# Dynamic analysis of Reynolds number effects on trailing edge Transonic Vortex Shedding

## and its impact on turbine blade aerodynamic performance


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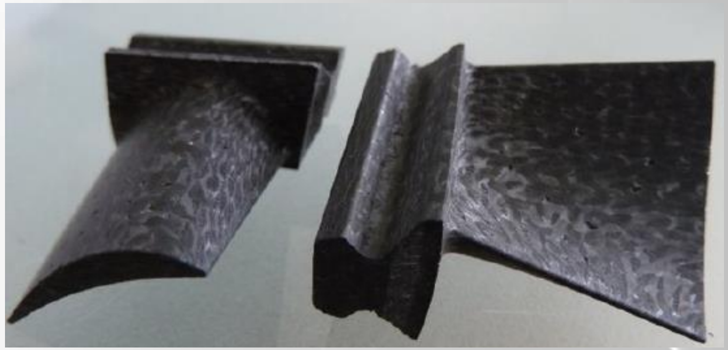
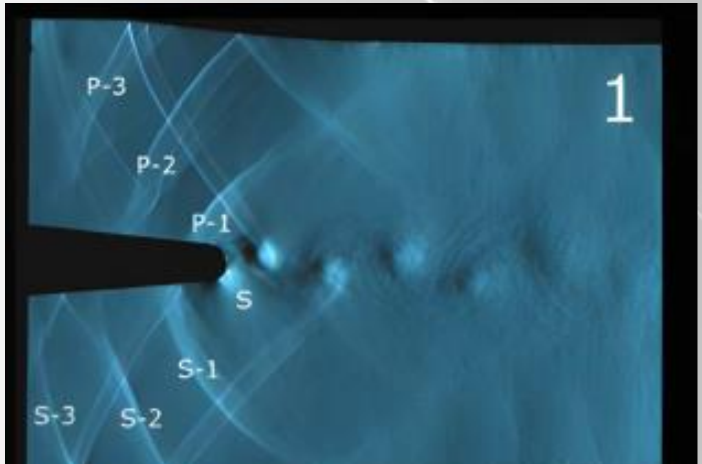
# Motivation

- The use of Ceramic Matrix Composite turbine blades creates the necessity for thick trailing edges due to manufacturing constraints.



Essongue,2016

- The rounded trailing edge introduces compressible shedding dynamics at near-sonic Mach numbers, called transonic vortex shedding.

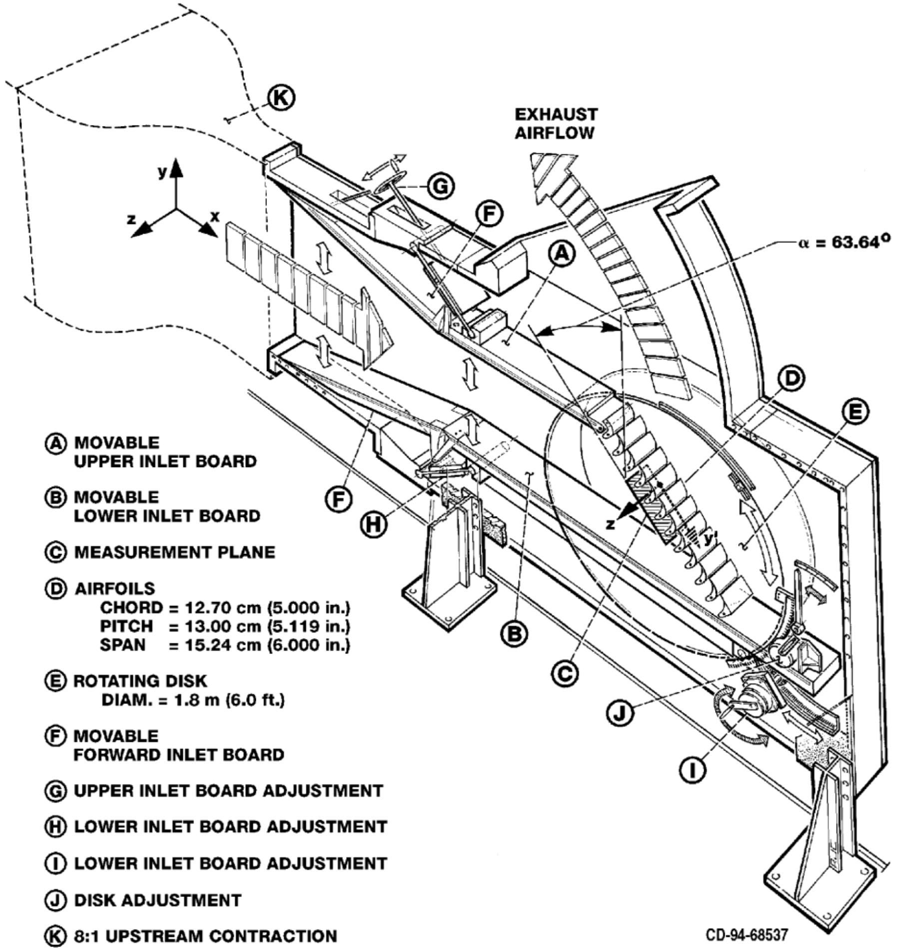



Rossiter,2022

# Facility & Past Observations

ASME
TURBO EXPO 2026
TURBOMACHINERY TECHNICAL
CONFERENCE & EXPOSITION

- The NASA Glenn Transonic Turbine Cascade Facility is a large-scale facility for turbine aerodynamics and heat transfer studies.




**We're able to control both $P_1$ and $P_2$, allowing for change of $Re$ with the same $M_{is} = 0.74$**

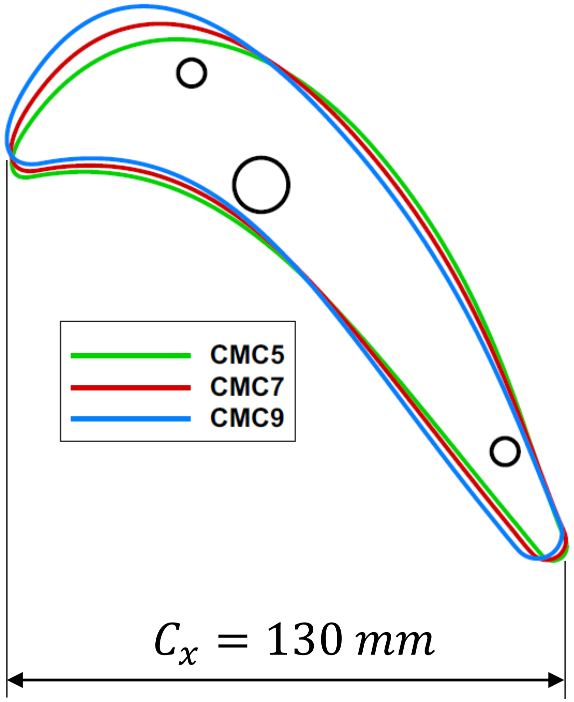
Blades:
- 11 blade passages
- span = 6.000″ (fixed)
- pitch = 5.119″ (fixed)
- axial chord ~4″-7″ (typical)

Inlet:
- ambient temperature inlet;
- dry, clean air:
  ($T_{dewpoint} \approx -50^\circ$ F; filtering: 98% of 0.35μm
  99.9% of 2 μm)
- well-documented inlet; nominal $\delta_{in} \approx 1.0$ inch
- various static and blown turbulence generating grids available.

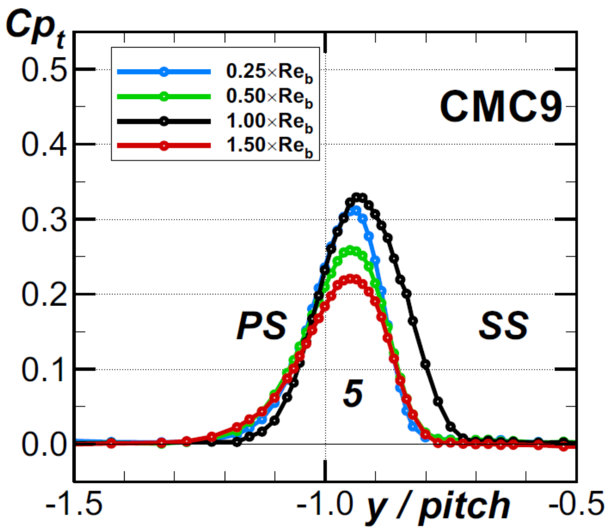
# Facility & Past Observations

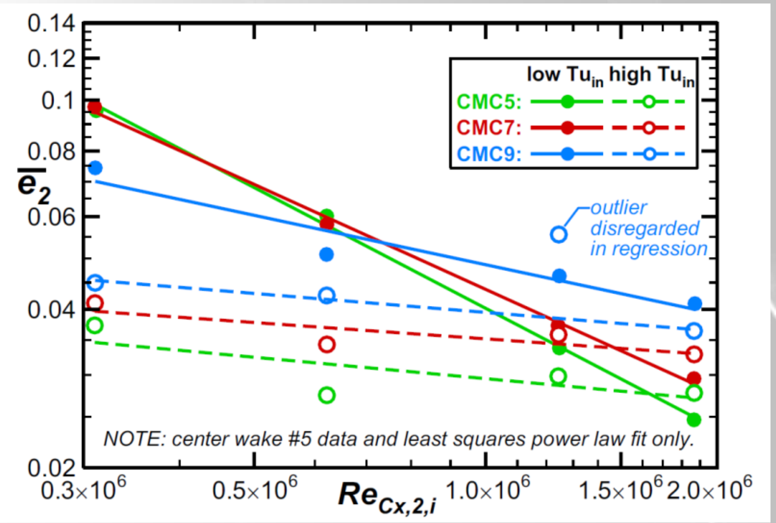


- We studied simulated CMC geometries to understand the effect of the Trailing Edge thickness.
- Wake total pressure survey indicated there was an anomaly with the $1.00 \times Re_b$ case:




Baseline Reynolds number:
$Re_b = 1{,}240{,}000$




Kinetic energy loss coefficient:

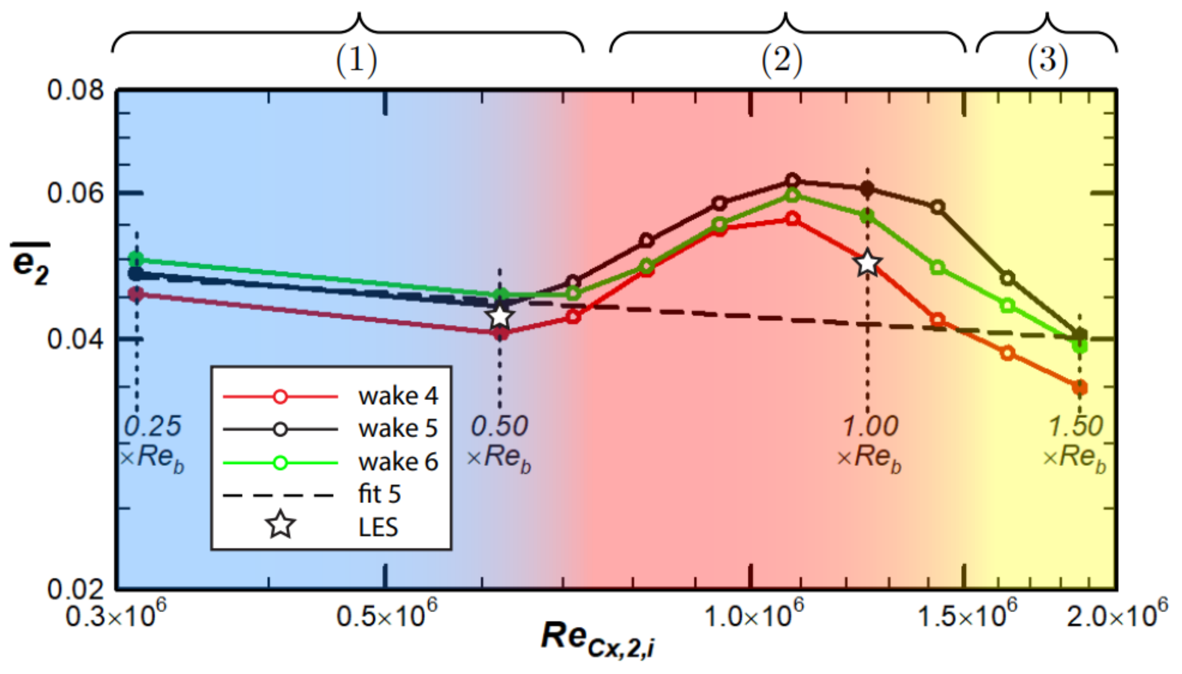
$$\overline{e_2} = \frac{\left(\frac{\overline{\overline{P_{t,1}}}}{P_{t,2}}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\left(\frac{P_{t,1}}{P_2}\right)^{\frac{\gamma-1}{\gamma}} - 1}$$

# Facility & Past Observations



- The high $Tu_1$ cases that showed the anomaly use an additional 1”square tube grid with upstream blowing.

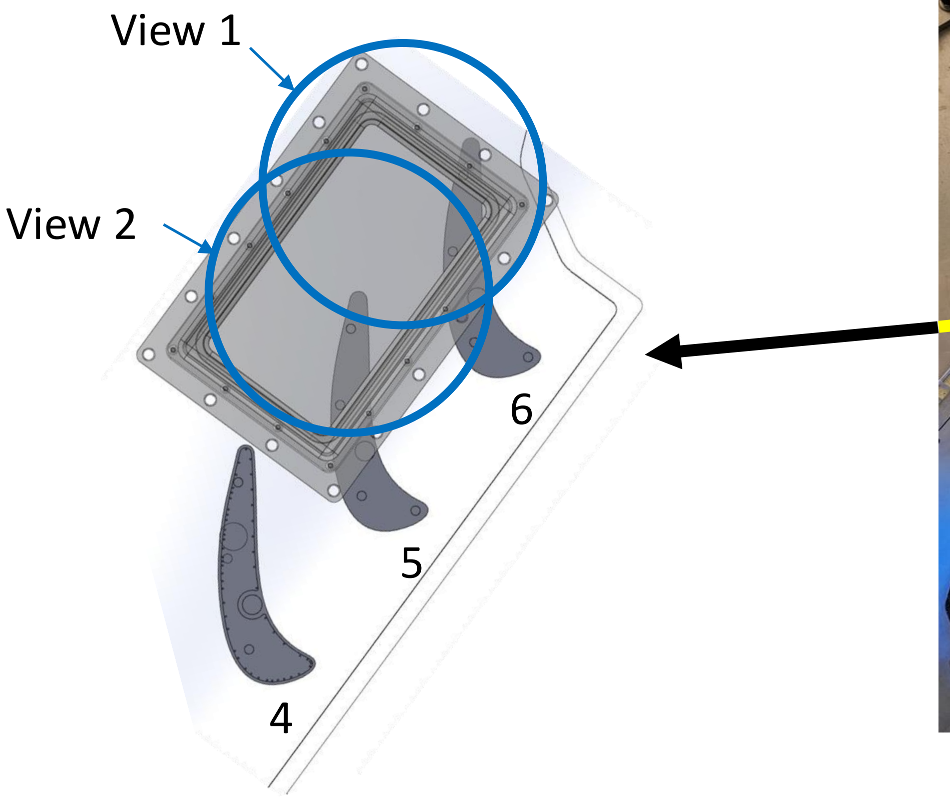
- A follow-up study on the CMC9 at a finer $Re_b$ scan showed the effect leads to a loss that smoothly builds up and peaks at $Re_b = 0.87$:

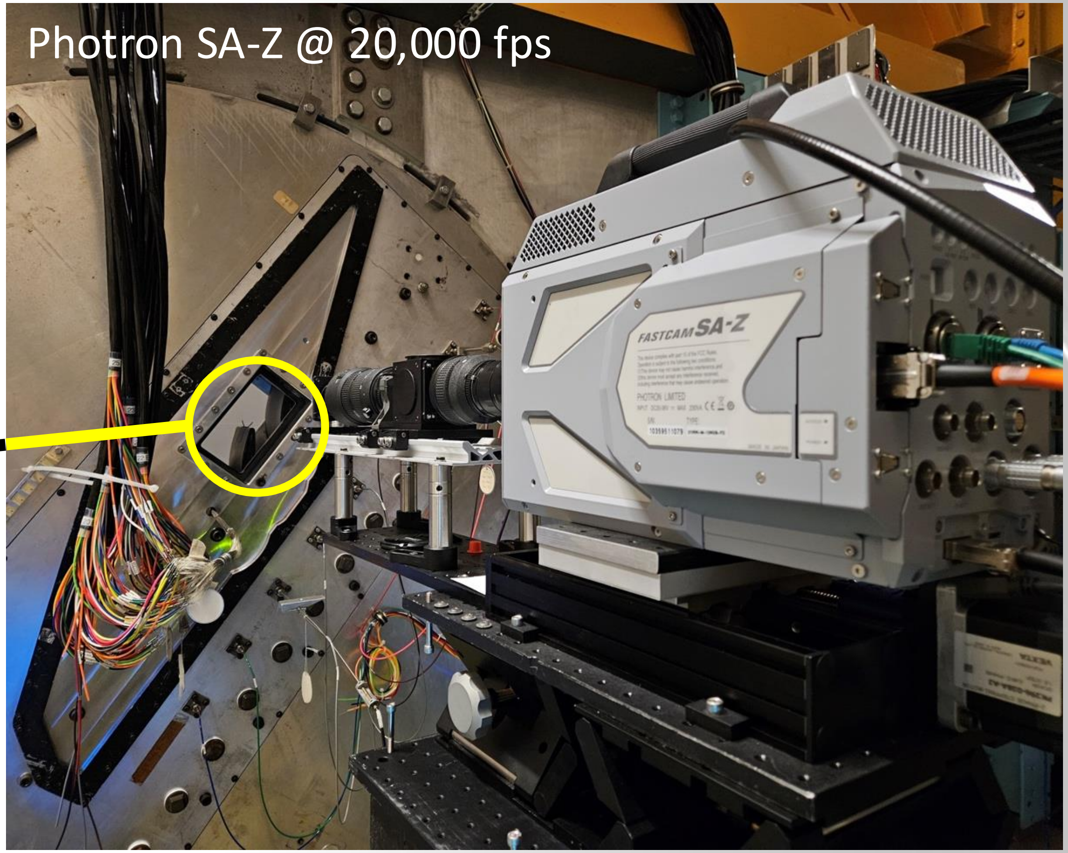


# This Study - Self-Aligned Focusing Schlieren (SAFS)



- We used time-resolved SAFS to visualize the phenomena in the blades.



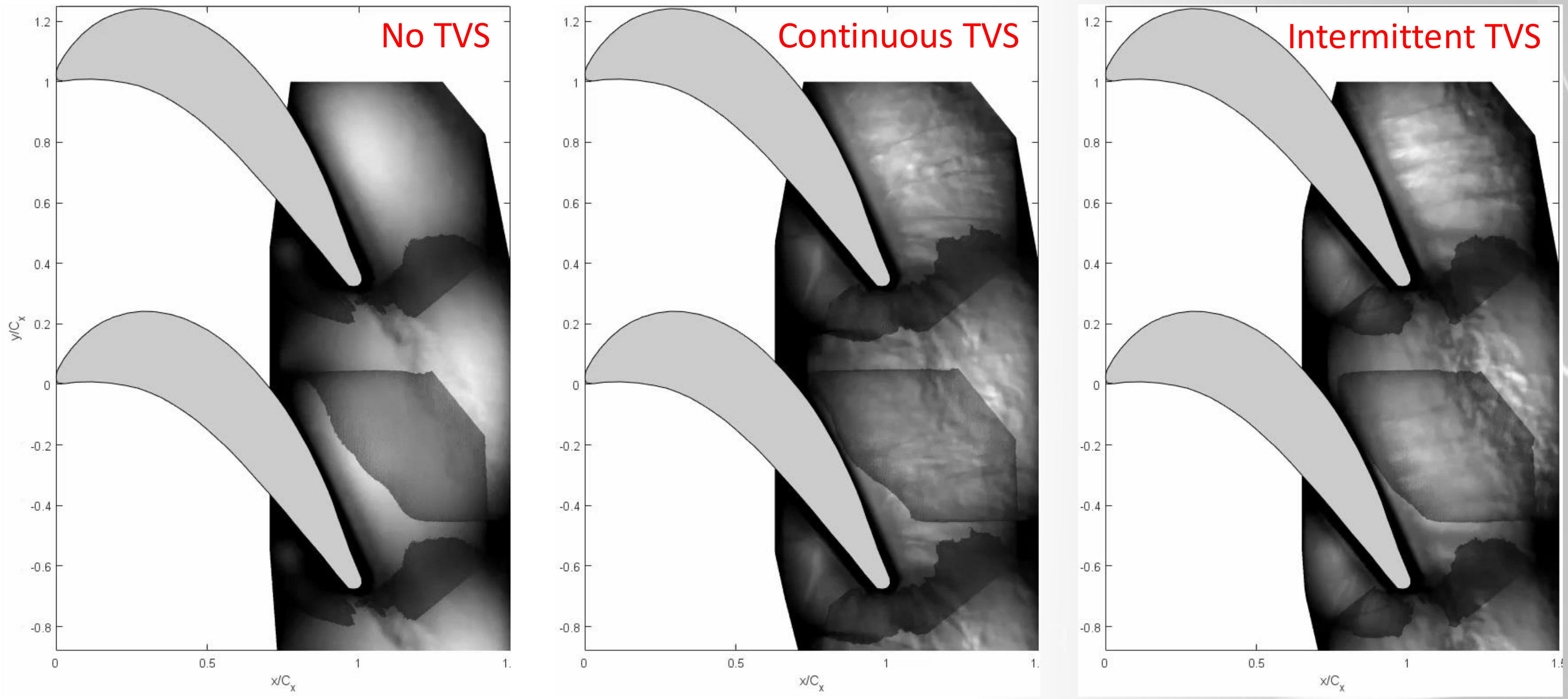



# Time-Resolved Schlieren Images



- First, the time-resolved Schlieren movies: (Two asynchronous views composited)

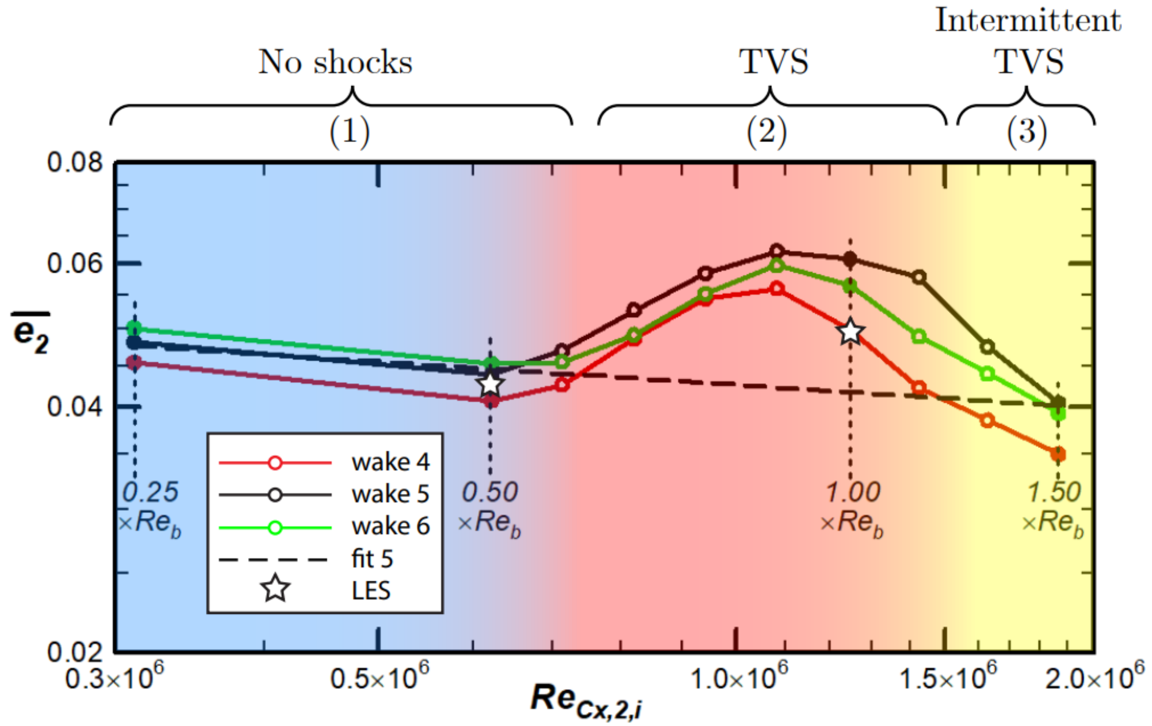
$Re/Re_b = 0.50$ $Re/Re_b = 1.00$ $Re/Re_b = 1.50$

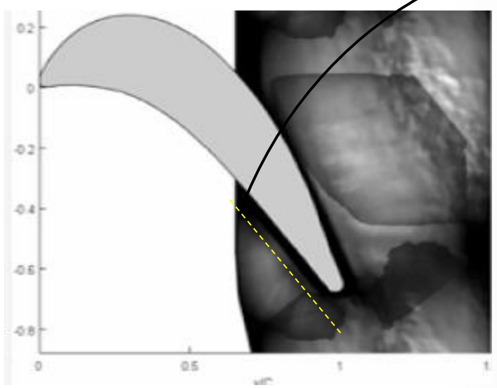


# Time-Resolved Schlieren Images

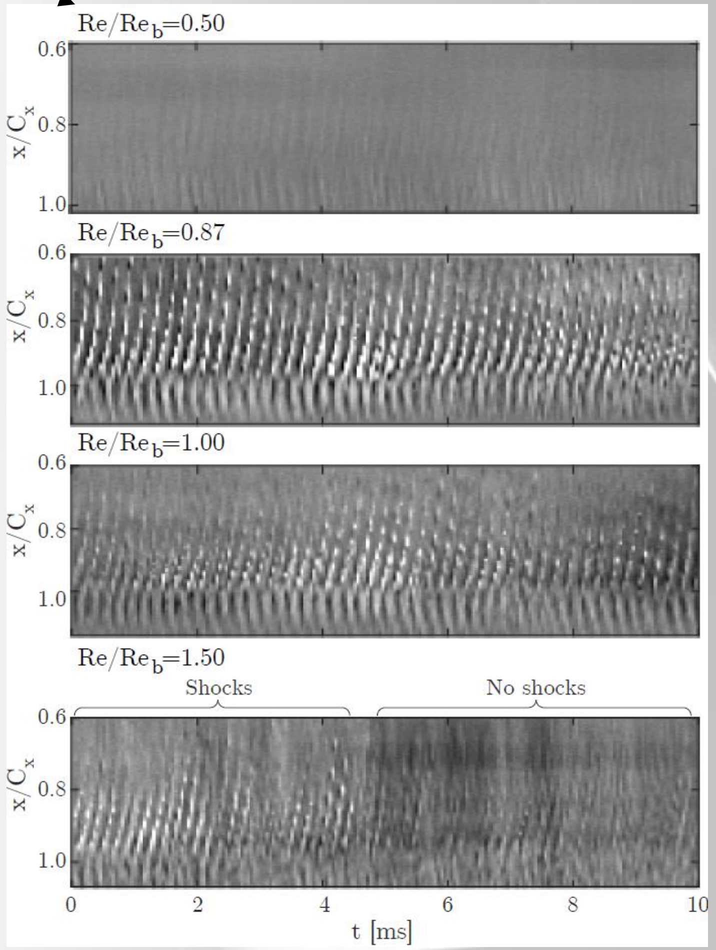


- We identify three regimes: No TVS, Continuous TVS and Intermittent TVS, with increasing Reynolds number:



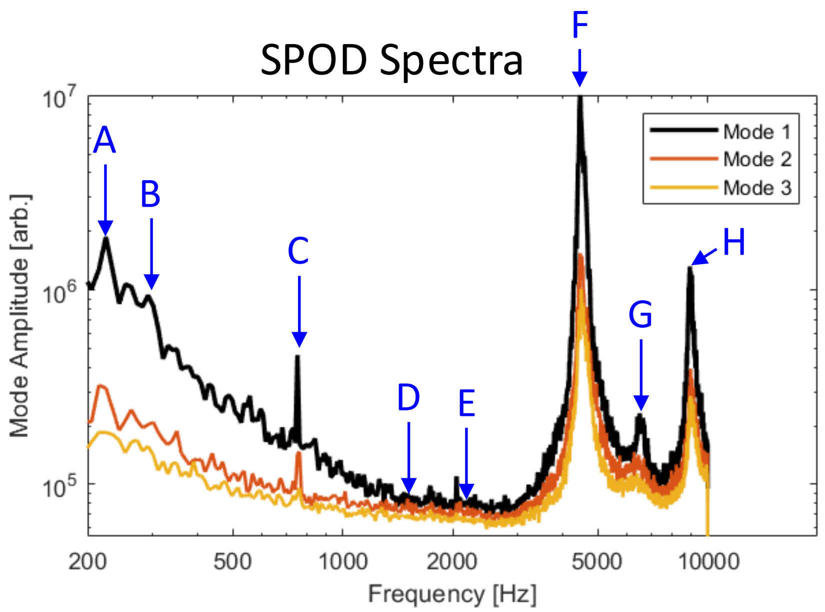



Intermittency is visible in the x-t diagram of the yellow slice shown.



# Spectral POD Analysis

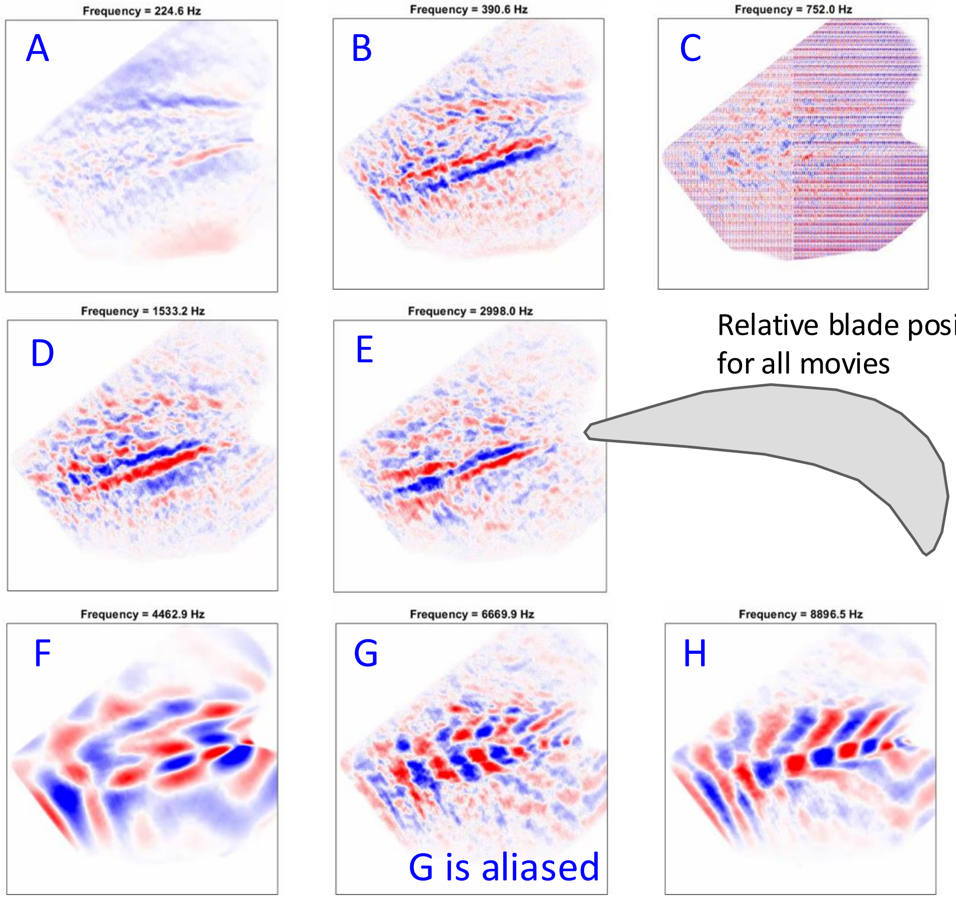
- Further insight can be gained using Spectral POD, to find structures in the images that are correlated at a single frequency.
- Typical result for $Re/Re_b = 1.0$:




**A,B,C:**
Light source oscillation, Camera Noise

**D,E:**
Modes related to Kelvin-Helmholtz instability

**F,G,H:**
<u>**Vortex shedding modes**</u> + Acoustic Coupling

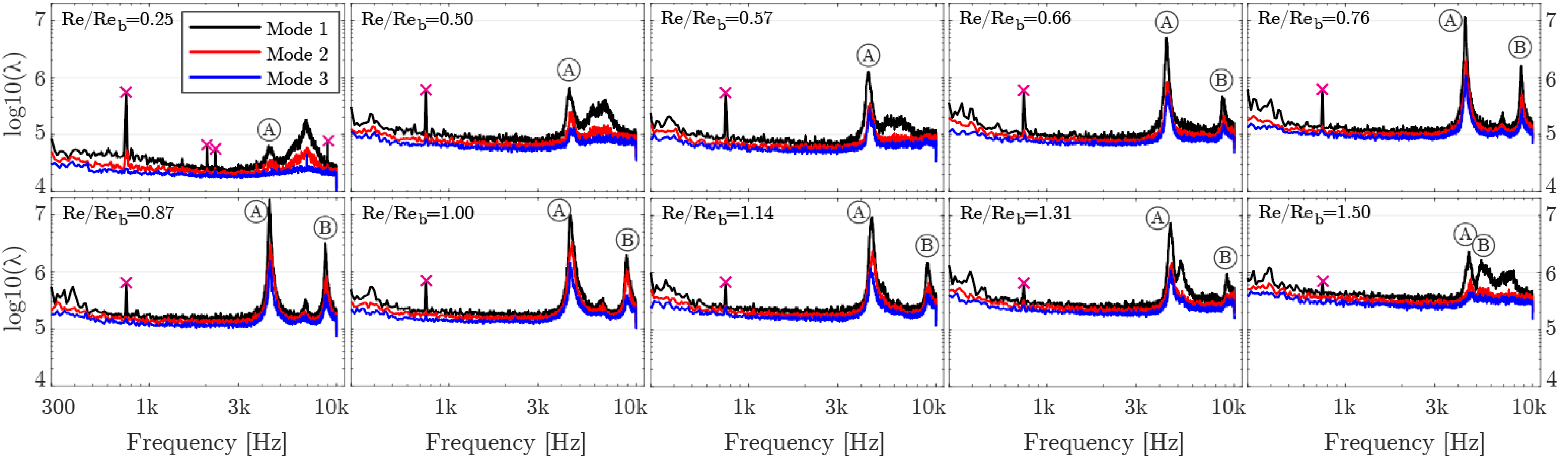



Relative blade position for all movies

# Spectral POD Analysis – All Blades

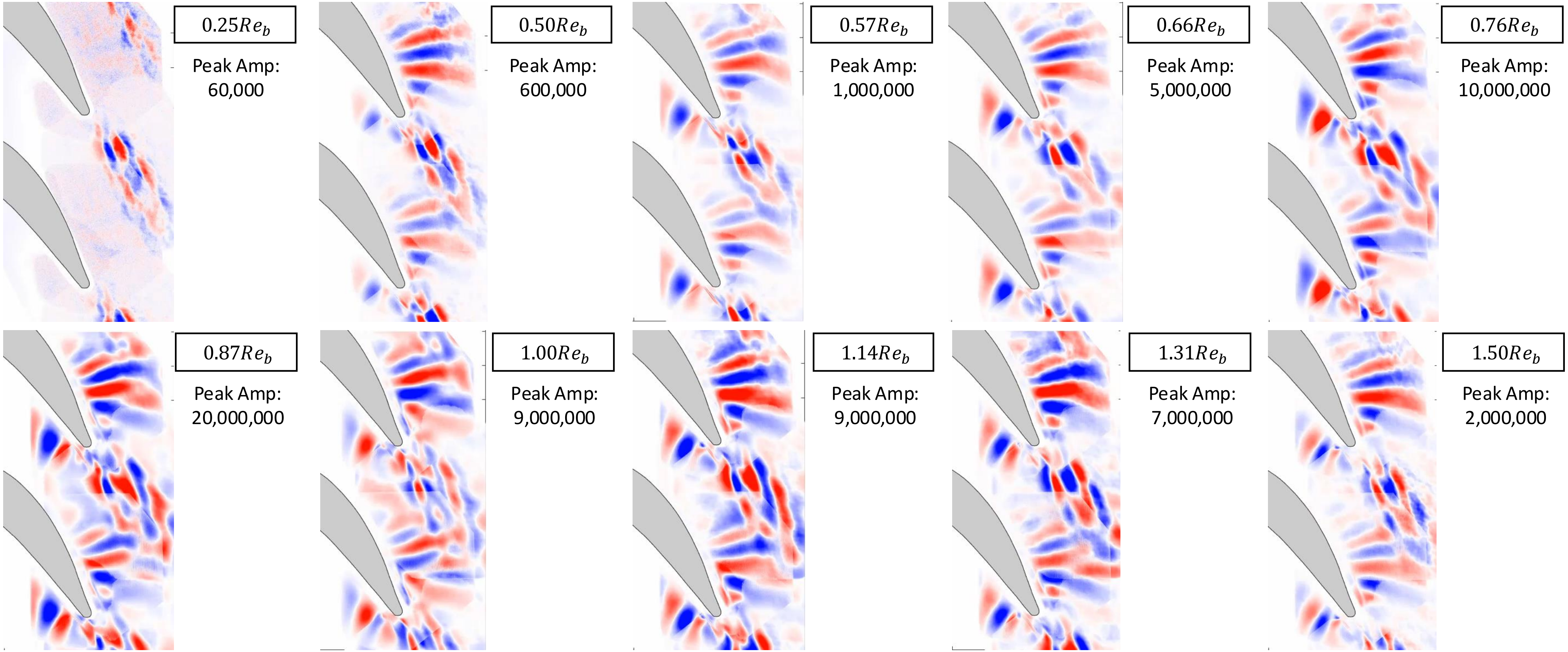


- SPOD Spectra & Eigenmodes are obtained for the 10 $Re_b$ test cases:



# Spectral POD Analysis – All Blades - Fundamental

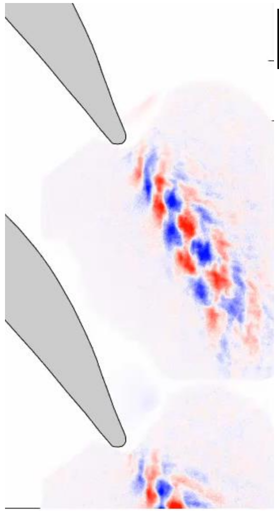
- Eigenmodes for Peak (A) $f \sim 4400\ Hz$ / $St \sim 0.21$:



# Spectral POD Analysis – All Blades -2nd Harmonic

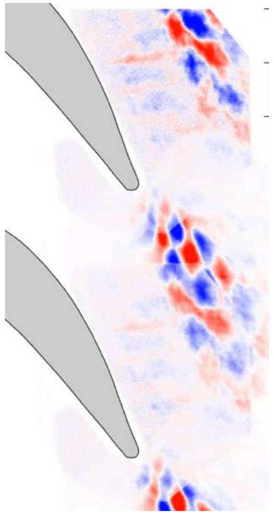


- Eigenmodes for Peak (A) $f \sim 8800\ Hz$ / $St \sim 0.41$:



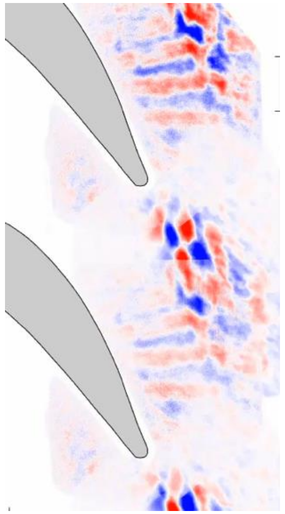
$0.25Re_b$

Peak Amp: 200,000



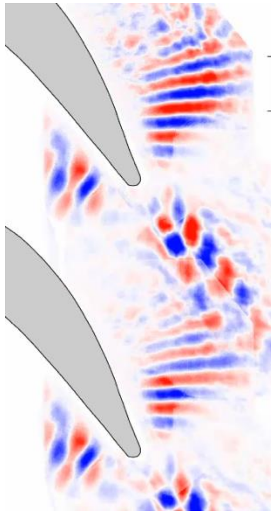
$0.50Re_b$

Peak Amp: 400,000



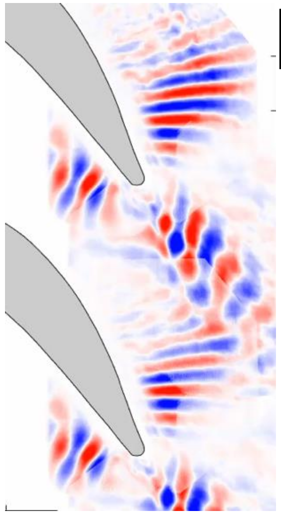
$0.57Re_b$

Peak Amp: 200,000



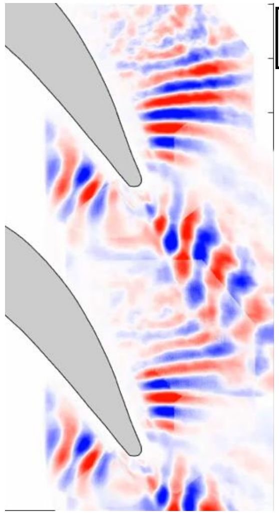
$0.66Re_b$

Peak Amp: 400,000



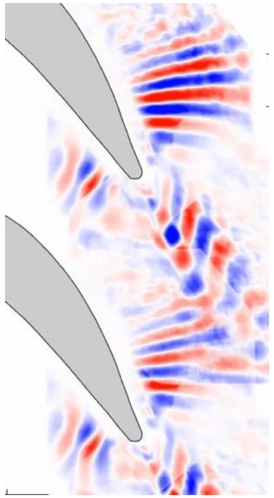
$0.76Re_b$

Peak Amp: 1,000,000



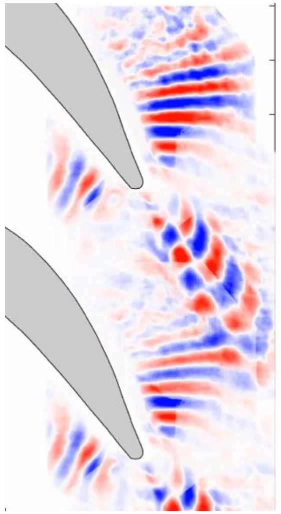
$0.87Re_b$

Peak Amp: 3,000,000



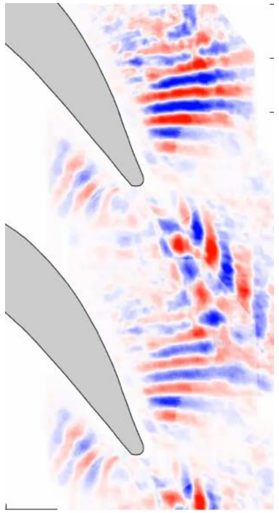
$1.00Re_b$

Peak Amp: 2,000,000



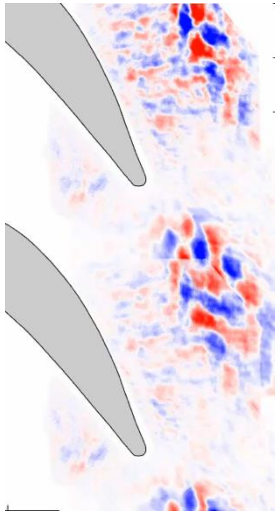
$1.14Re_b$

Peak Amp: 1,000,000



$1.31Re_b$

Peak Amp: 900,000



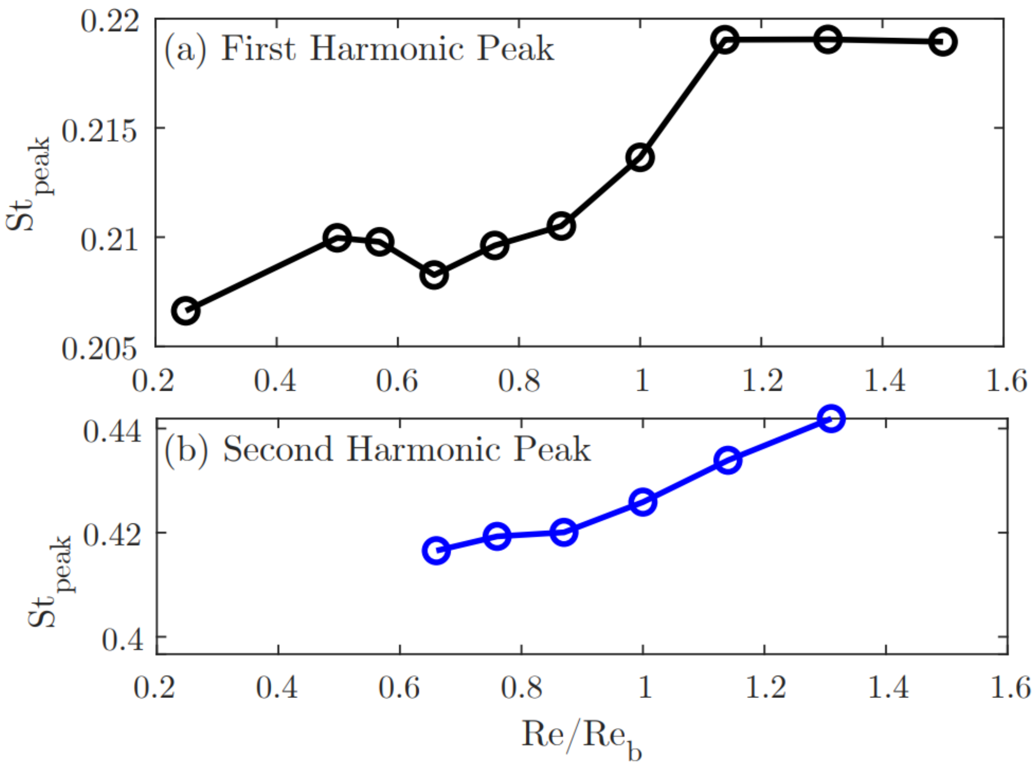
$1.50Re_b$

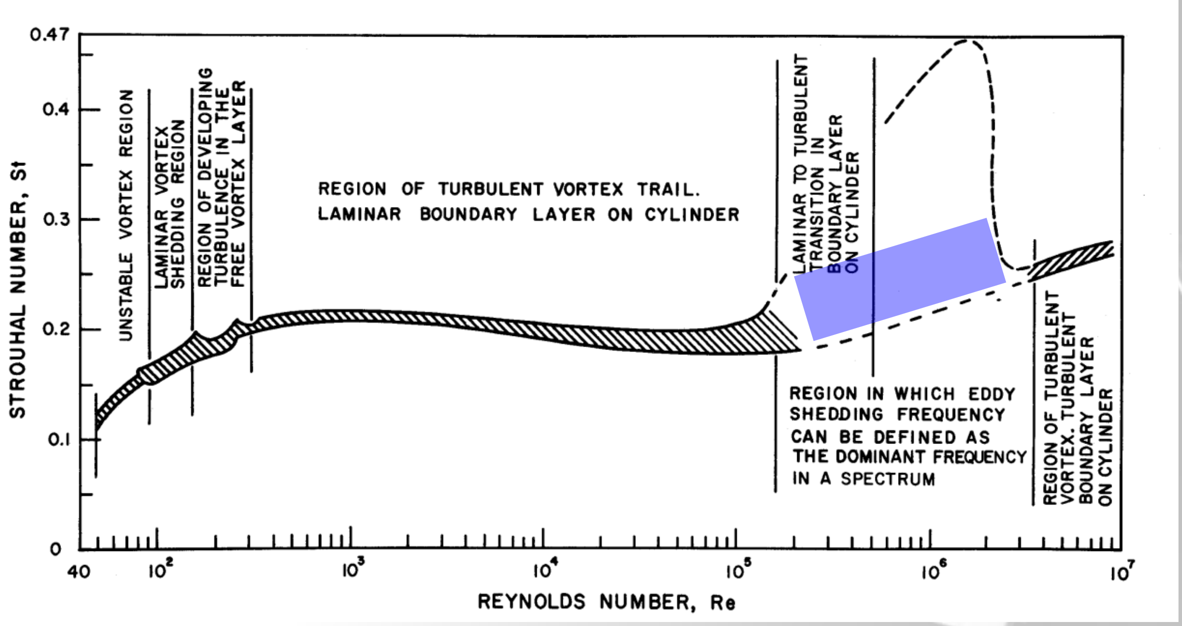
Peak Amp: 1,000,000

# Spectral POD Analysis – All Blades

- Looking more closely, we see there's a slow increase in the shedding frequency as a function of $Re$.

Relation resembles the classical $St$ vs $Re$ relationship in cylinders (Lienhard 1966):



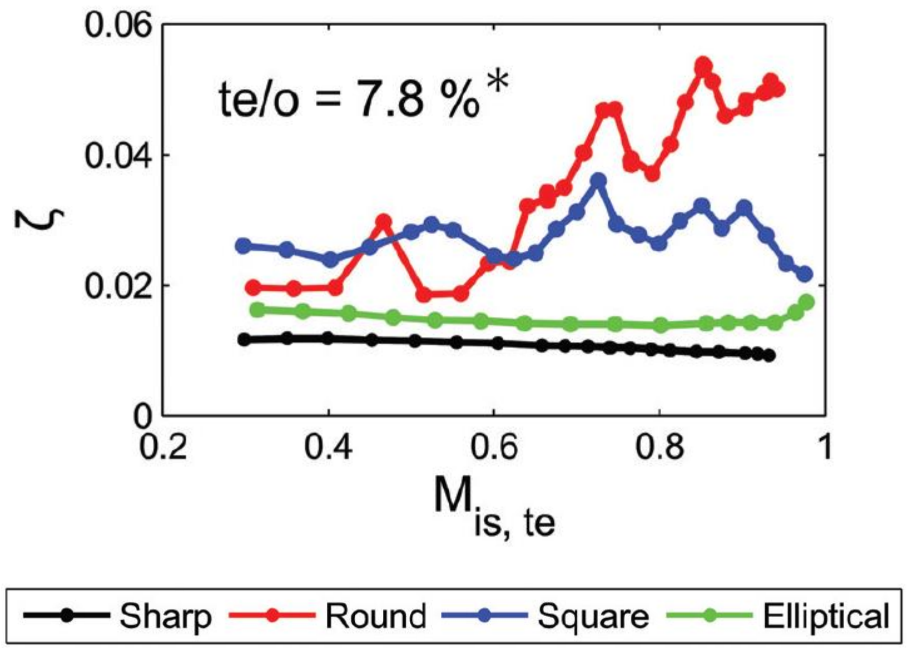

$Re_{C_x} = 1.08 \times 10^6$ (BL Development)

$Re_{TE} = 97 \times 10^3$ (Vortex Shedding)

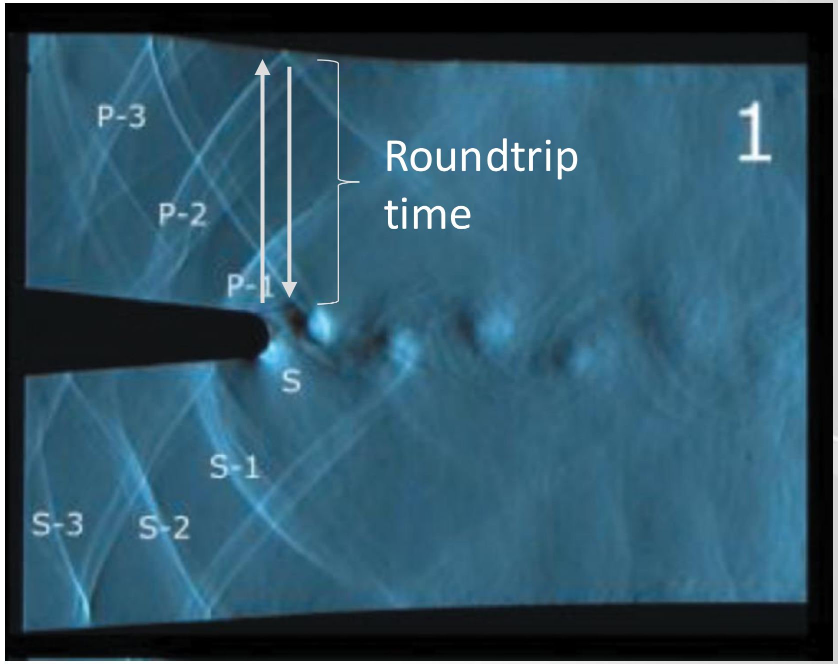
# Acoustic Disturbances & Feedback



- The idea that acoustic disturbances from the vortex shedding can excite a resonant TVS is proposed by Melzer and Pullan (2019) in their observations.
- Troughs and peaks are observed for a single blade depending on the phase-match condition of the wall-reflected shockwave:




Melzer and Pullan (2019)




Melzer and Pullan (2019)

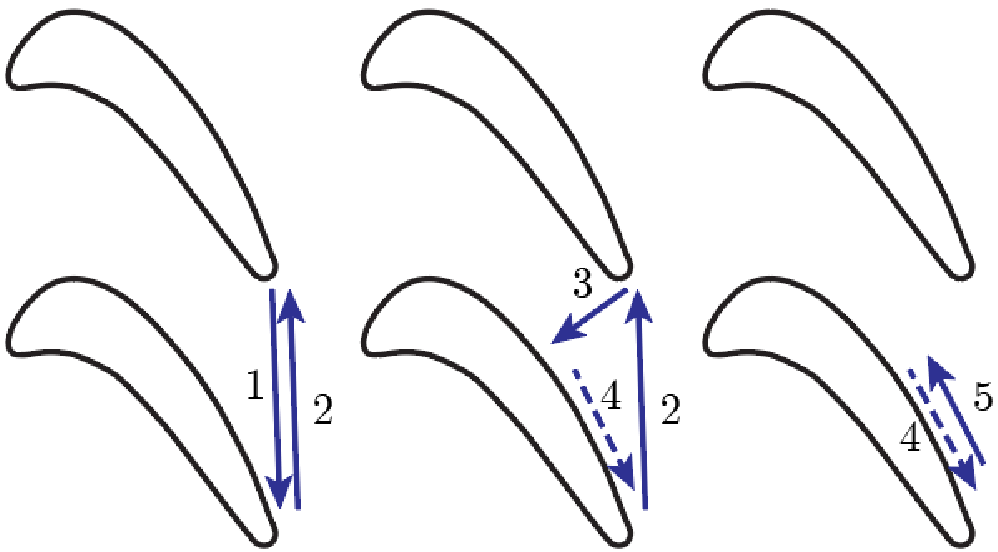
Peak loss @ half-integer number of cycles

Loss trough @ integer number of cycles

# Feedback timing analysis



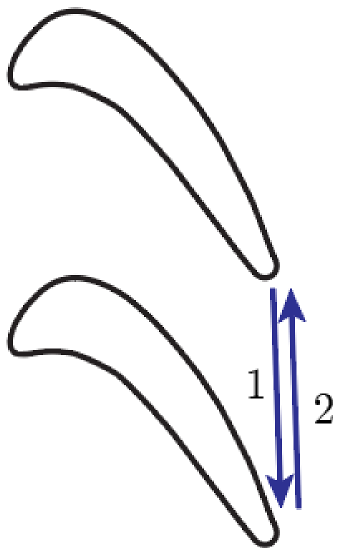
- The following feedback pathways are considered, leveraging the mean LES field:



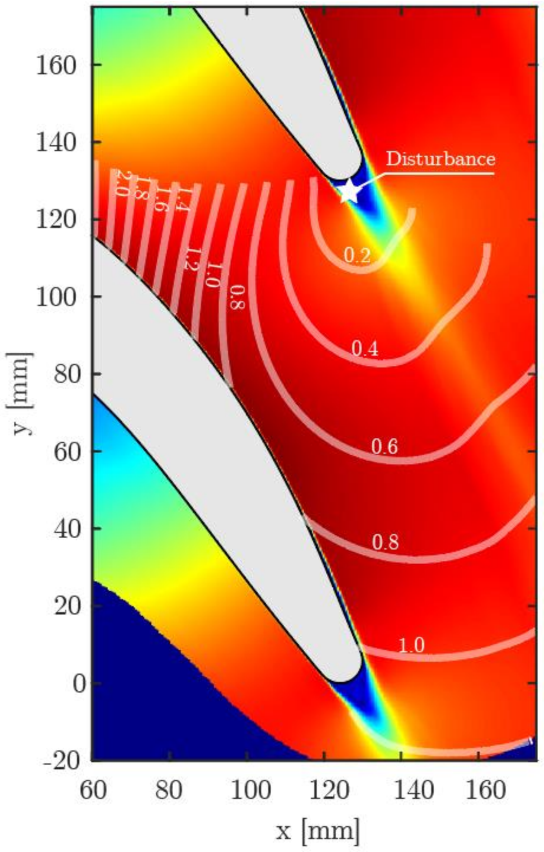

1: Downstream-running acoustic wave originating at T.E.
2: Upstream-running acoustic wave originating at T.E.
3: Cross-stream acoustic wave exciting B.L. on reflection
4: Boundary layer instability wave
5: Upstream-running acoustic wave along B.L.

# Feedback timing analysis: 1+2

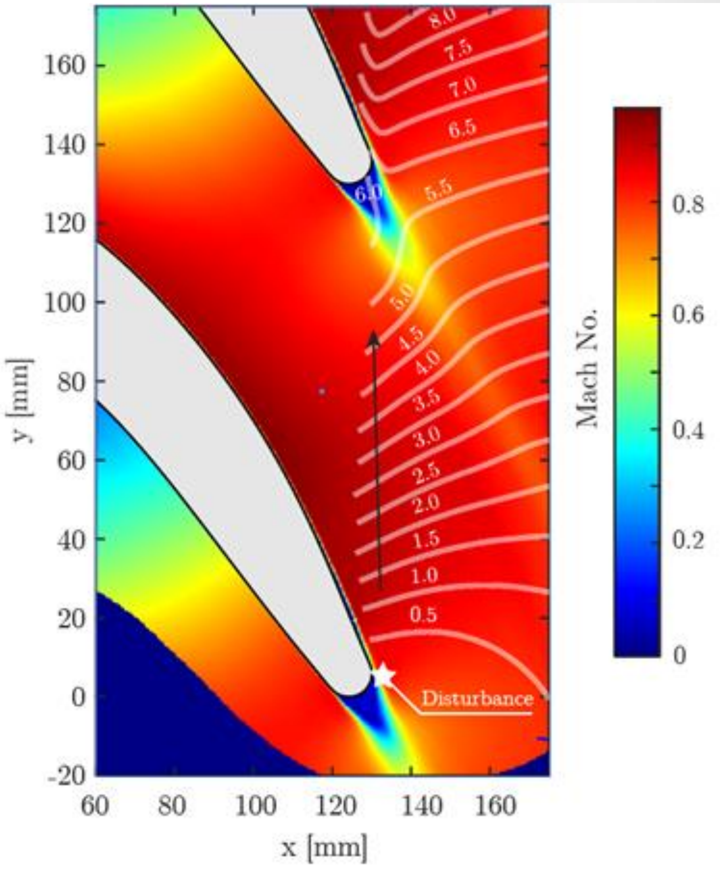
- Path 1+2, considering 4375 Hz fundamental ($Re = 1.0Re_b$peak) :




Path 1



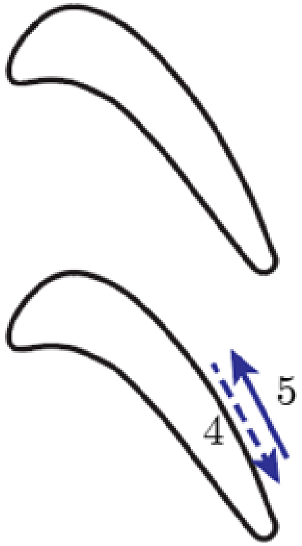

Path 2



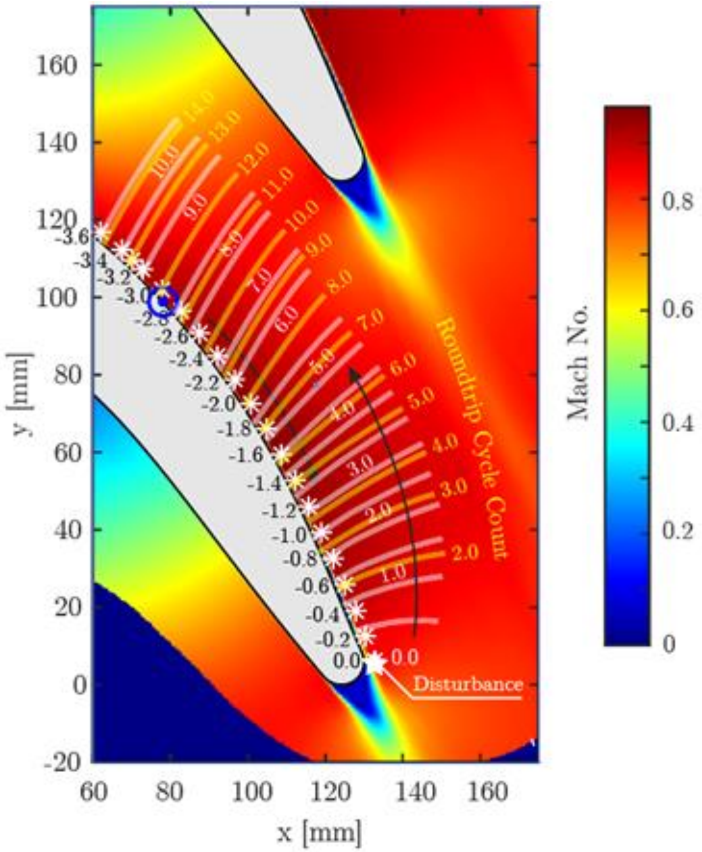

- Total number of cycles = 7.0
- Reflection mechanism is unclear, though.

# Feedback timing analysis: 4+5

- Path 4+5, considering 4375 Hz fundamental ($Re = 1.0Re_b$peak) :




Path 4+5

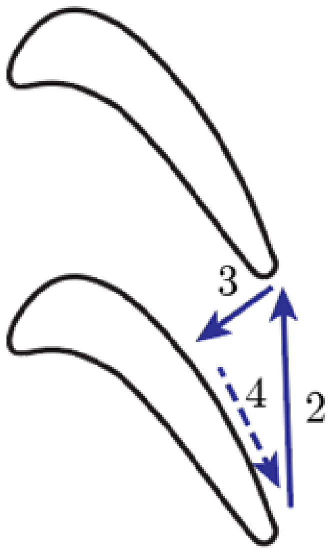



Instability speed: $0.6u_{local}$

- Total number of cycles:
  Anywhere between 2 and 12 cycles is viable
- Wave diffraction is required to go around the curved suction surface
- BL Instability velocity is assumed at $0.6u_{local}$
- Looks like any $Re$ could have viable timing

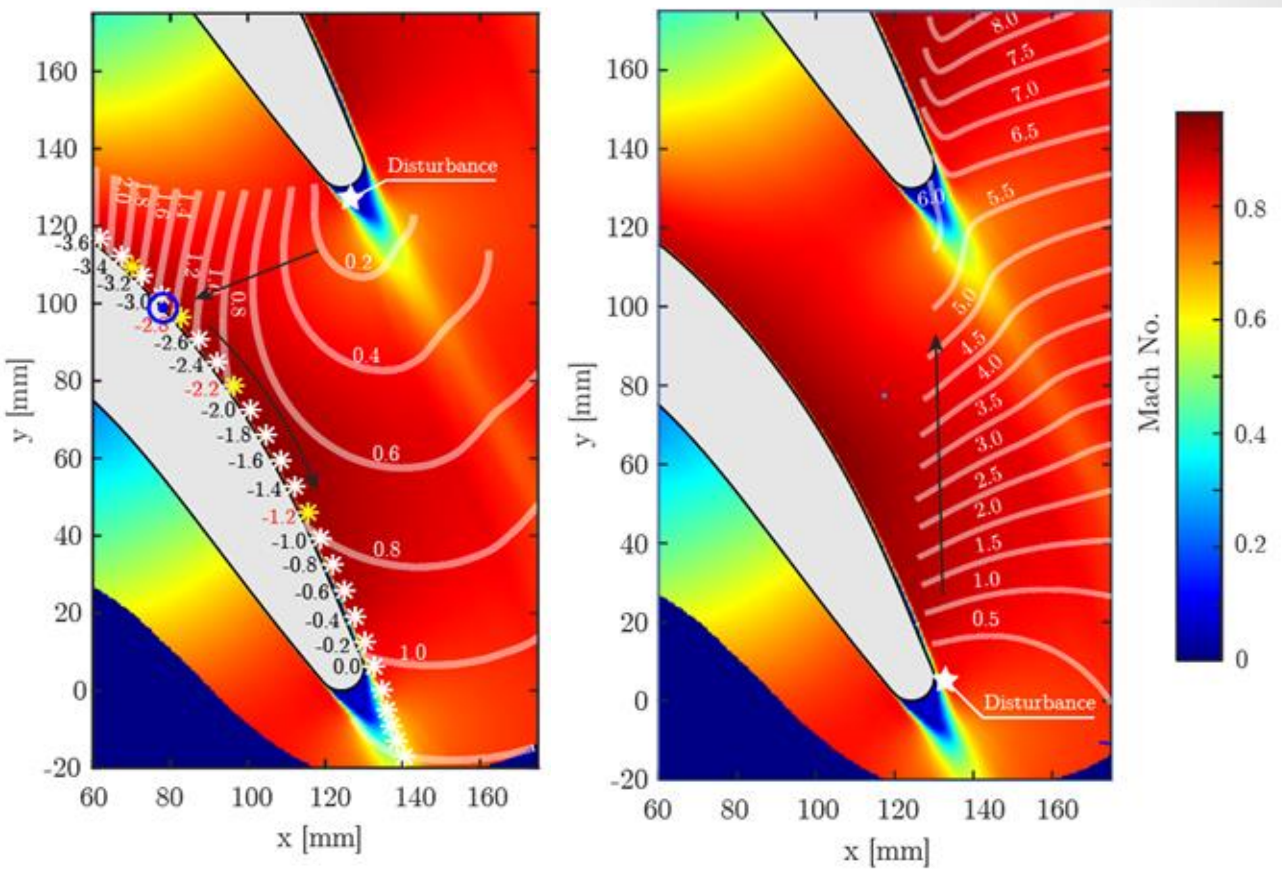
# Feedback timing analysis: 3+4+2

- Path 3+4+2, considering 4375 Hz fundamental ($Re = 1.0Re_b$peak) :




Path 3+4

Path 2



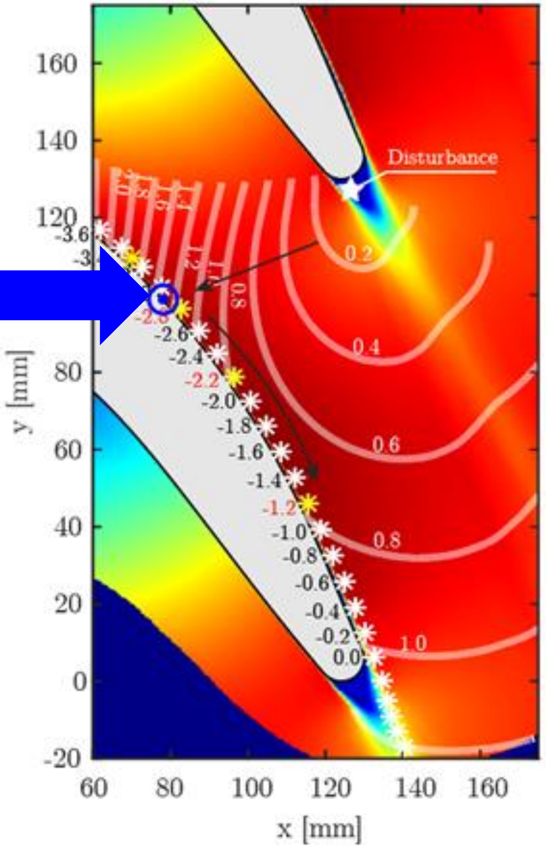

Instability speed: $0.6u_{local}$

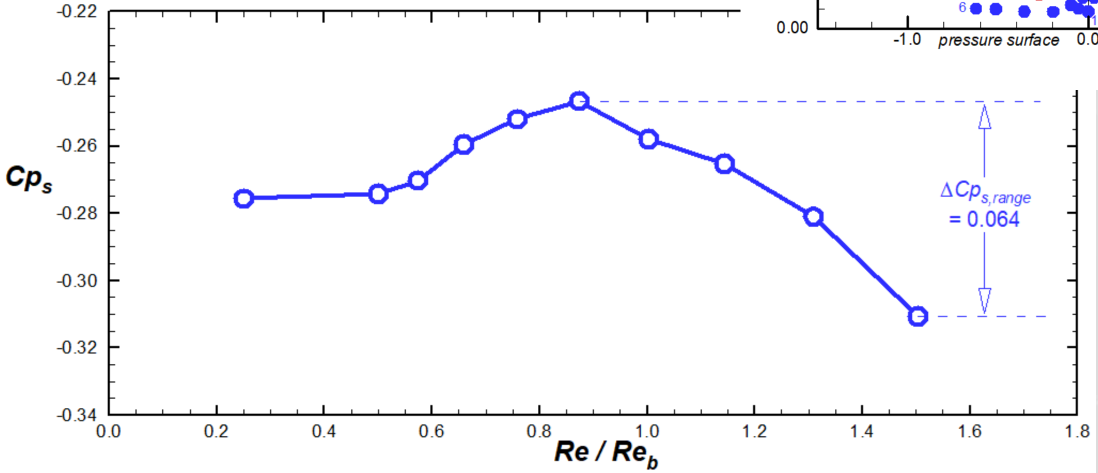
- Total number of cycles: 8, 9 and 10 are viable
- Also possible that the upstream path is not necessary (only 3+4 sufficient)
- BL Instability velocity is assumed at $0.6u_{local}$
- Looks like any $Re$ could have viable timing

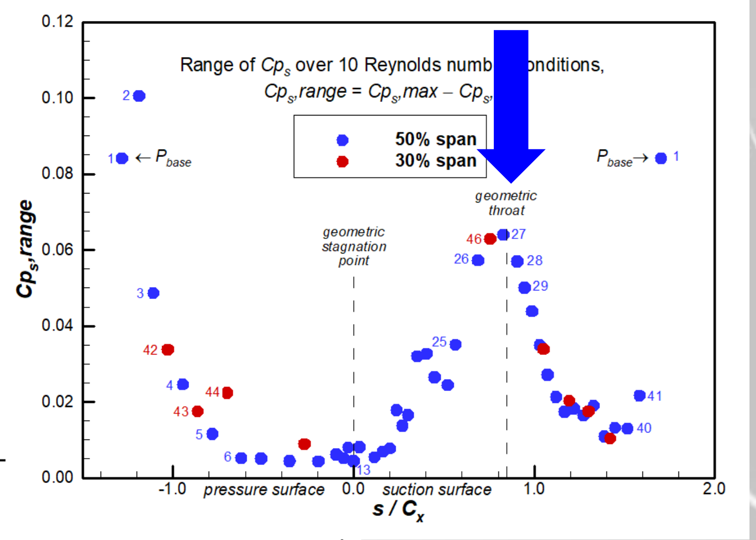
# Circumstantial evidence: Geometric Throat



- We noted that the geometric throat has the largest variation in surface pressure.
- Perhaps the BL is being most disturbed by the acoustic wave (either 3 or 5) at the geometric throat?



# Conclusions

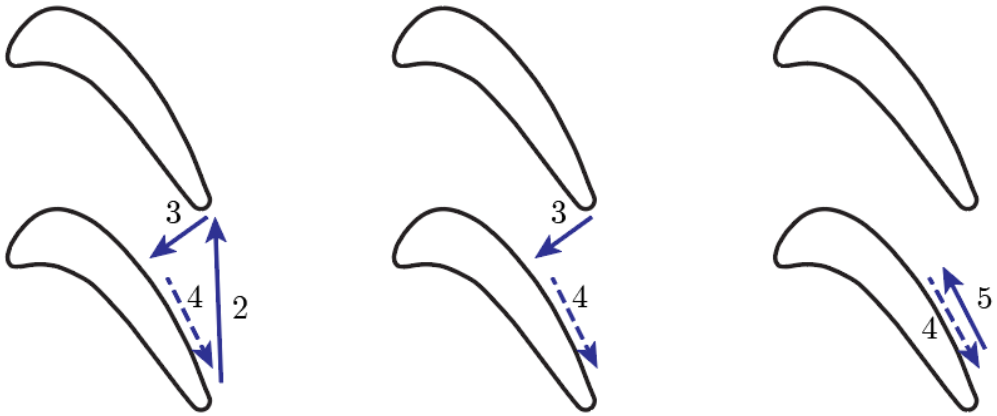


- Through SPOD analysis of time-resolved SAFS images of a realistic 11-blade cascade at 10 Reynolds numbers, we identified a transonic vortex shedding that is maximal at a specific $Re_{C_x} = 1{,}078{,}800$.

- The TVS frequency varies slightly with $Re$ -> Points to a potential feedback/timing mechanism?

- Viable feedbacks considered in timing analysis, but not all are ruled out. Possible mechanisms:

Neighbor blade feedback | Neighbor blade SBLI cascade | Self-excited SBLI/acoustics




$0.87Re_b$