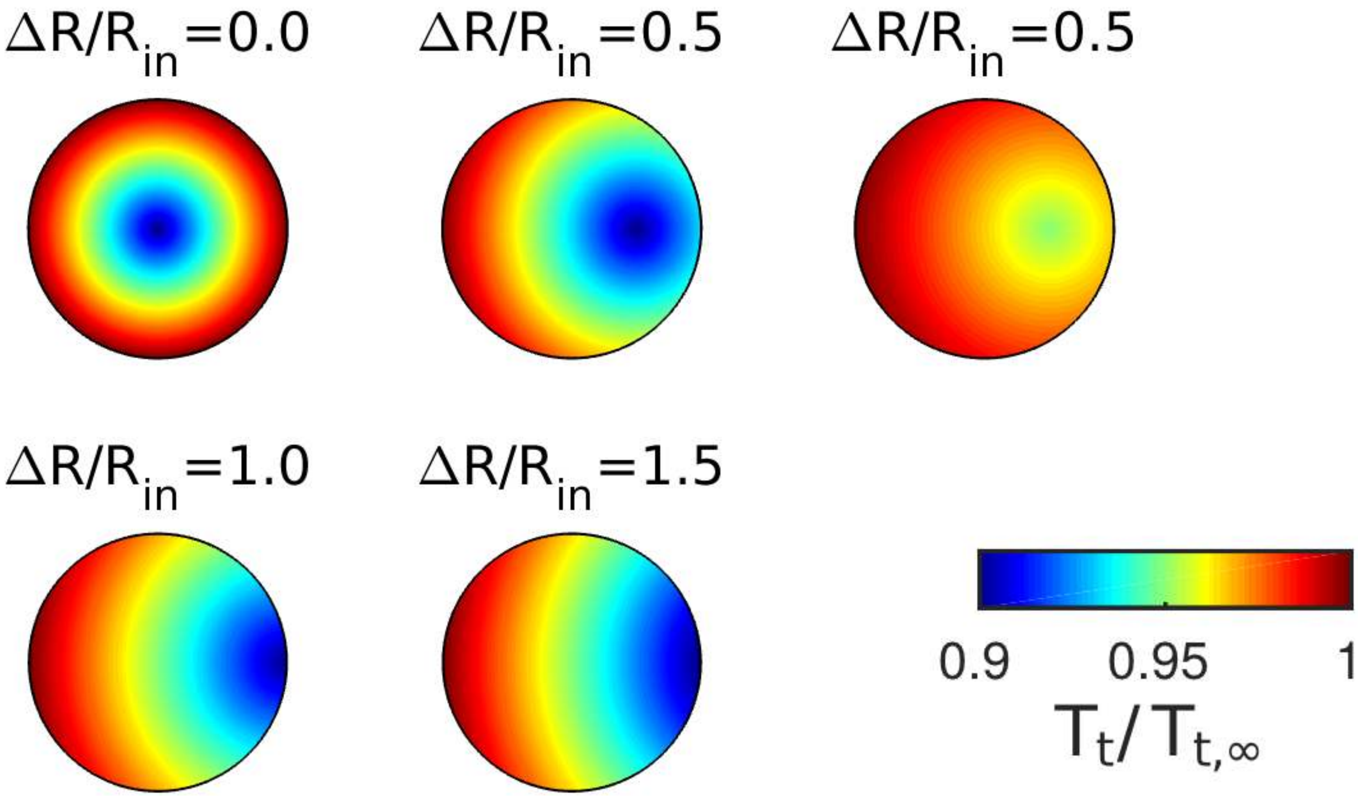
$\delta/2R_{in}$=0.5,

V_{min}/V_{max}=0.5

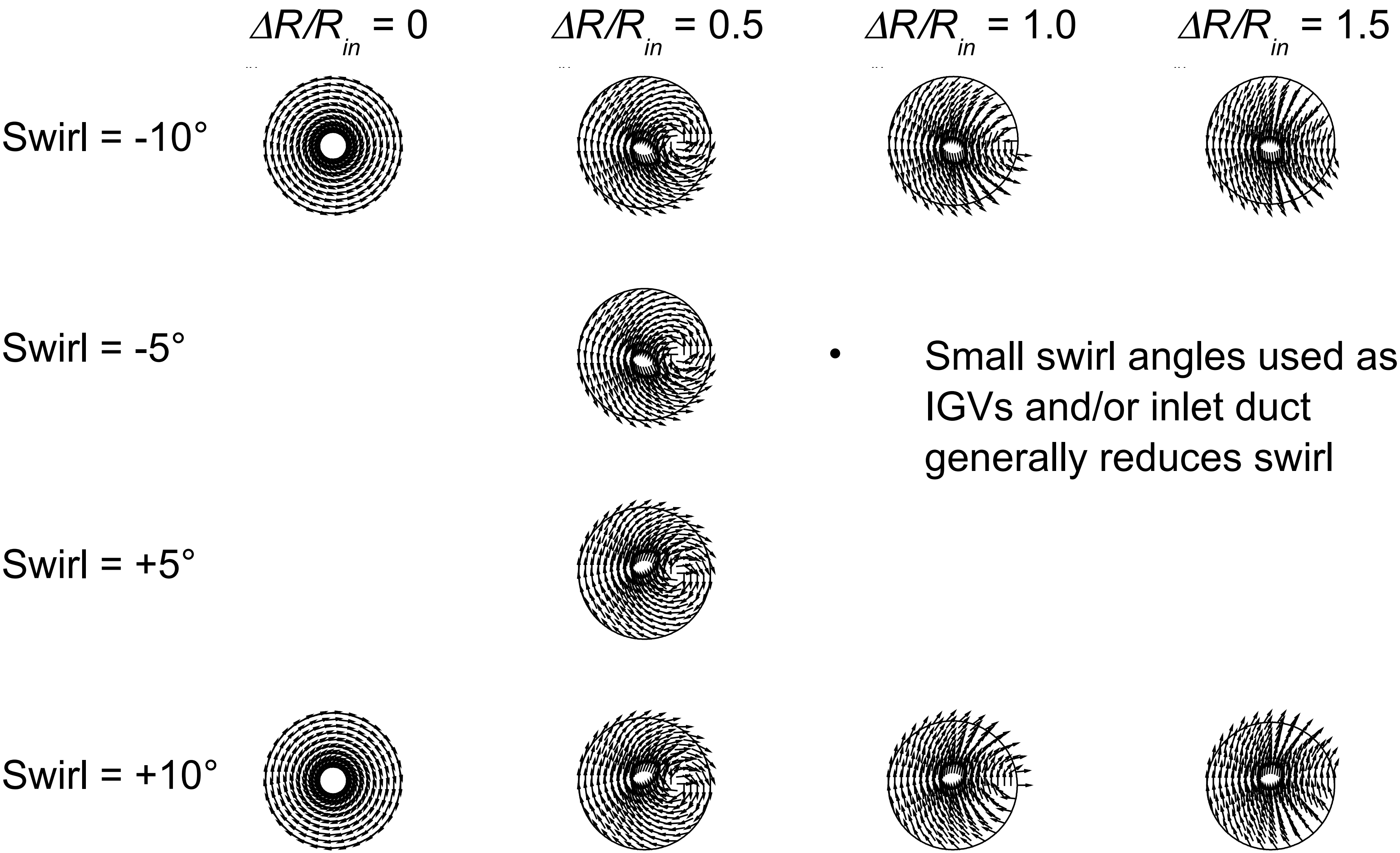


Radially Stratified Stagnation Temperature/Pressure Dist.

- Emulates radially-varying work input from propeller



Radially Stratified Swirl Distortions (Low-Speed Fan Only)



- Small swirl angles used as IGVs and/or inlet duct generally reduces swirl

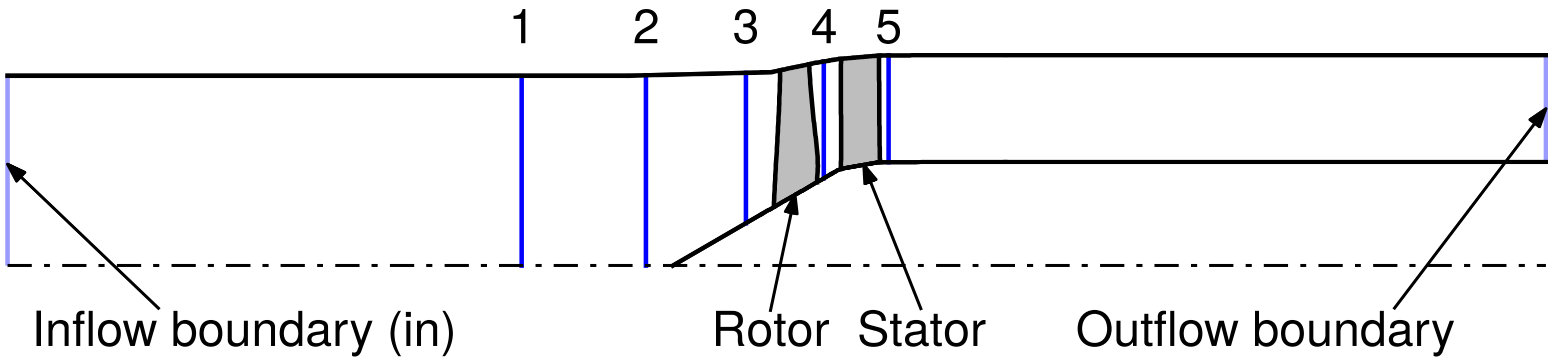
Diffusion Factor Used as Proxy for Entropy Generation

- Local diffusion factor approximated as:

$$D = 1 - \frac{W_{i+1}}{W_i} + \frac{1}{2}\frac{\left|W_{\theta,i+1} - W_{\theta,i}\right|}{W_i}\frac{2\pi r_i}{N\ell_{i\to i+1}}$$

Changes: $\Delta D = D - D_{des}$

- Higher local diffusion → increase in local entropy generation → contribution to reduced efficiency



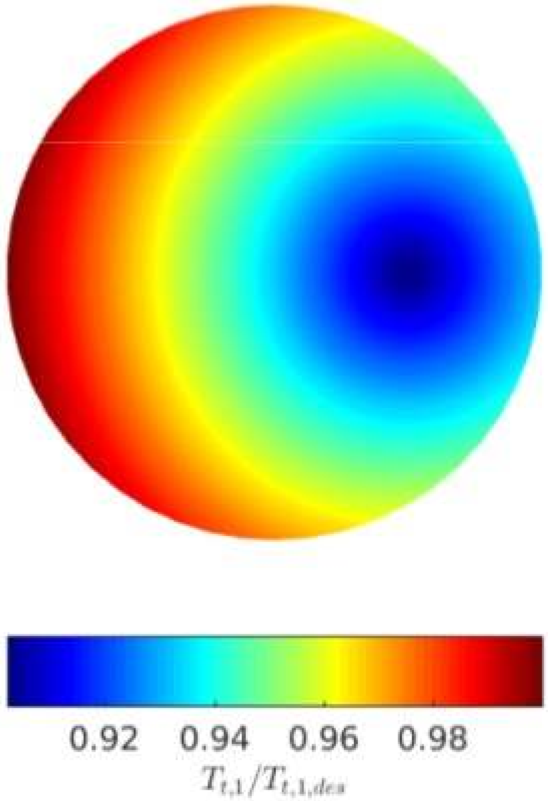
Stagnation Temperature vs. Stagnation Pressure Distortion

- Stagnation pressure distortion: mechanism well understood
  - Velocity distortion attenuated by nature of fan/compressor characteristic
  - Upstream flow redistribution yields relative flow angle changes which give rise to changes in diffusion factor

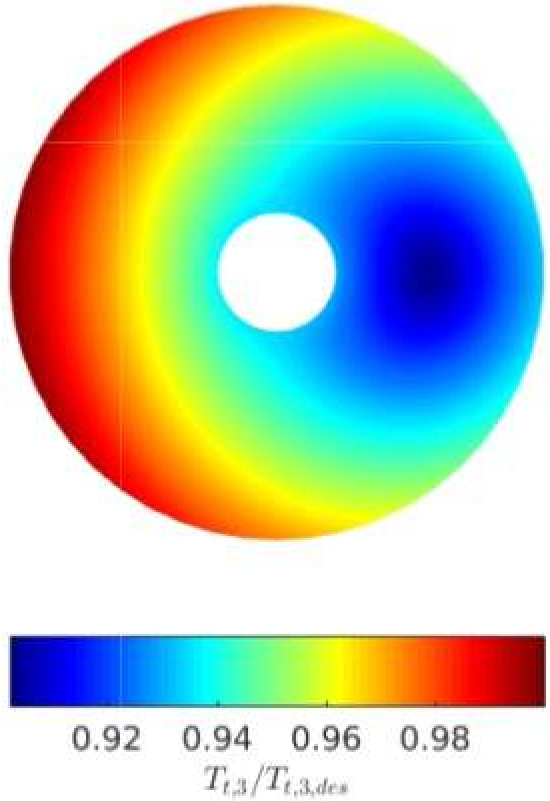
- Stagnation temperature distortion: new insight into interaction mechanism
  - Velocity and mass flux scale differently: $u_x \propto T_t^{\frac{1}{2}}$, $\rho u_x \propto T_t^{-\frac{1}{2}}$
  - Velocity distortion attenuation yields **amplification** of mass flux distortion
  - Changes in diffusion factor governed by variable mass flux

Stagnation Temperature Evolution

Far upstream

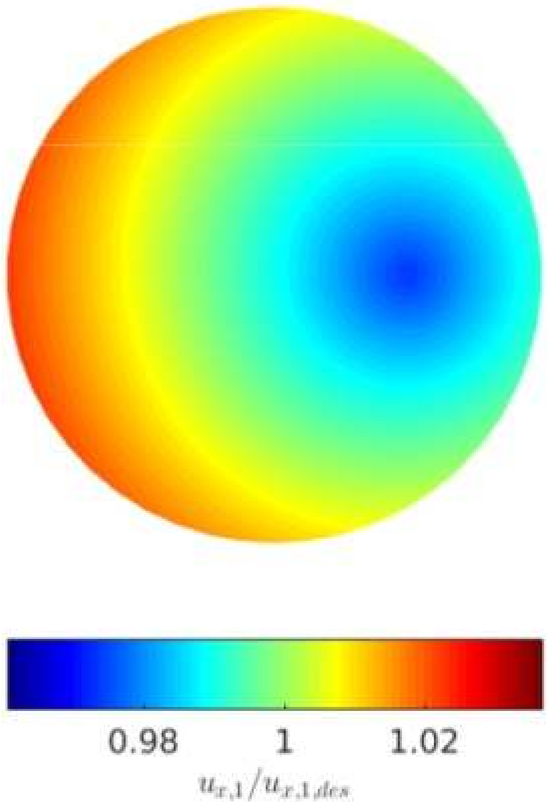


Rotor inlet

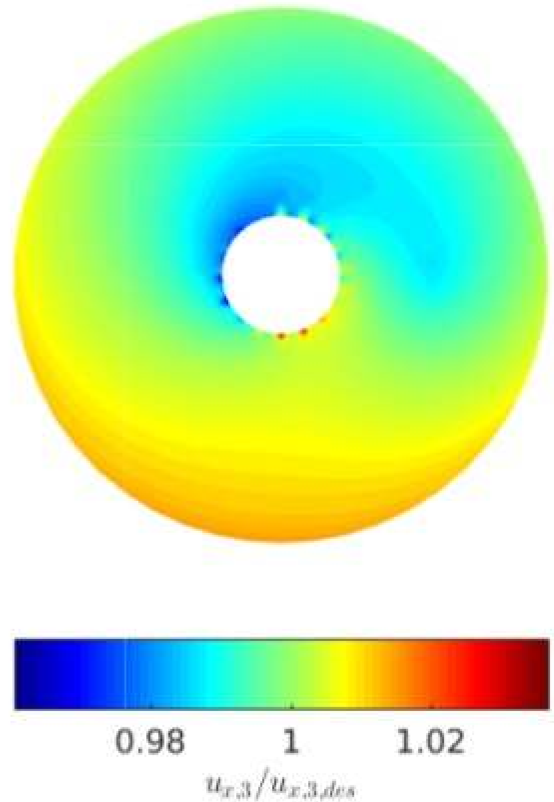


Velocity Distortion Attenuated

Far upstream



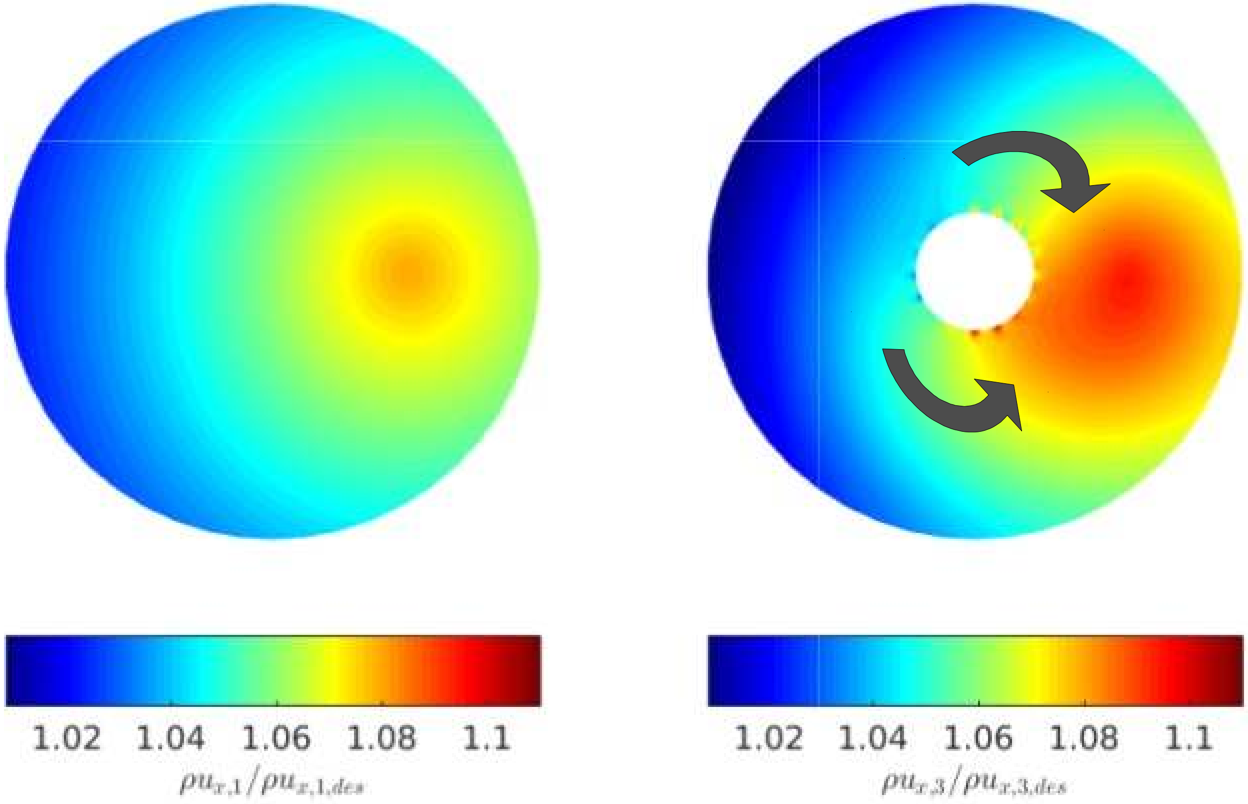
Rotor inlet



Mass Flux Distortion Amplified

Far upstream

Rotor inlet



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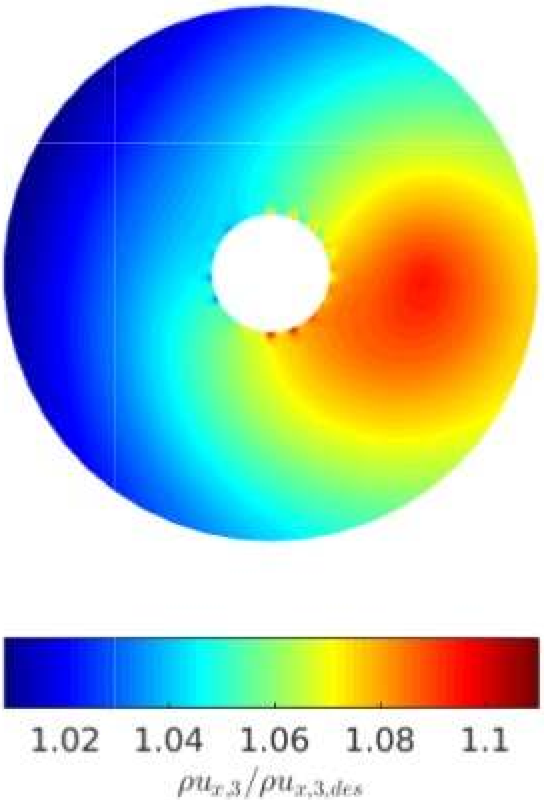
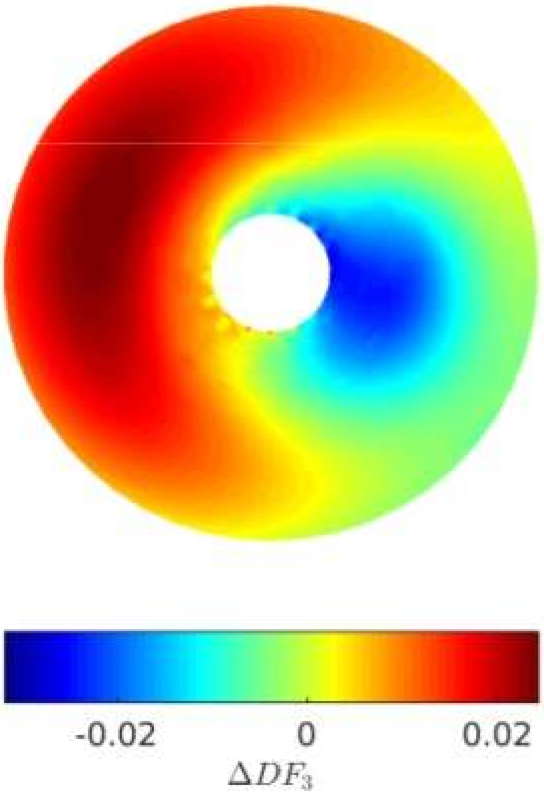
Changes in Diffusion Factor Related to Mass Flux Distortion

Rotor inlet



Rotor inlet

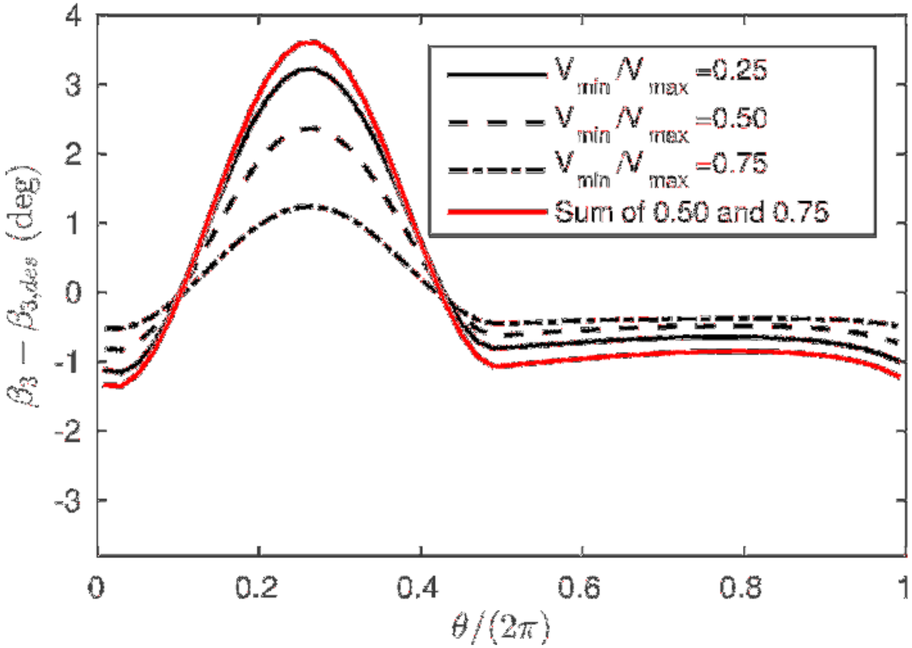


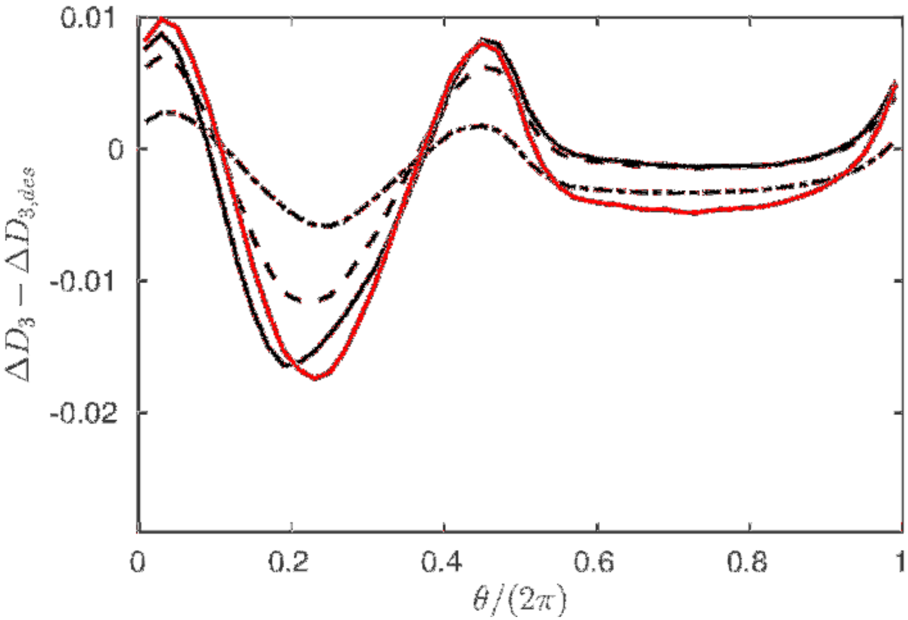
Overview of Distortion Study Results: Low Speed Fan

- For individual distortions, changes in diffusion:
  - Scale linearly with distortion severity for:
    - Vertically-stratified stagnation pressure distortions
    - Radially-stratified stagnation temperature distortions
  - Do not scale linearly for:
    - Radially-stratified swirl distortions
    - Variations in geometric location of stagnation quantity distortions
- For combined distortions, changes in diffusion for the combination can be predicted by summing the effects of the constituent distortions

Vertically-Stratified p_t Distortion: Linear Effect of V_{min}/V_{max}

- Changes in diffusion well-predicted for V_{min}/V_{max} = 0.25 by summing effects from V_{min}/V_{max} = 0.50 and V_{min}/V_{max} = 0.75 cases

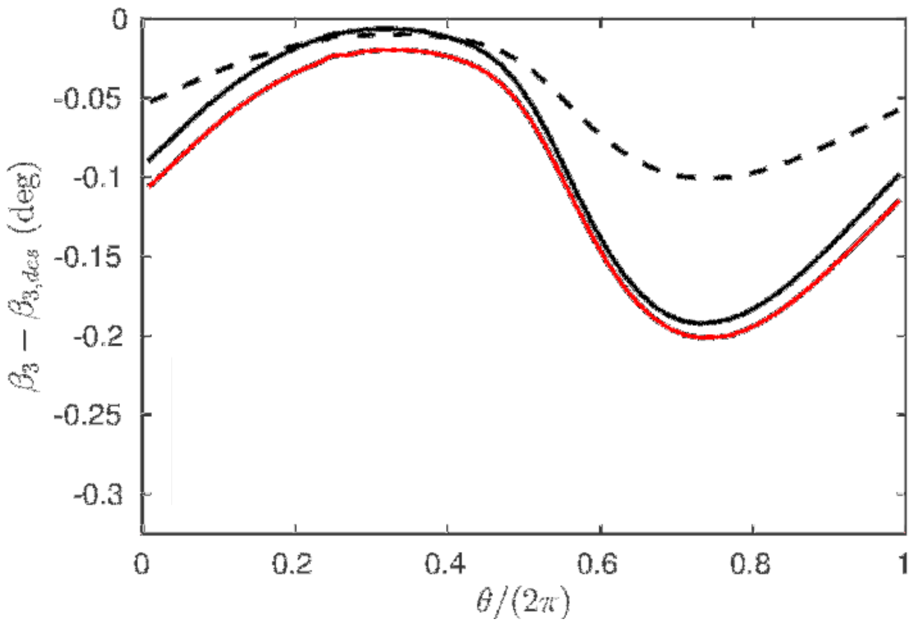


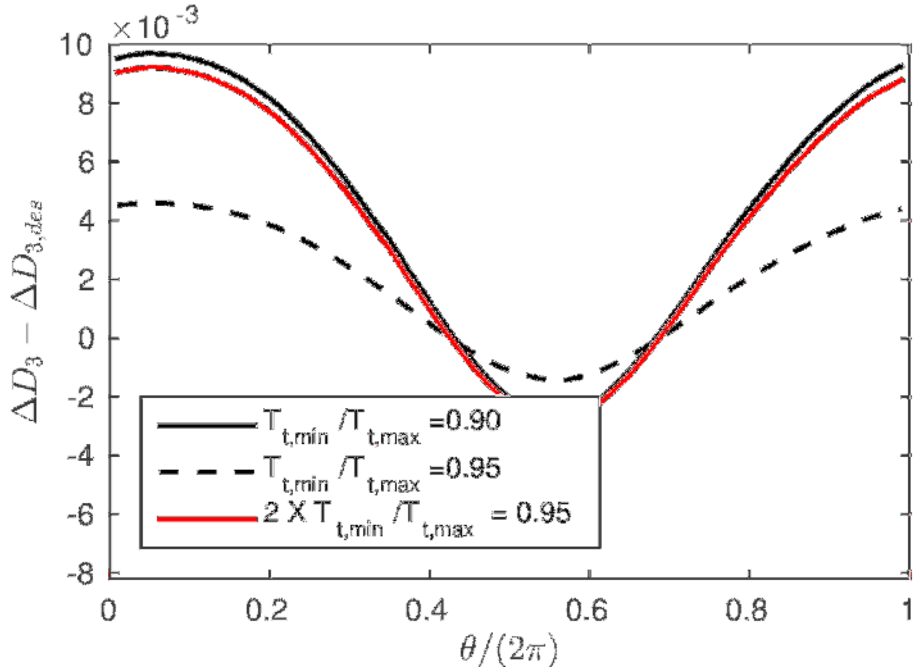


Rotor, 75% span, $\delta/2R_{in}$ = 0.5

Radially-Stratified T_t Distortion: Linear Effect of $T_{t,min}/T_{t,max}$

- Altering depth of distortion produces linear changes in incidence and diffusion factor





Rotor, 90% span, $\Delta R/R_{in}$ = 0.5

Hypothesized mechanism: mass flux variation due to density change

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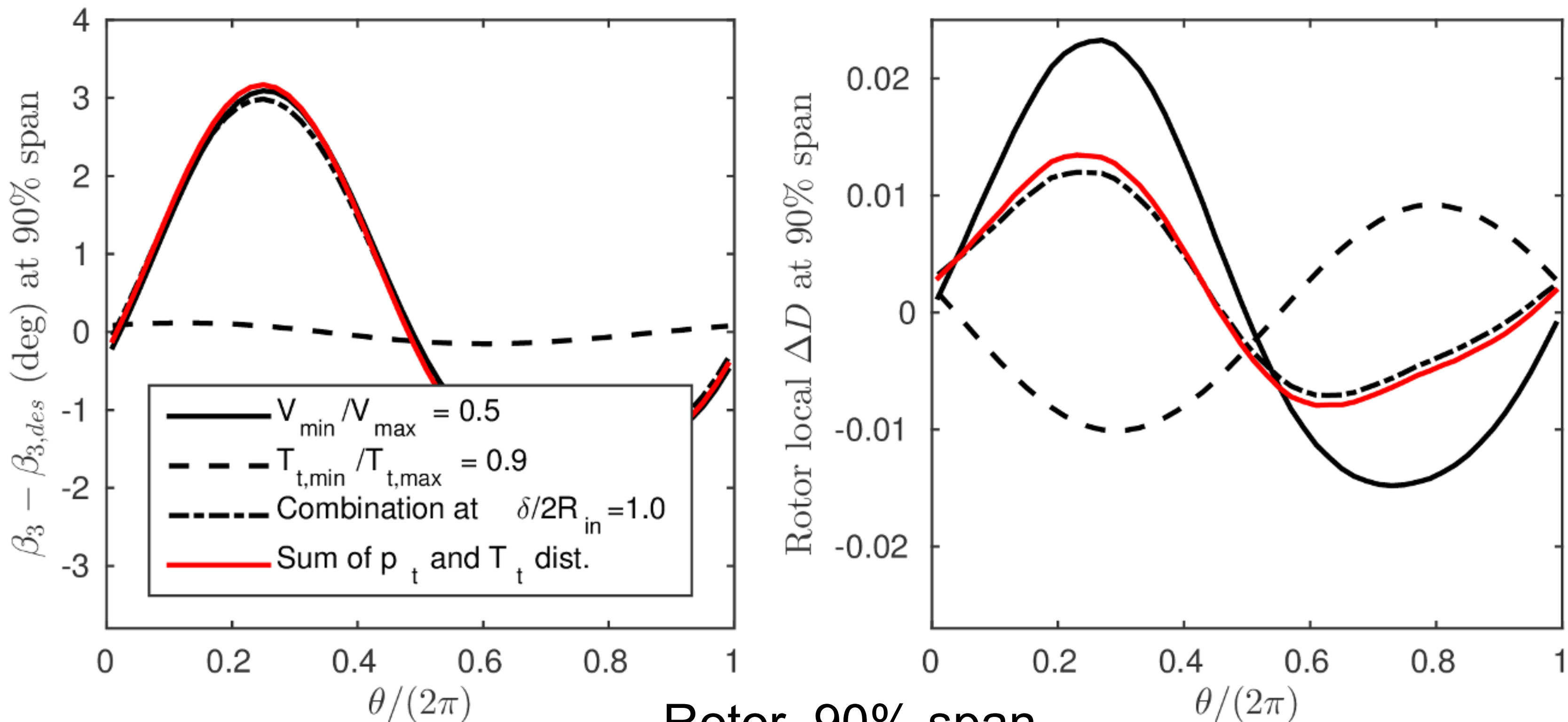
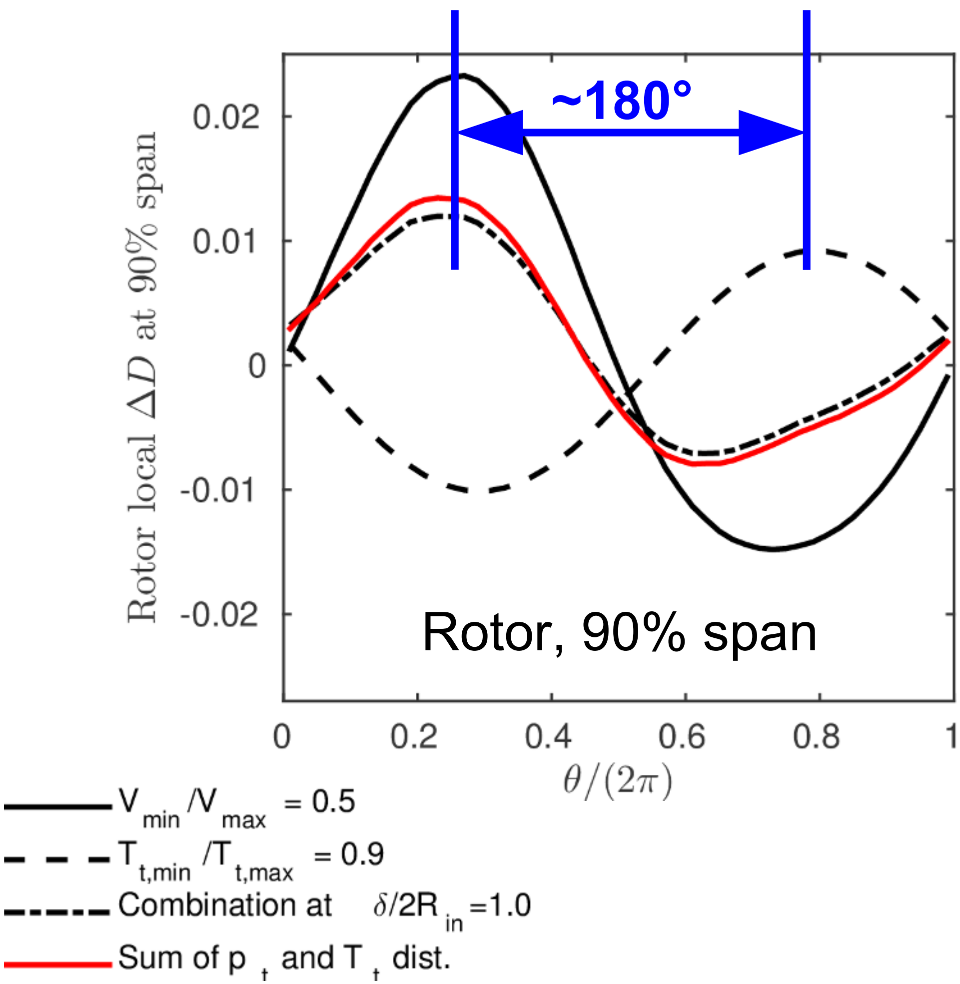
Combined Stagnation Pressure and Temperature Distortion

- Vertically-stratified, $\delta/2R_{in} = 1.0$, $V_{min}/V_{max} = 0.5$, $T_{t,min}/T_{t,max} = 0.9$
- Diffusion changes for combination can be predicted accurately



Rotor, 90% span

Distortions Out of Phase due to Impact on Mass Flux



- Stagnation pressure: velocity and mass flux vary in the same way
- Stagnation temperature: velocity and mass flux vary opposite ways
- Impact of distortions with same spatial distribution ~180° out of phase

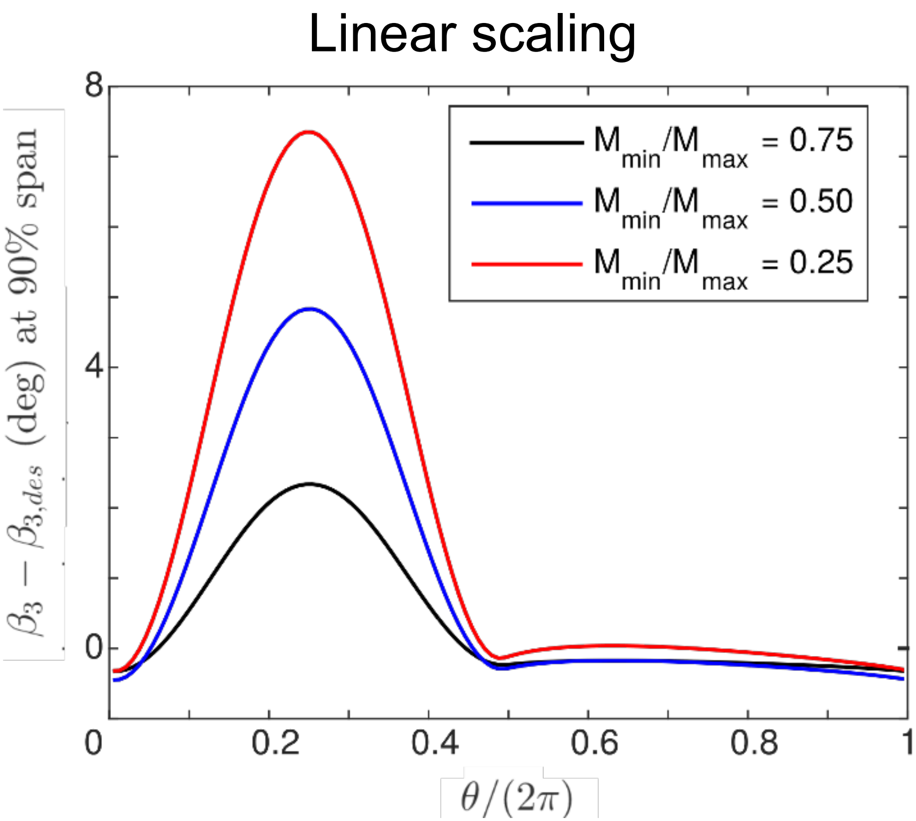
Summary – Low-Speed Fans

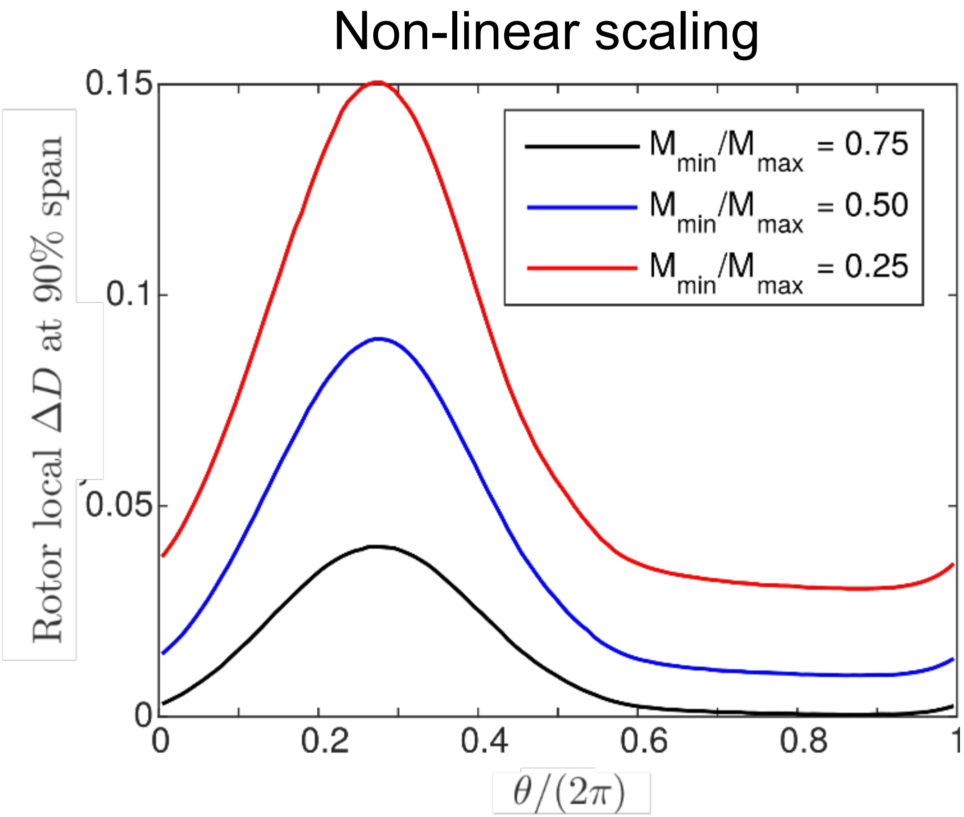
- Source-term-based blade row model enabled numerical investigation of scaling of impact of inlet flow distortion for a low-speed fan
- Changes in diffusion for distortions of inlet stagnation quantities scale linearly with distortion severity
- Changes in diffusion for combinations of distortions of different inlet parameters with the same spatial variation can be predicted by summing effects of individual distortions
- Effects of other aspects of distortions considered scale non-linearly

High-Speed Compressor: Overall Findings

- Qualitative behaviour similar to low-speed fan
- Quantitative: increases in distortion intensity lead to:
  - linear increases in mass flux and flow angle distortions
  - *more than linear* increases in diffusion factor distortion

High Speed: Changes in Diffusion Factor Scale > Linearly





Rotor, 90% span

Conclusions

- Mechanism for interaction of a stagnation temperature distortion with a fan/compressor rotor identified
  - Mass flux distortion amplified for variable stagnation temperature
- Low-speed fan: distortion effects behave linearly for same spatial distribution of quantities at inlet
- Transonic compressor: distortion intensity increase leads to *more than linear* changes – scaling breaks down