Smart Twisting Active Rotor (STAR2): U.S. Update

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(*)With acknowledgments to other members of the U.S. Prediction Team:

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- Matthew L. Wilbur

- **Because this is a meeting to show status of where we are in the work, this presentation has a lot of slides - mainly to document the work done since the last meeting…**

- **So, I will only hit some of the highlights during the presentation…**

Outline

Cases Examined:

- Low Speed (μ = 0.151) Shaft Tilt Sweep
- Descent (μ = 0.151) 2p @ 50% Amplitude
- Descent (μ = 0.151) 3p @ 50% Amplitude
- Level Flight μ Sweep

Low Speed (μ = 0.151) Shaft Tilt Sweep

For reference… Flight Path Angle and Shaft Tilt

Flight Path Angle [º]	6	3	0	-3	-4	-5	-6	-7	-8	-9	-12
Shaft Tilt [º]	-8.10	-5.11	-2.12	0.88	1.88	2.88	3.88	4.89	5.89	6.89	9.91

Flight Path Angle is in degrees and is positive for climb.
Shaft Tilt Angle is in degrees and is positive aft.

All cases have a slightly different Thrust, but all are close to 3600 [N].
All cases are executed using shaft tilt in CAMRAD II and advance ratio = 0.151.

However, all following slides show Flight Path Angle (based on previous conventions).

The term “Flight Path Angle” and “Flight Path” are used interchangeably in this presentation.
The term “Shaft Tilt Angle” and “Shaft Tilt” are used interchangeably in this presentation.
BVI SPL means sum of 6th through 40th BPF (Blade Passage Frequency).

Trim Strategy

Trim Targets: Thrust = ~3600 [N]
H-force = 0 [N]
M_x = 0 [Nm] (Roll Moment)

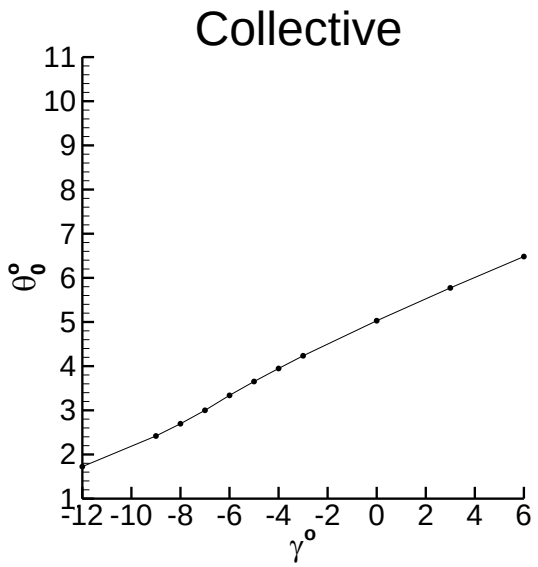
Trim Variables: Collective, Lateral and Longitudinal Cyclic

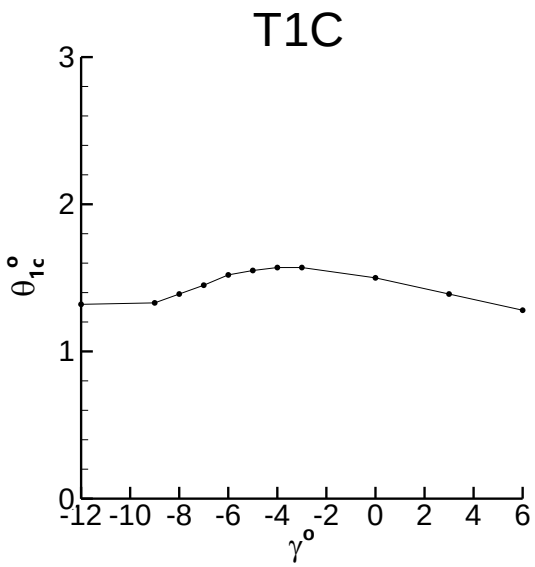
CAMRAD II analysis:

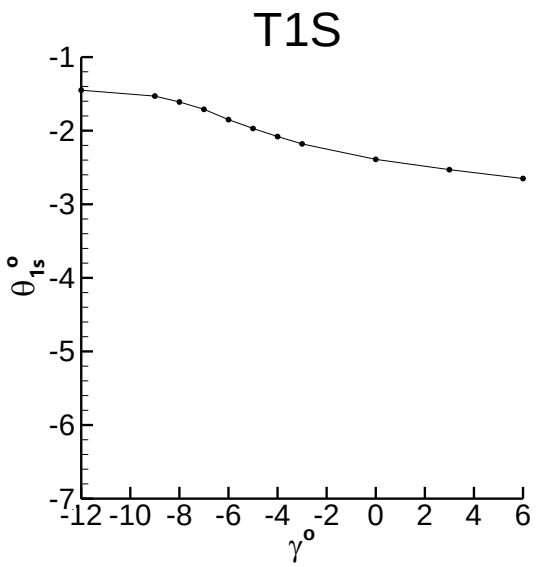
- 23 aerodynamic panels
- Free wake
- Core size = 0.8c [from correlations with HART II BVI SPL]
- Post trim azimuthal resolution = 1.5º

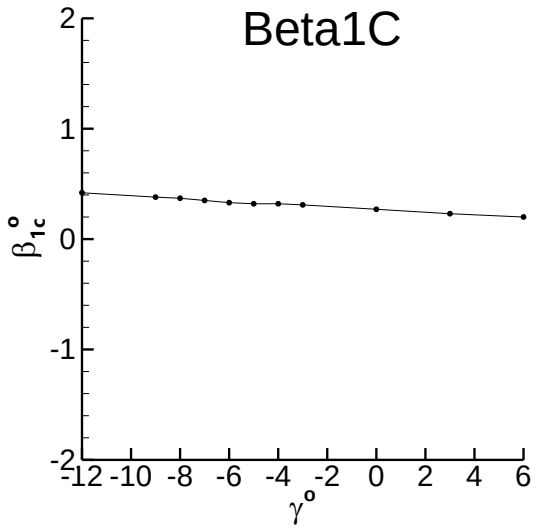
Pilot (Rotor) Controls

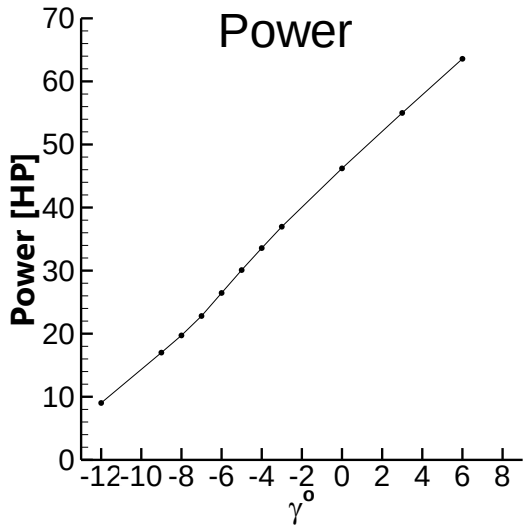
Controls, Long. Flap, Power vs. Flight Path







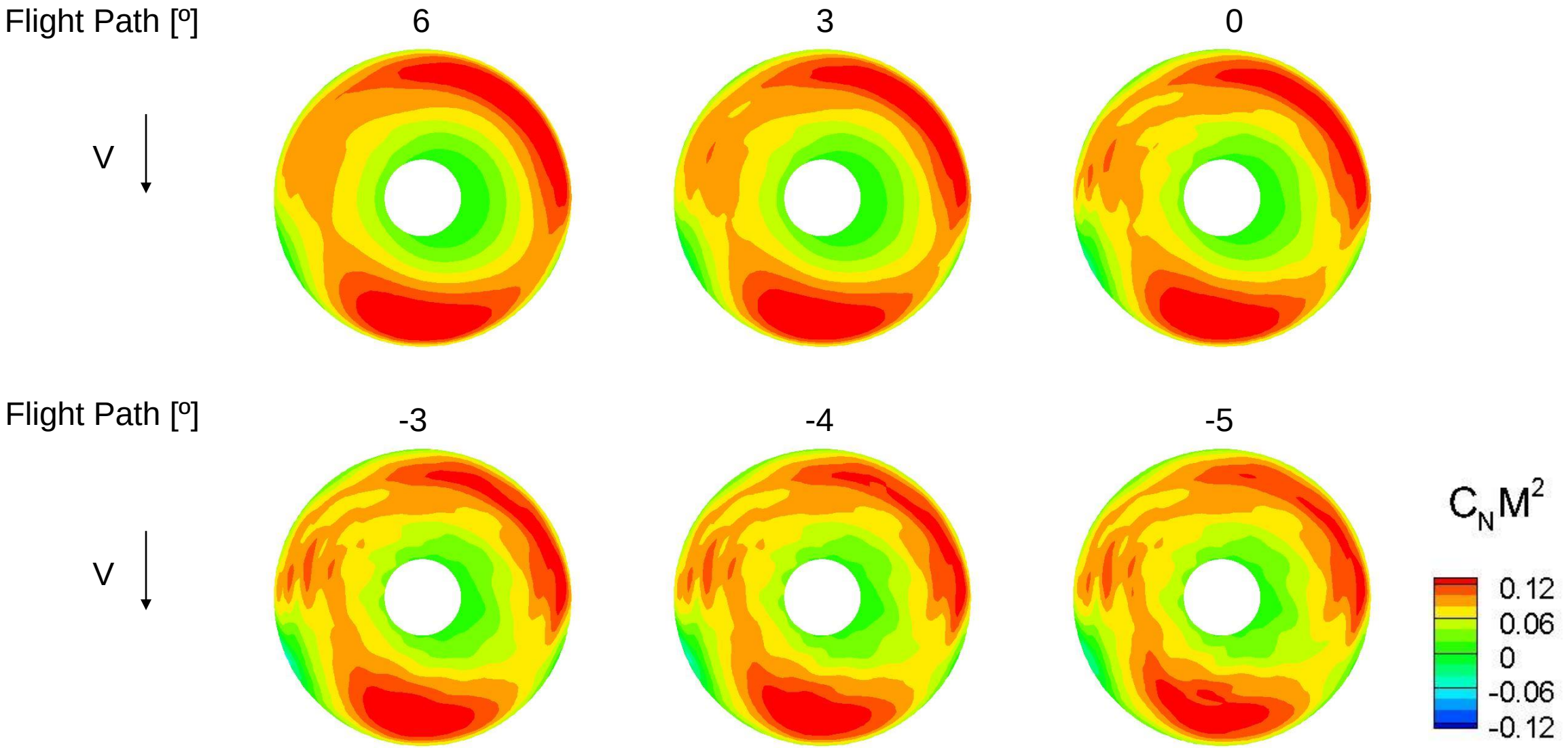




$\gamma^o > 0$ means climb.

$C_N M^2$ Contours

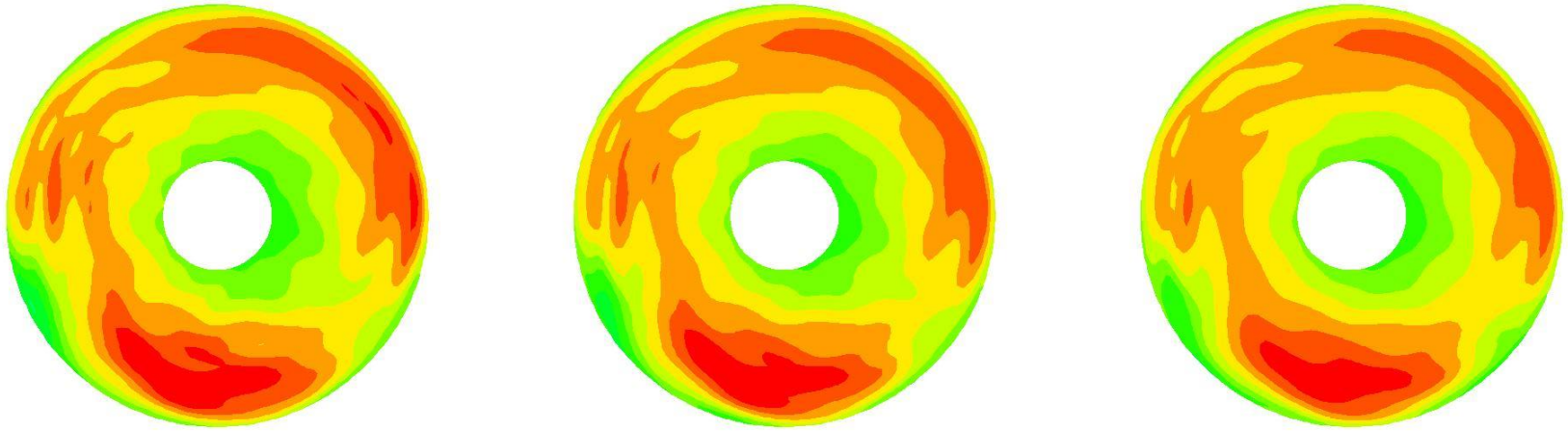
Low Frequency (0-10 BPF) $C_N M^2$ vs. Flight Path (1 of 2)



Low Frequency (0-10 BPF) $C_N M^2$ vs. Flight Path (2 of 2)

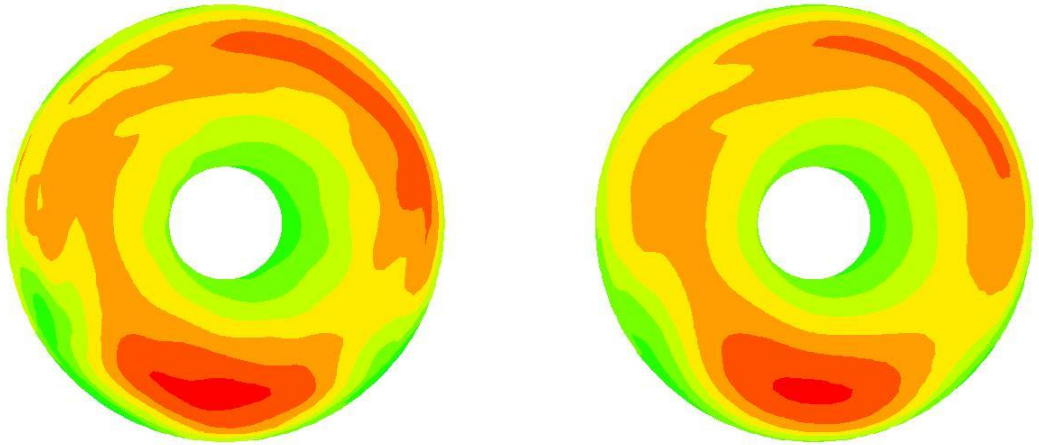
Flight Path [º] -6 -7 -8

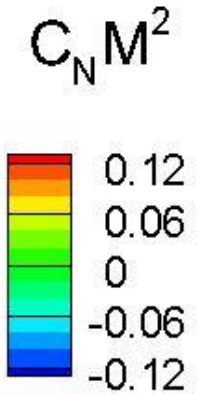
V



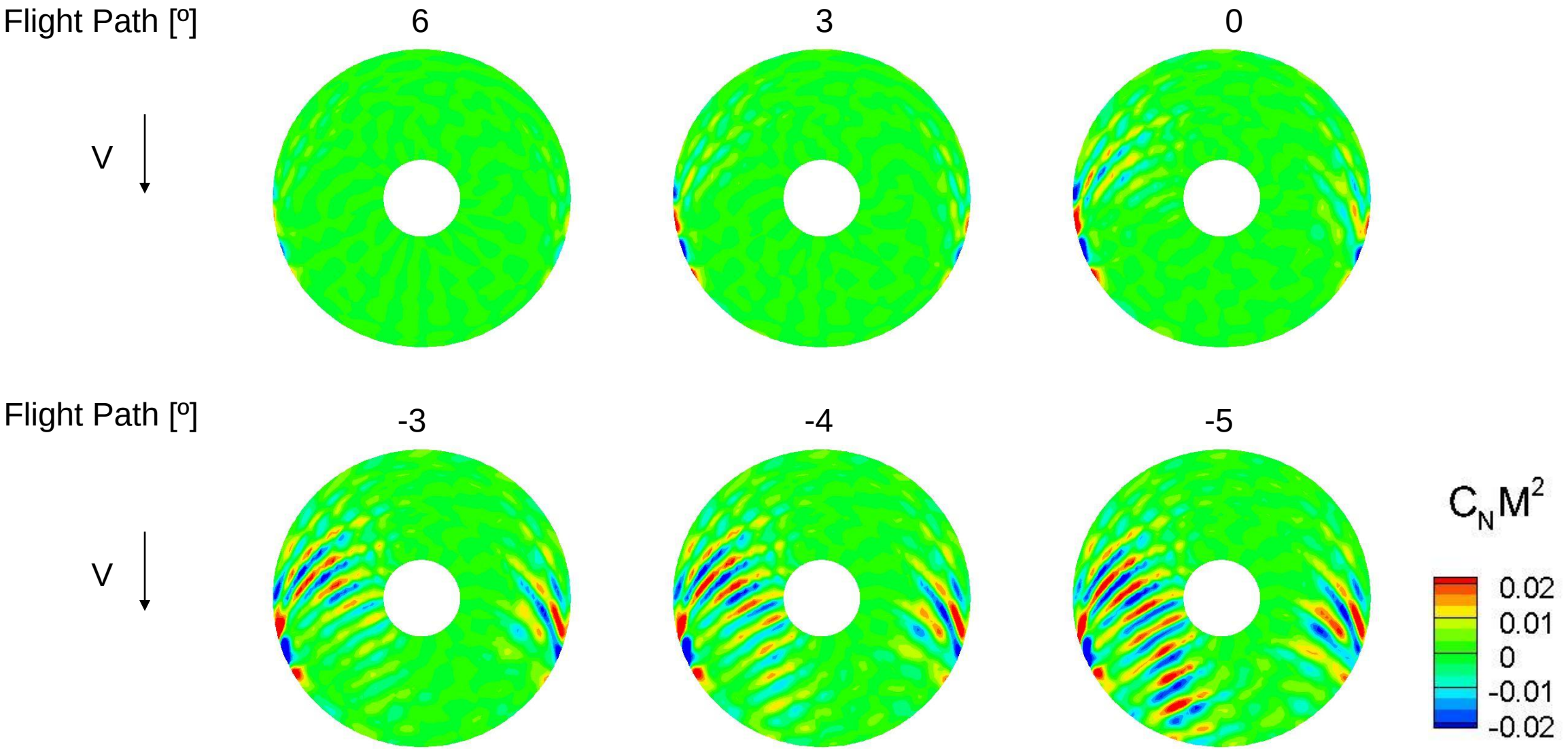
Flight Path [º] -9 -12

V

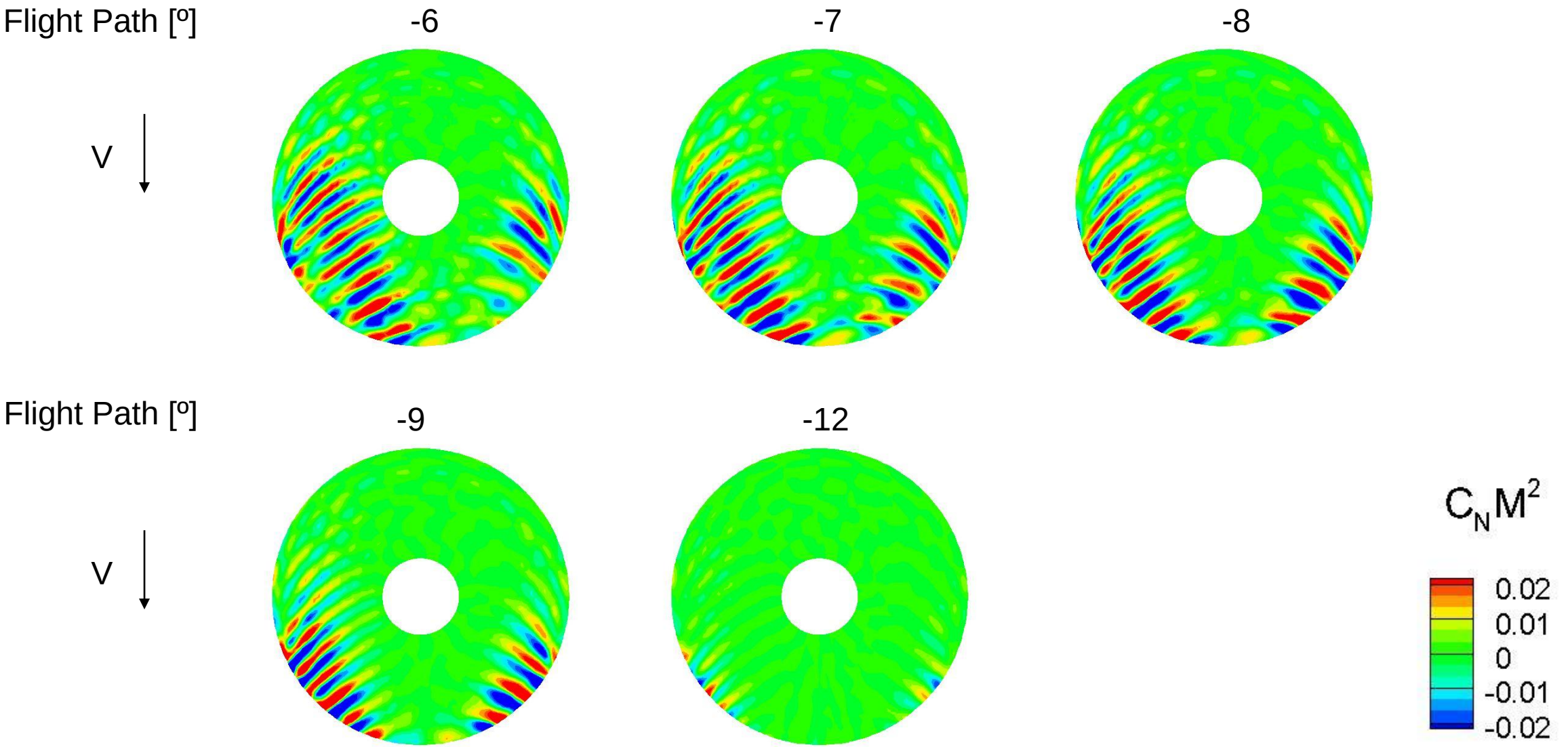




Mid Frequency (> 10 BPF) $C_N M^2$ vs. Flight Path (1 of 2)



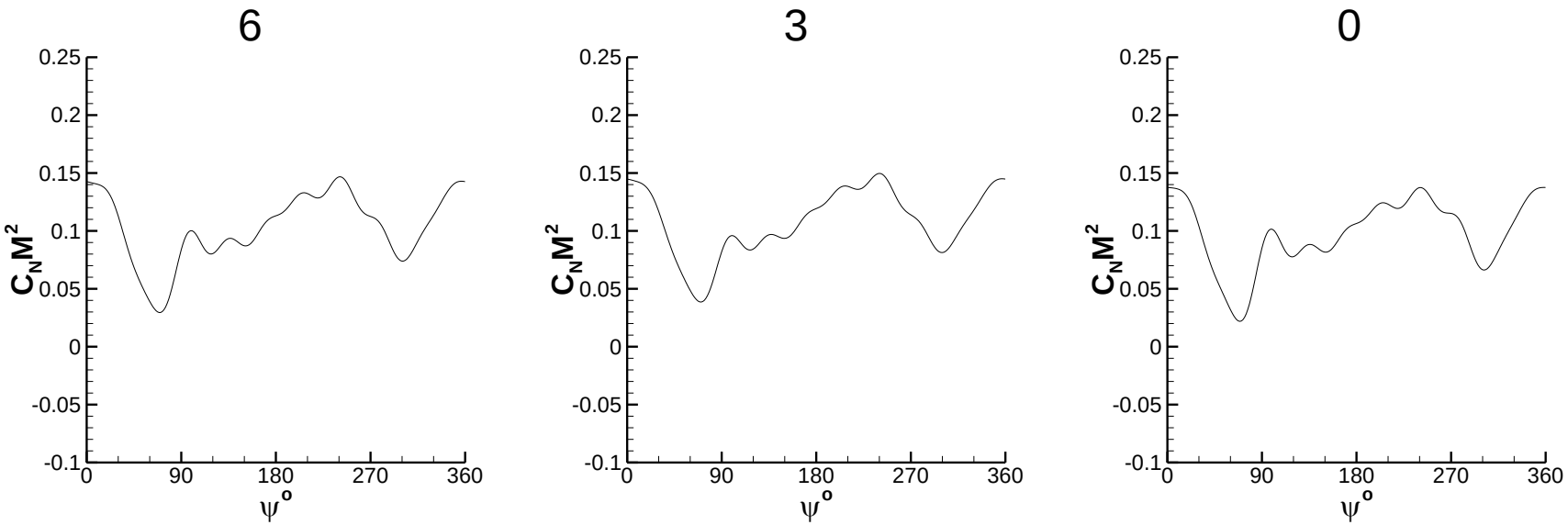
Mid Frequency (> 10 BPF) $C_N M^2$ vs. Flight Path (2 of 2)



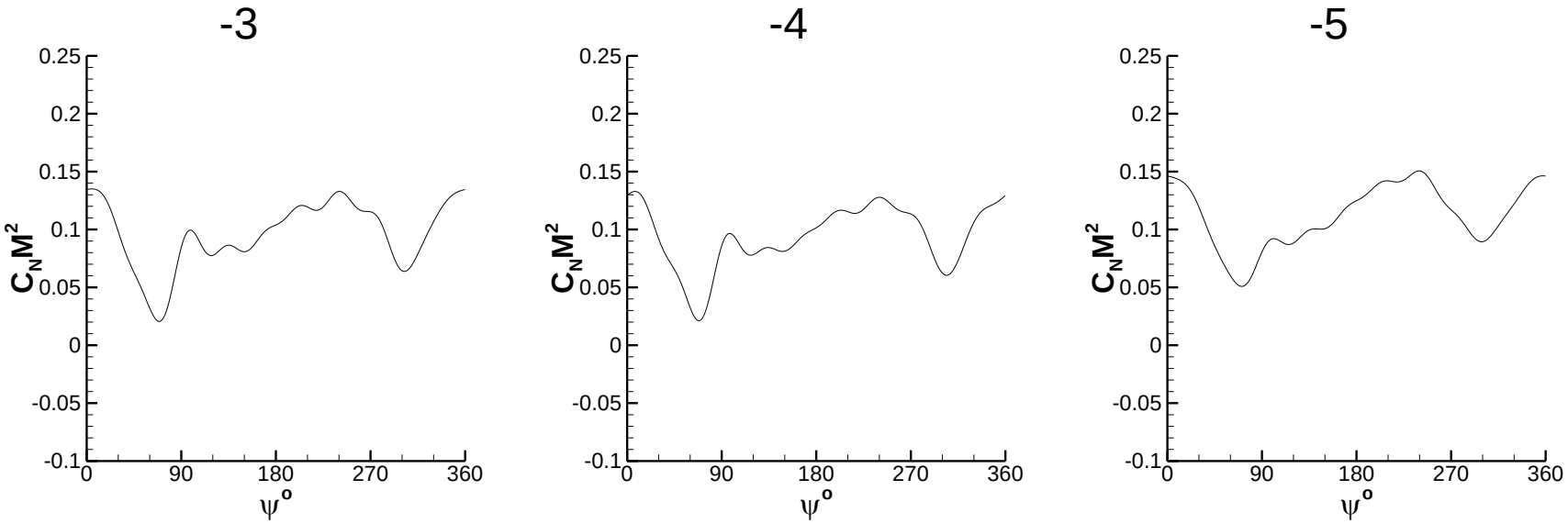
$C_N M^2$ at r/R = 0.875

Low Frequency (0-10 BPF) C_NM^2 at 0.875R (1 of 2)

Flight Path [º]



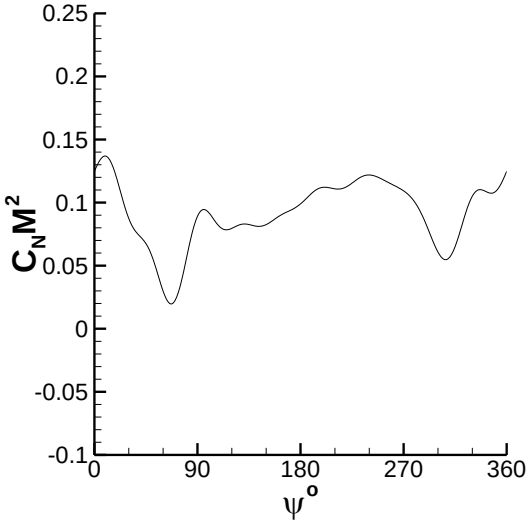
Flight Path [º]



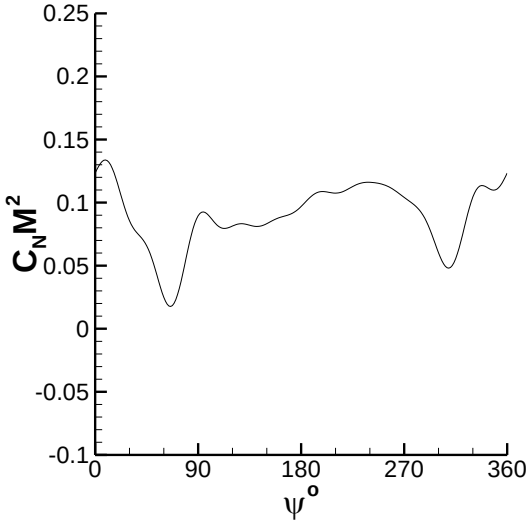
Low Frequency (0-10 BPF) C_NM^2 at 0.875R (2 of 2)

Flight Path [º]

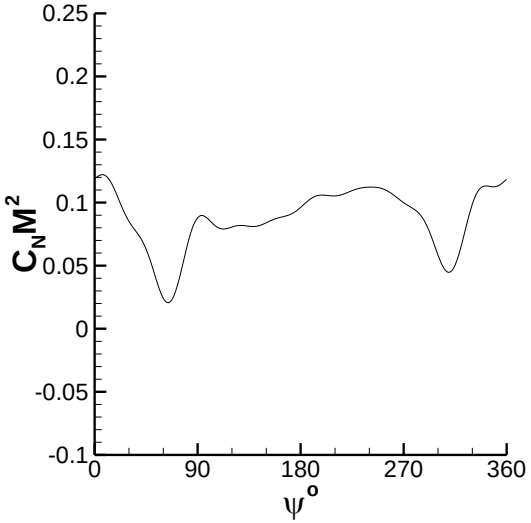
-6



-7

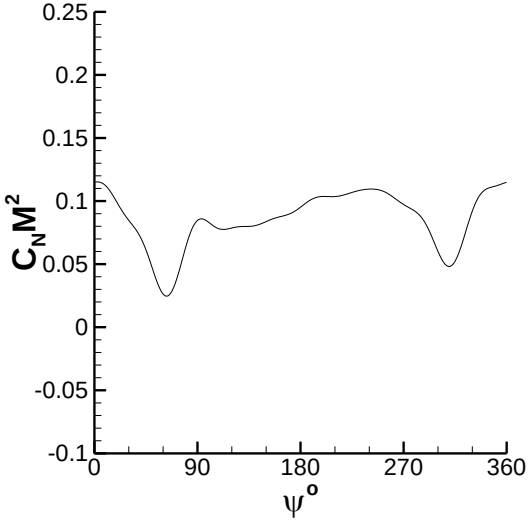


-8

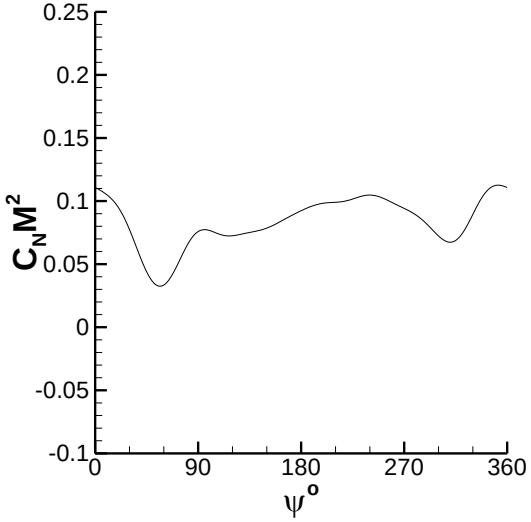


Flight Path [º]

-9

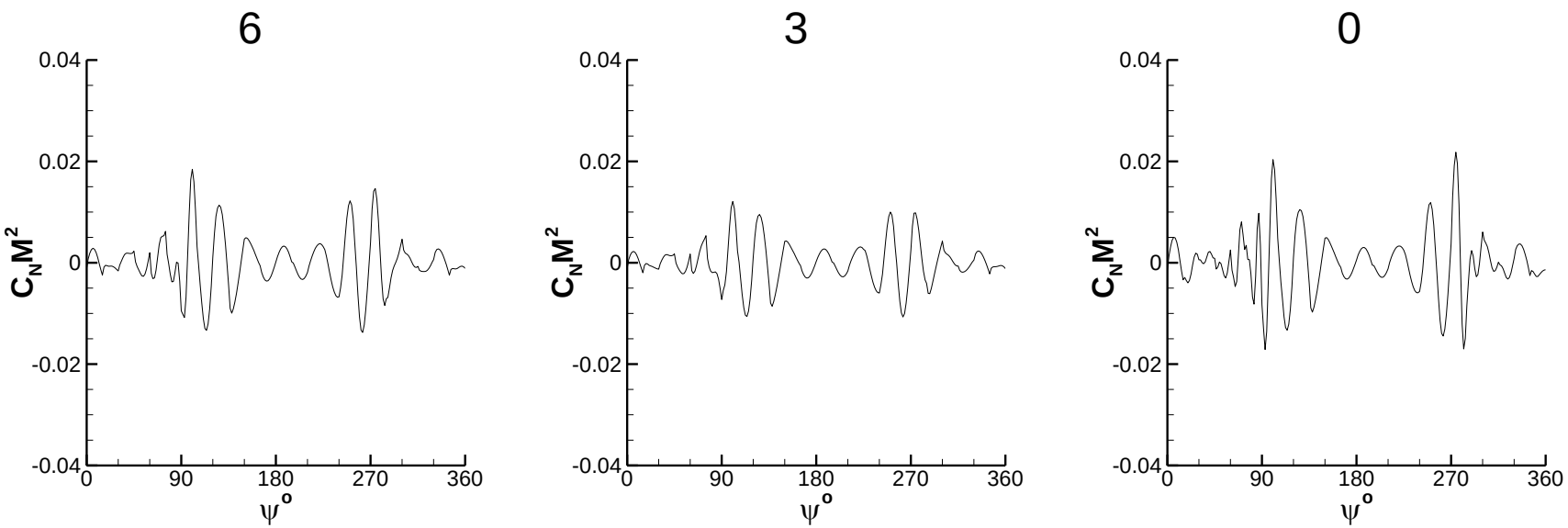


-12

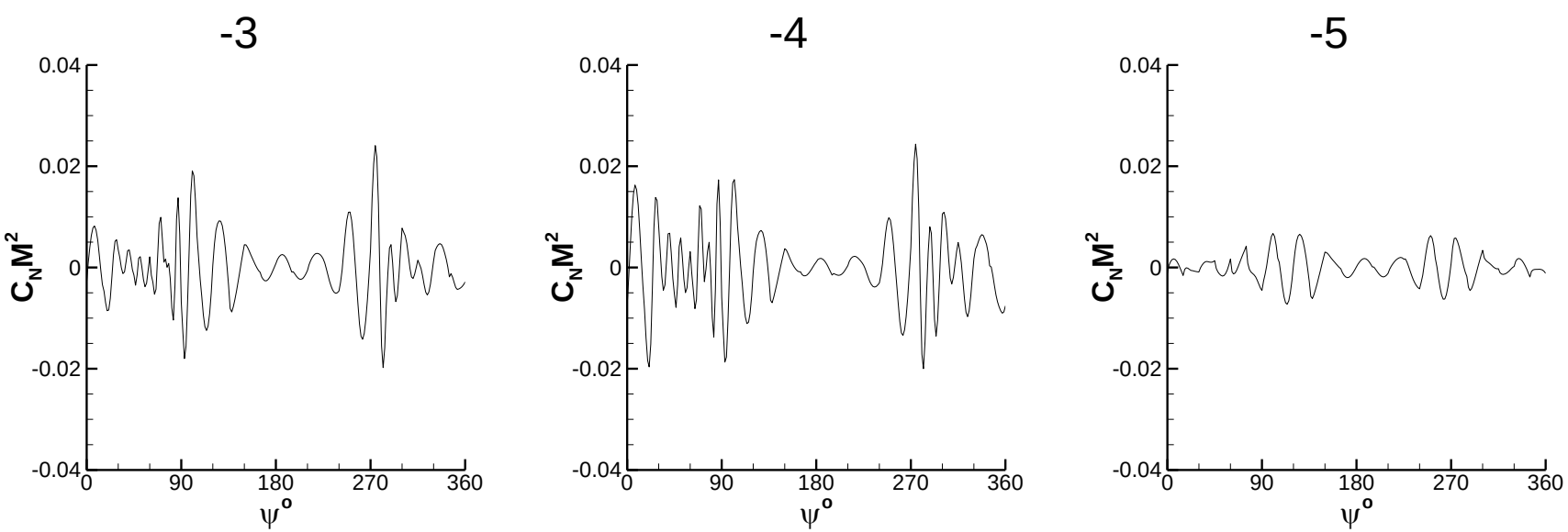


Mid Frequency (> 10 BPF) C_NM^2 at 0.875R (1 of 2)

Flight Path [º]



Flight Path [º]

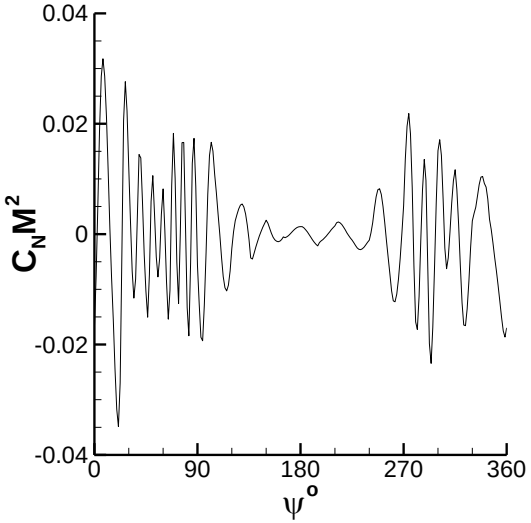


The -5º case looks "odd" due to its lack of strong pulses seen in -4º and -6º; however, the lack of pulses is due to a fortuitous location of the r/R=0.875 radial. (refer to mid-frequency C_NM^2 contour plot)

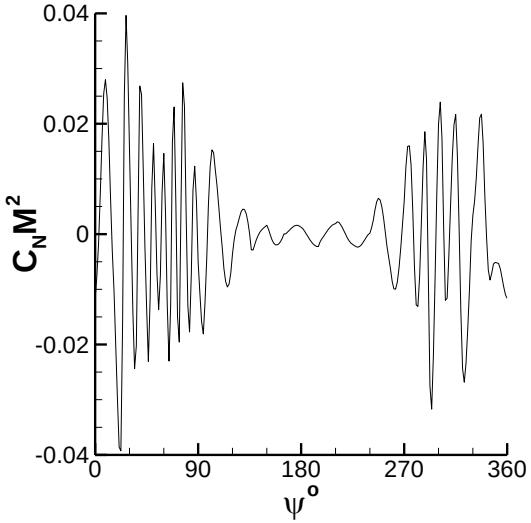
Mid Frequency (> 10 BPF) C_NM^2 at 0.875R (2 of 2)

Flight Path [º]

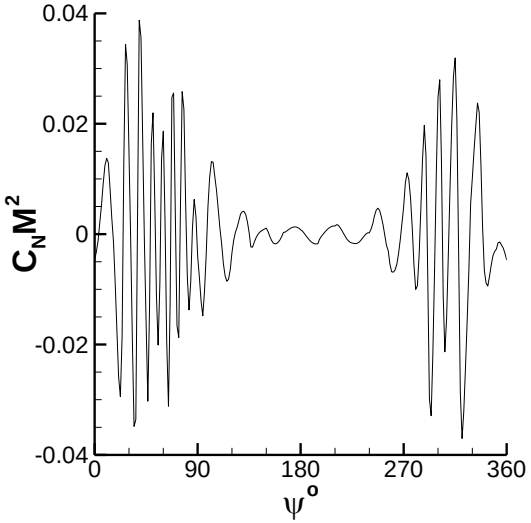
-6



-7

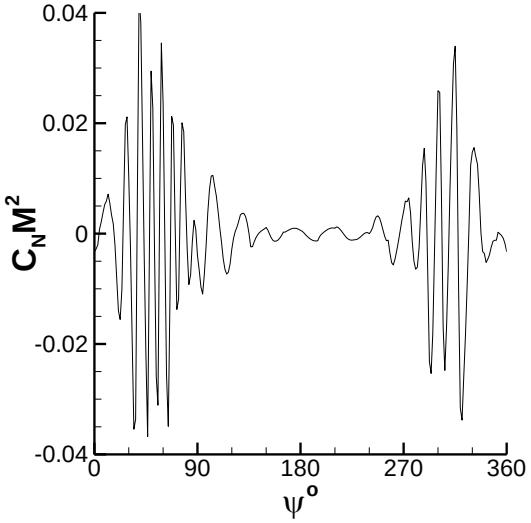


-8

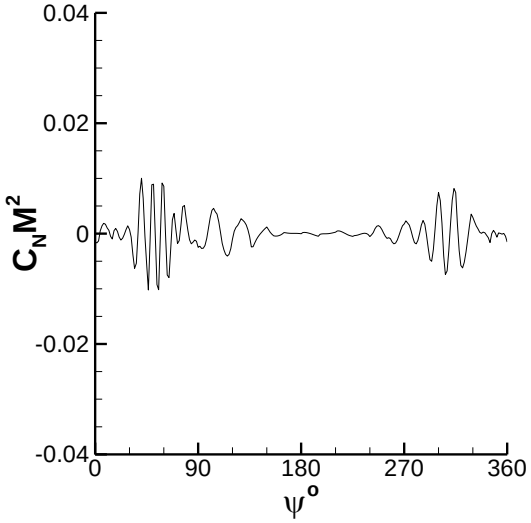


Flight Path [º]

-9



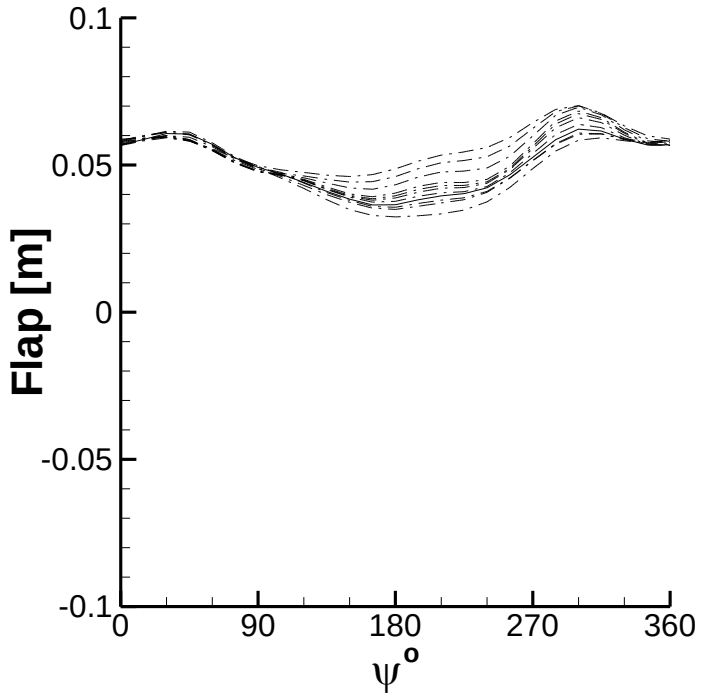
-12

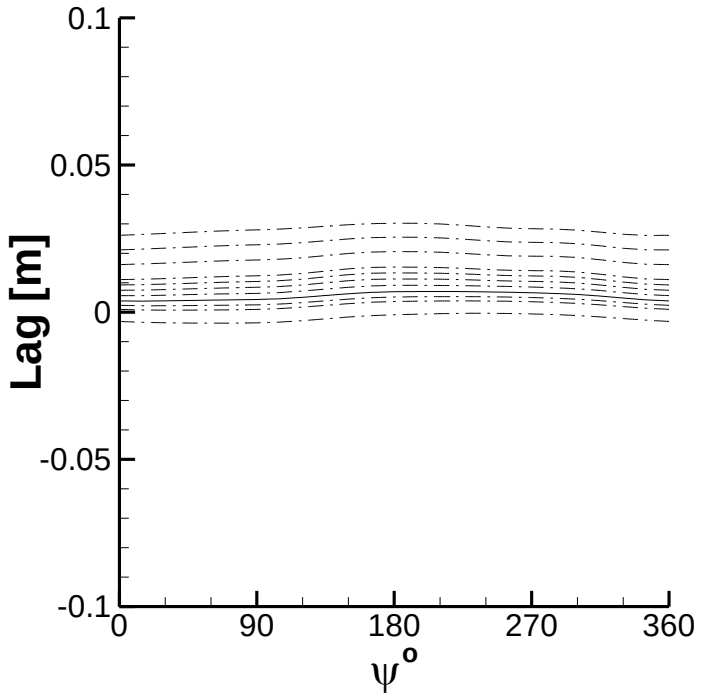


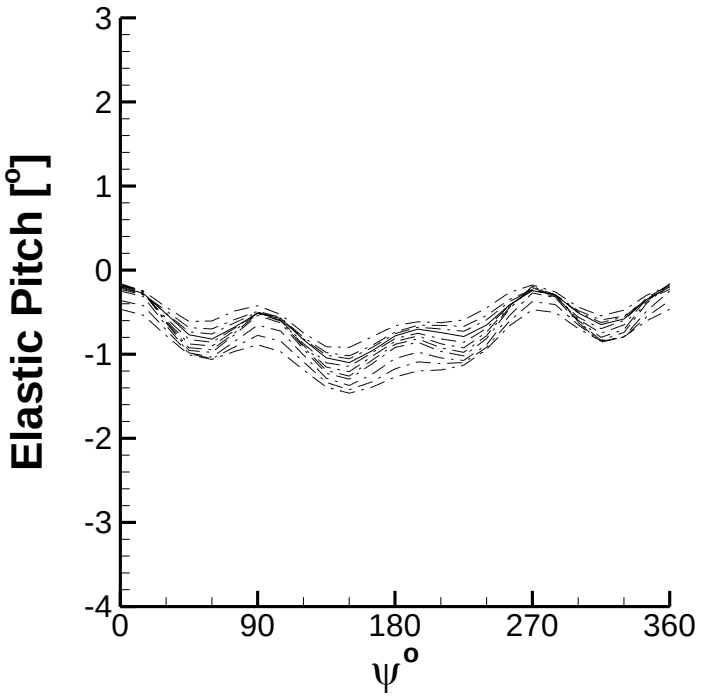
Tip Deflections

Tip Deflections

All shaft tilt angles shown on each plot.
Solid line is the γ = -7º case.



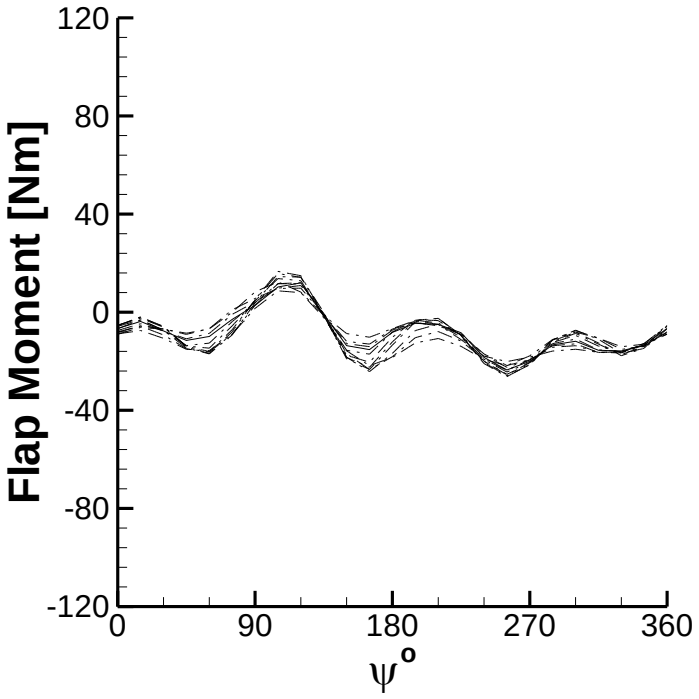


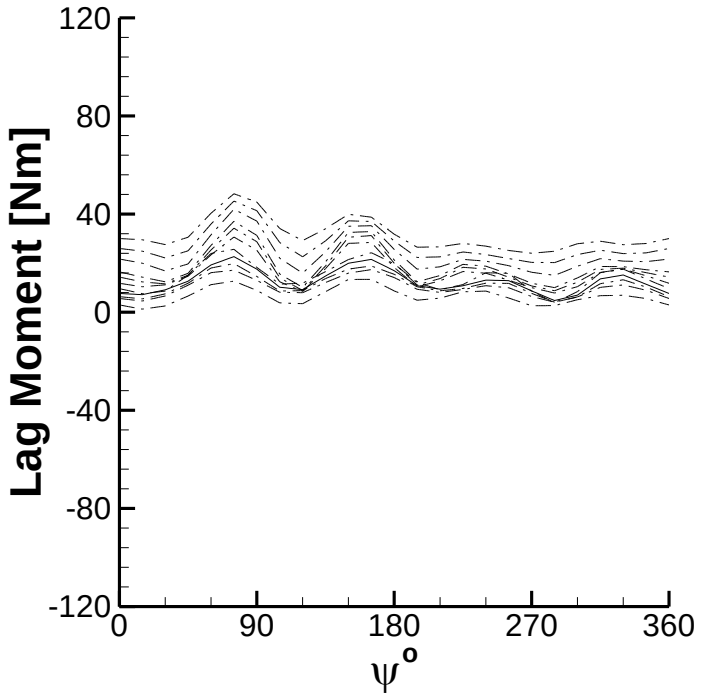


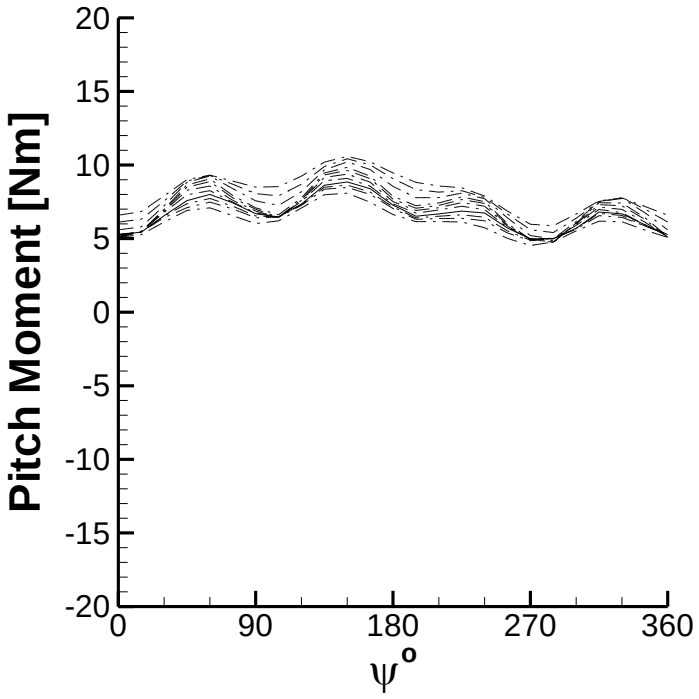
Moments at r/R = 0.26

Moments at 0.26R

All shaft tilt angles shown on each plot.
Solid line is the γ = -7º case.

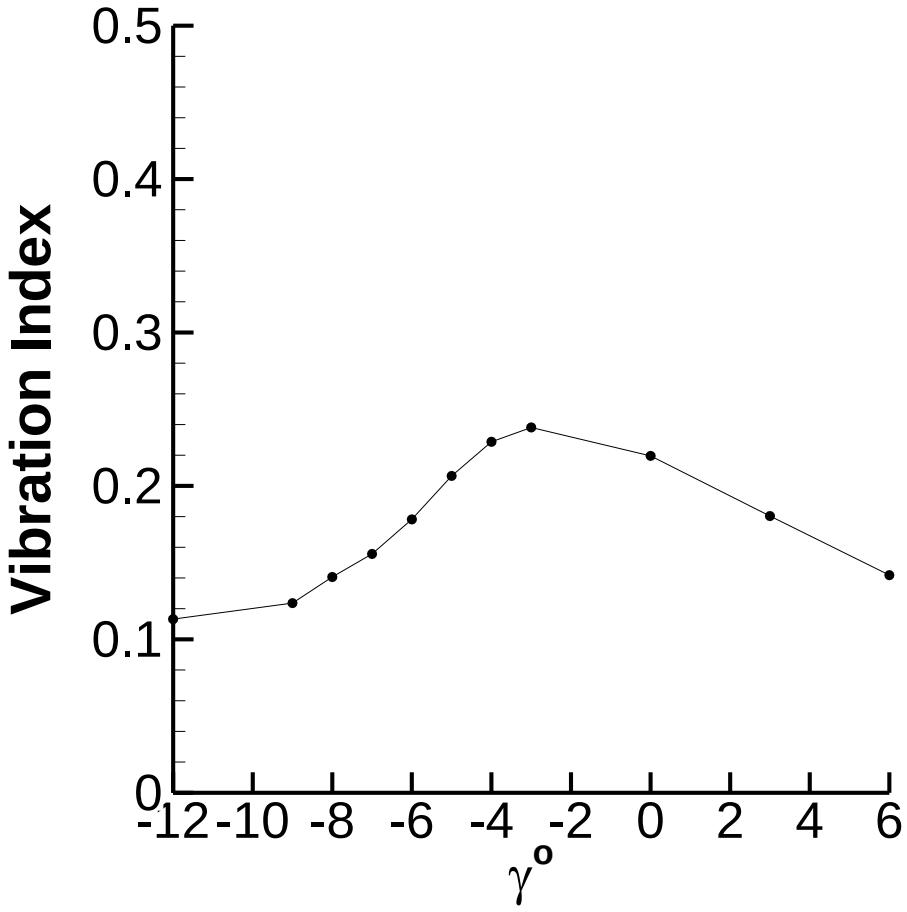






Vibration Index

Vibration Index



$$F = \sum_{n=4}^{8} \frac{\sqrt{(C_x f_x[n])^2 + (C_y f_y[n])^2 + (C_z f_z[n])^2}}{W_o}$$

$$M = \sum_{n=4}^{8} \frac{\sqrt{m_x^2 + m_y^2}}{R W_o}$$

$$V_I = F K_f + M K_m$$

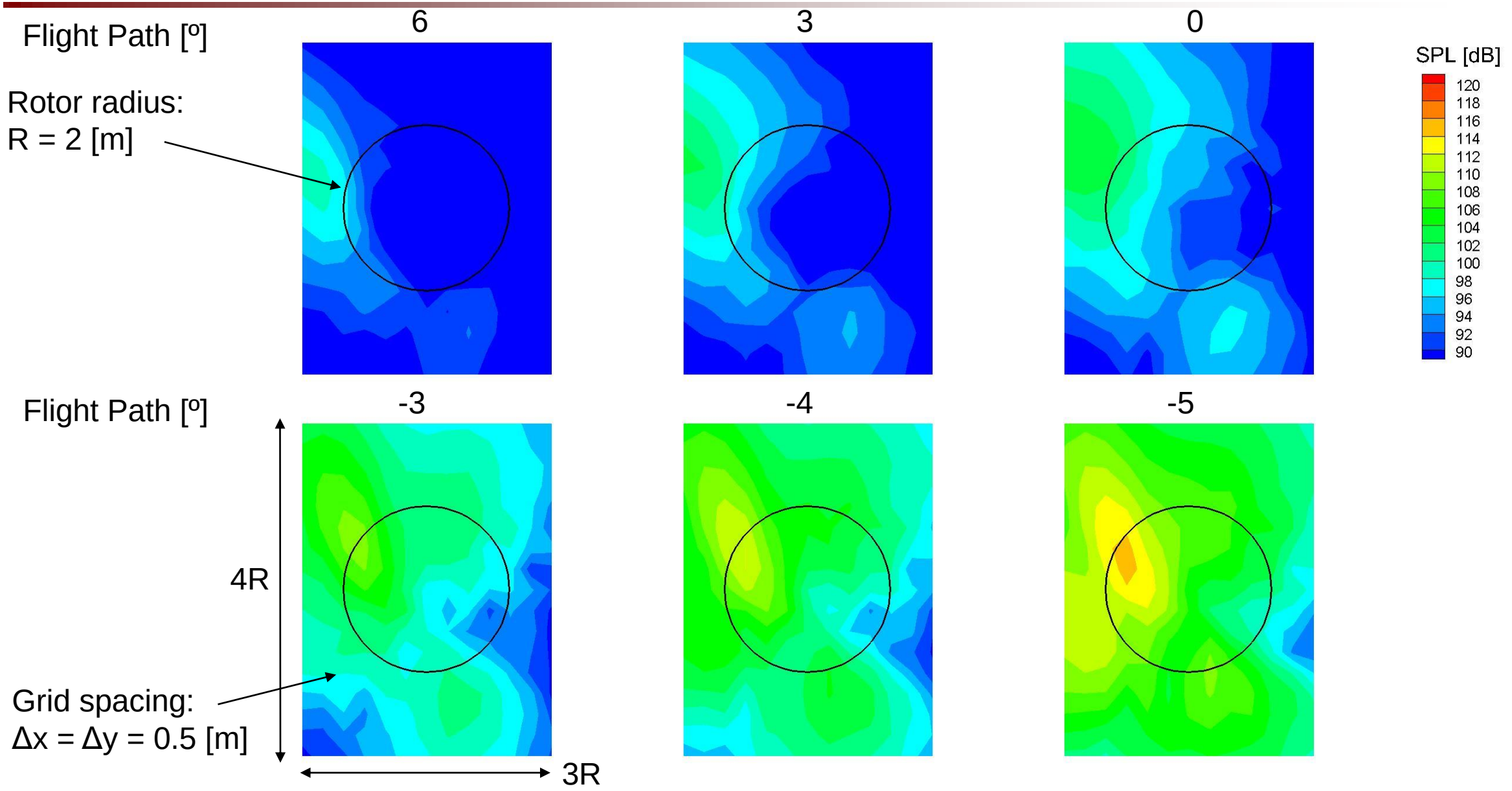
$C_x = 0.5$
$C_y = 0.67$
$C_z = 1.0$
$K_f = 1.0$
$K_m = 1.0$
$W_o = 3581$ N
$R = 2.0$ m

V_I = Vibration Index

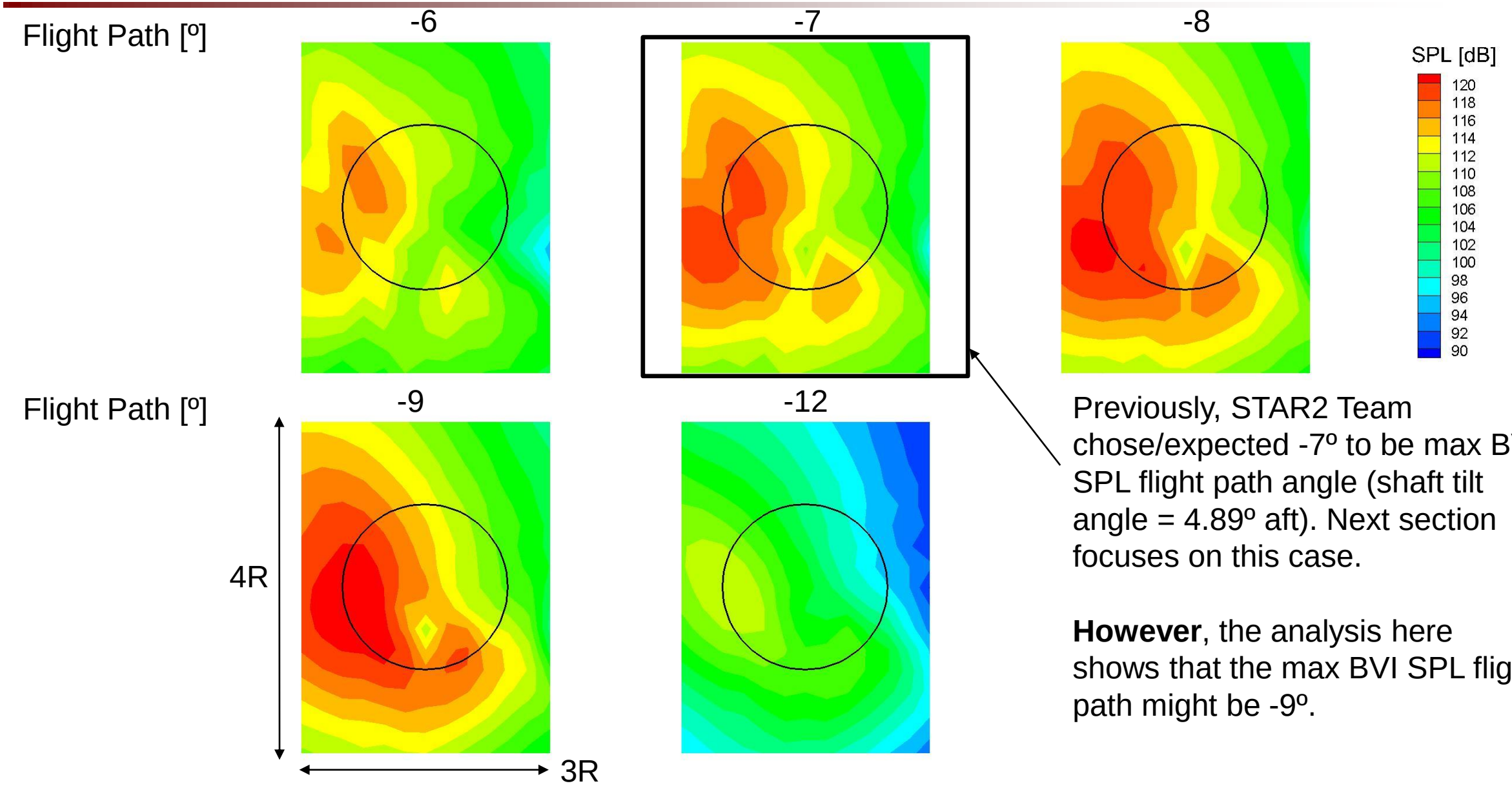
n = harmonic number
f[n] = force harmonic
m[n] = moment harmonic

Mid Frequency Noise on Microphone Plane

Mid Frequency (6 – 40 BPF) Overall Sound Pressure Level (OASPL) (1 of 2)



Mid Frequency (6 – 40 BPF) OASPL (2 of 2)



Previously, STAR2 Team chose/expected -7º to be max BVI SPL flight path angle (shaft tilt angle = 4.89º aft). Next section focuses on this case.

However, the analysis here shows that the max BVI SPL flight path might be -9º.

Descent case
-7º Flight Path (4.89º shaft tilt aft)

2p and 3p at 50%

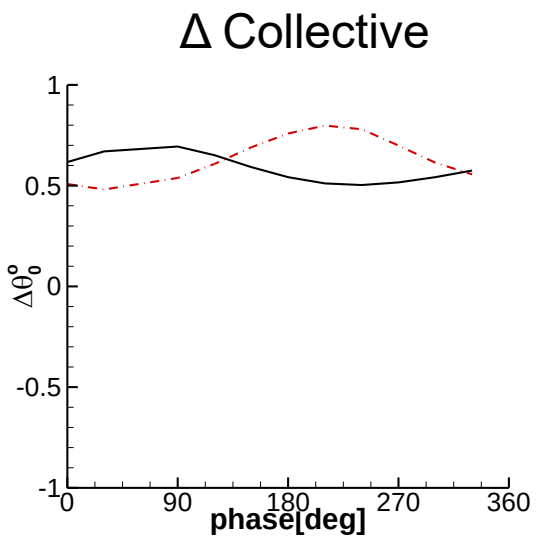
- **Mean 2.08 Nm**
- **Amp 2.70 Nm**

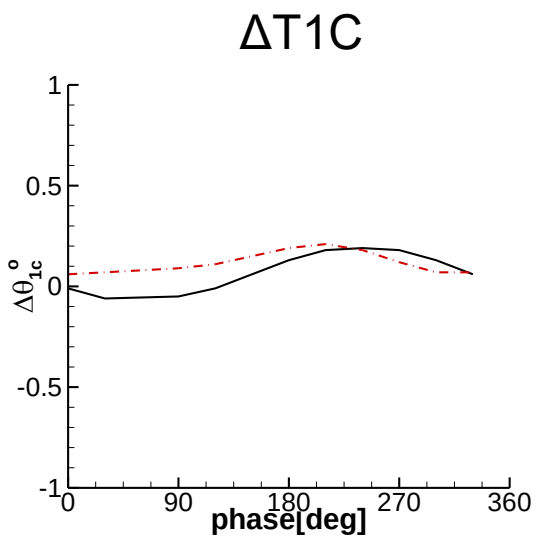
Mostly, only examine the deltas from the BL case.

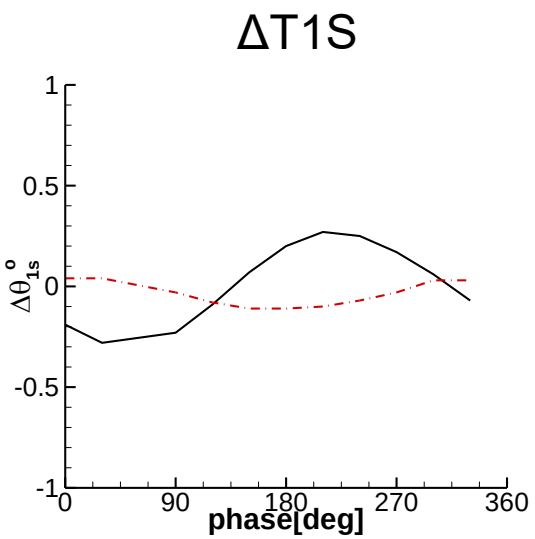
Δ Controls and Δ Power (relative to Baseline)

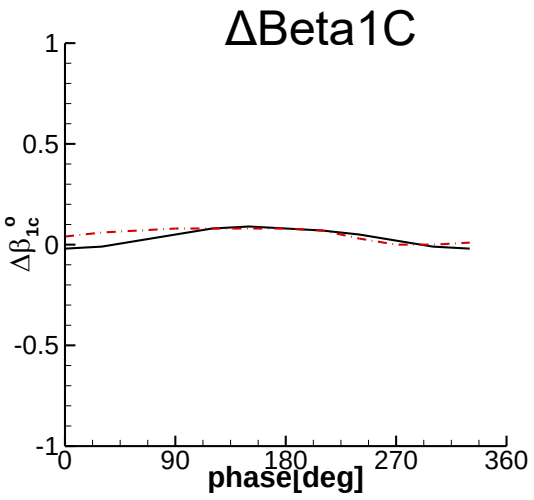
For 2p and 3p
50% Amplitude at various phase angles.

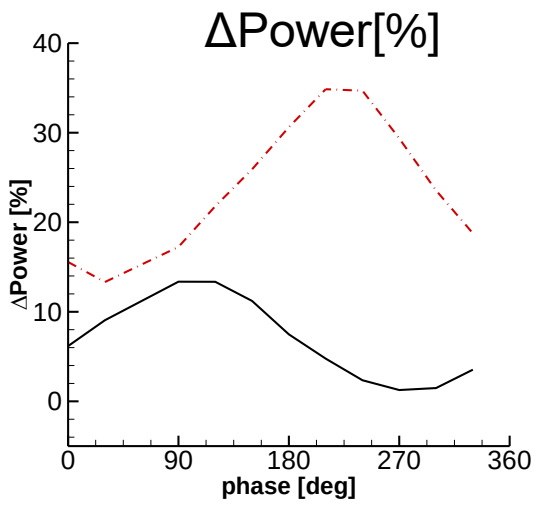
ΔControls, Long. Flap, Power vs. Phase

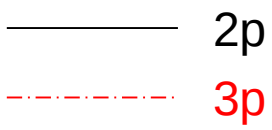








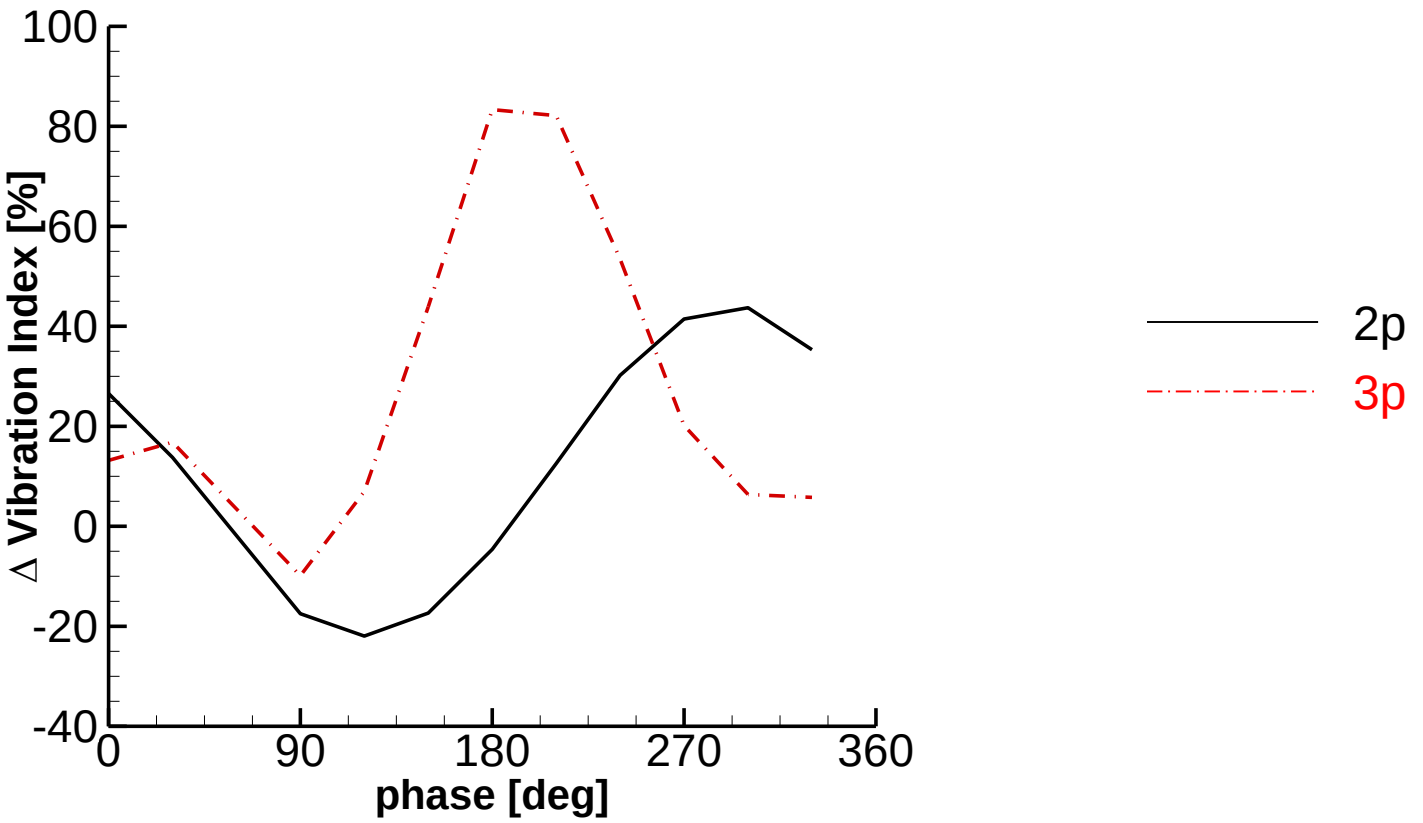




Δ Vibration Index
(% change from baseline)

For 2p and 3p
50% Amplitude

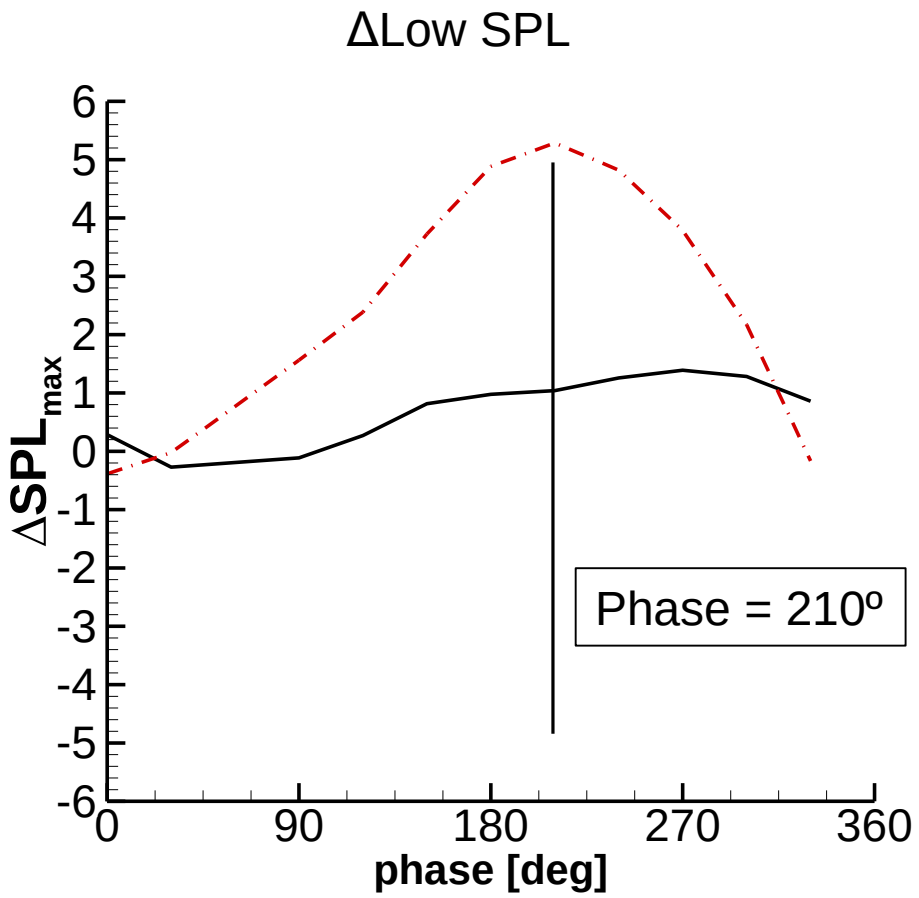
ΔVibration Index

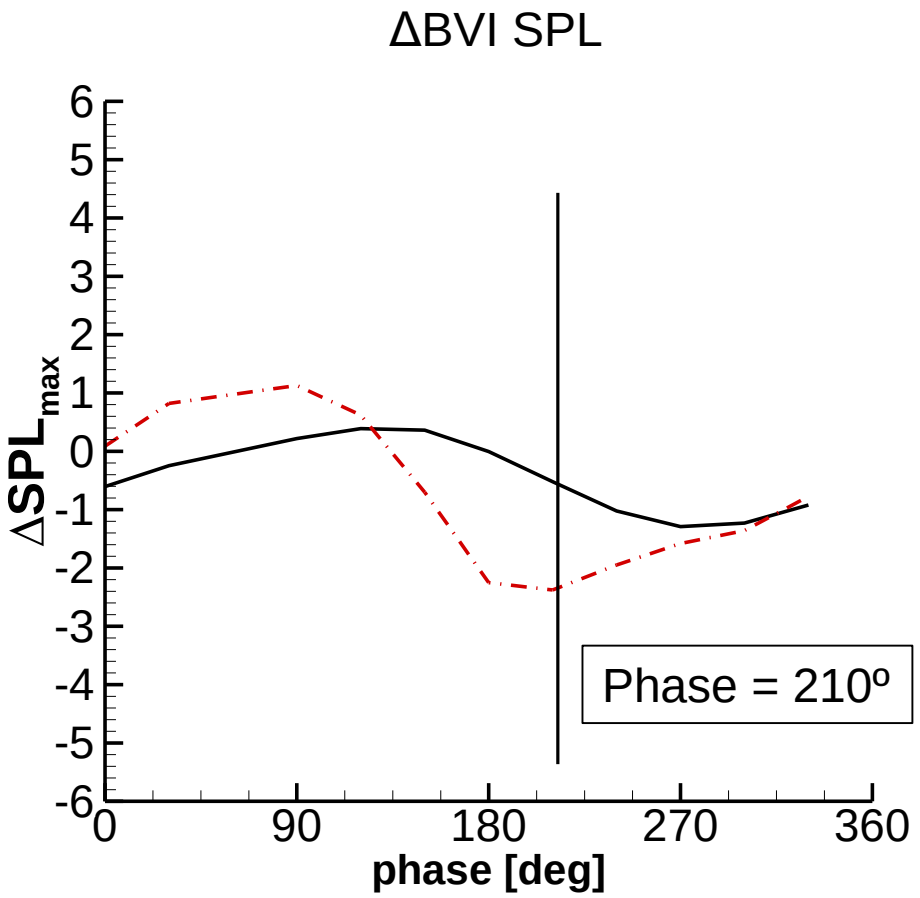


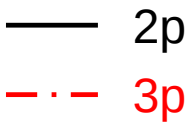
Evaluated 2p and 3p with 50% Amplitude
For Phases from 0º to 330º (steps of 30º).

Searched for Max BVI SPL noise on Plane under rotor and find difference from Baseline.

Δmax SPL







Phase = 210º:

3p: Most BVI SPL reduction; little effect on the low SPL.

2p: Little BVI SPL noise reduction, but large increase in low SPL.

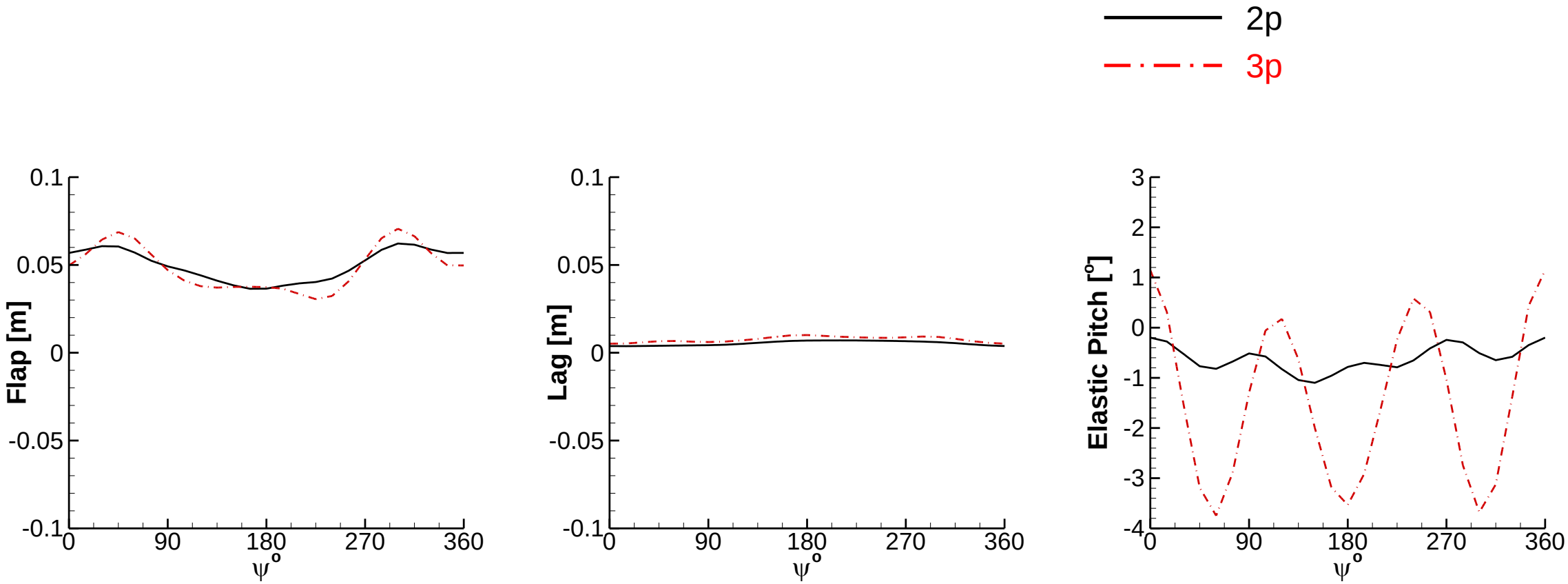
Most effect at reducing max BVI SPL noise:
3p, 50% Amplitude, Phase = 210º

So, focus on 3p and Phase = 210º
(Some plots also show 2p with Phase = 210º for comparison)

Tip Deflections (magnitudes)

For 2p and 3p
50% Amplitude

Tip Deflections for Phase = 210º

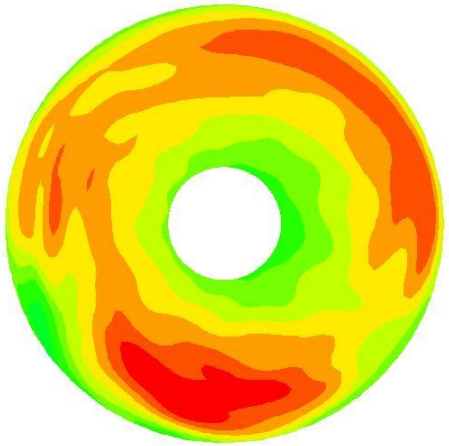


$C_N M^2$ Contours

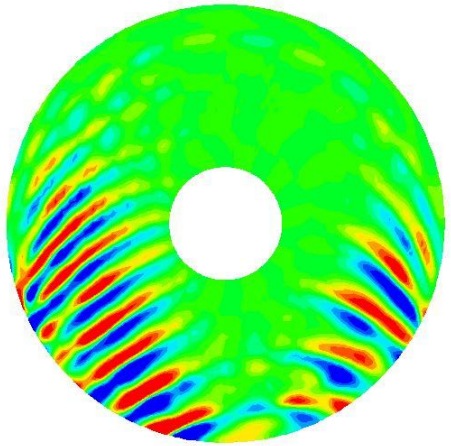
3p, 50% Amplitude, Phase = 210º

Baseline vs 3p with mean + 50% amplitude at phase = 210º

Baseline Low C_NM^2

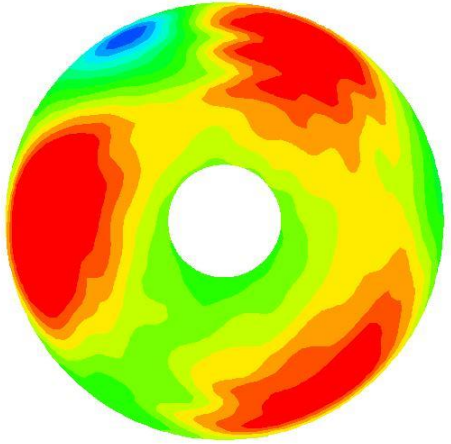


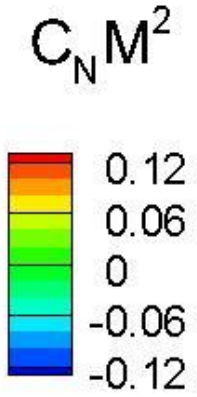
Baseline Mid C_NM^2



V

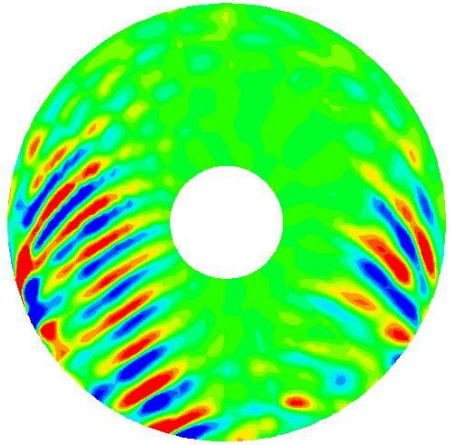
3p Low C_NM^2 phase 210º

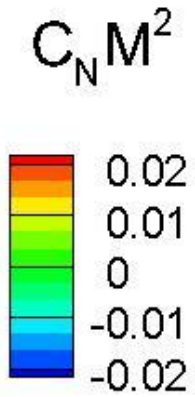




V

3p Mid C_NM^2 phase 210º





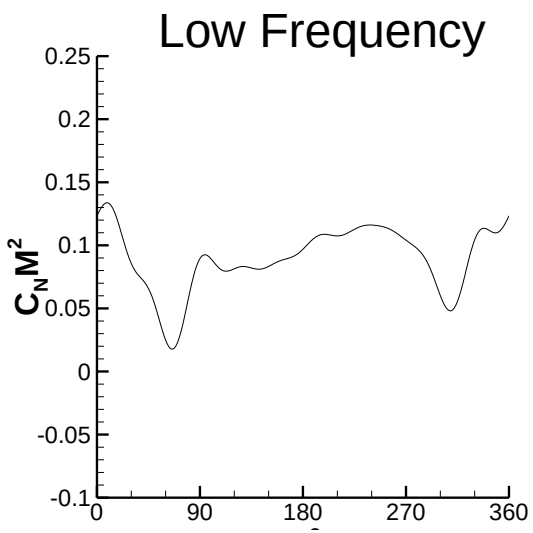
$C_N M^2$ at r/R = 0.875

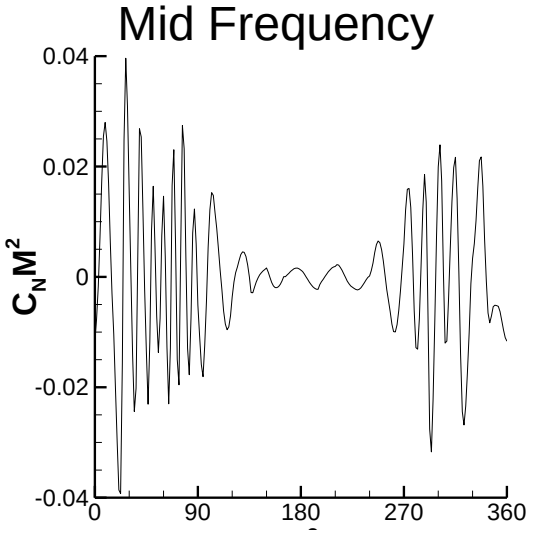
3p, 50% Amplitude, Phase = 210º

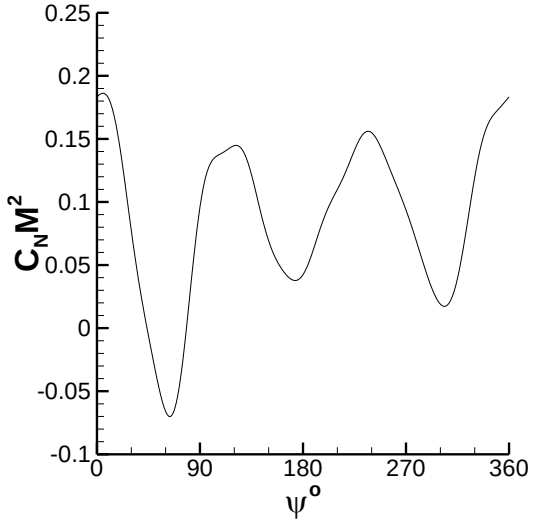
$C_N M^2$ at 0.875R: BL vs 3p with 50% Amplitude, Phase = 210º

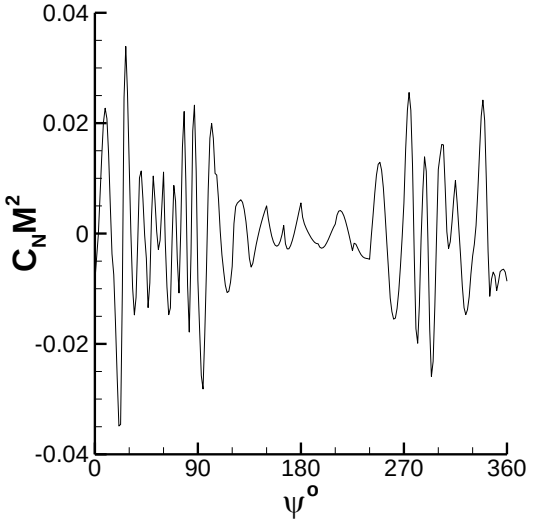
Baseline

3p, Amp 50%
Phase = 210º





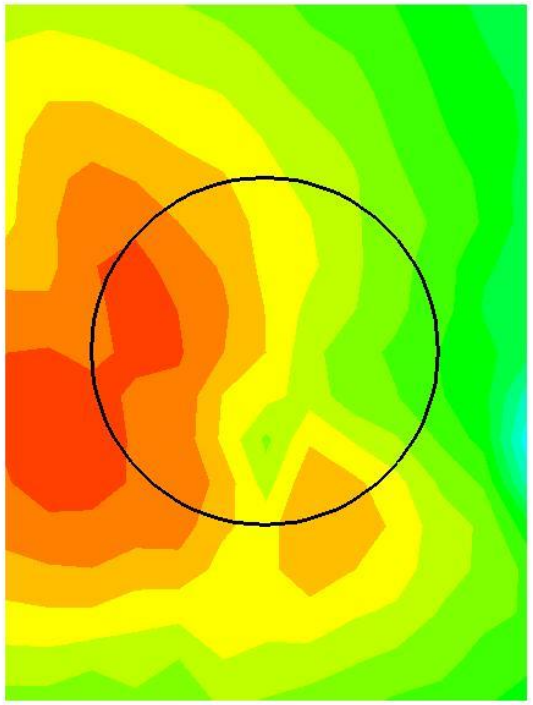




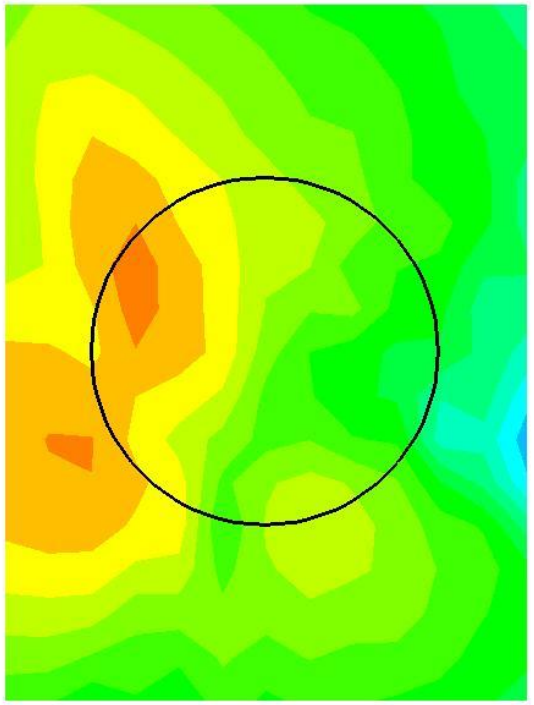
Mid Frequency Noise on Microphone Plane

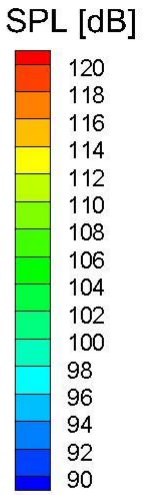
Mid Frequency OASPL: BL vs 3p with 50% amplitude at phase = 210º

Baseline



3p, Amp=50%, phase= 210º





Level Flight μ Sweep

For reference… Flight Condition

Advance ratio	Shaft tilt [º] , positive aft
0.1010	-9.6515
0.1515	-7.2749
0.2020	-5.0520
0.2525	-3.2333
0.3030	-1.8187
0.3409	-0.8083

Trim Strategy

Trim Targets: Thrust = ~3600 [N]

$\beta_{1c} = \beta_{1s} = 0^o$

Note: Resultant $M_x < -71$ [Nm] for all cases

Resultant $M_y < -20$ [Nm] for all cases

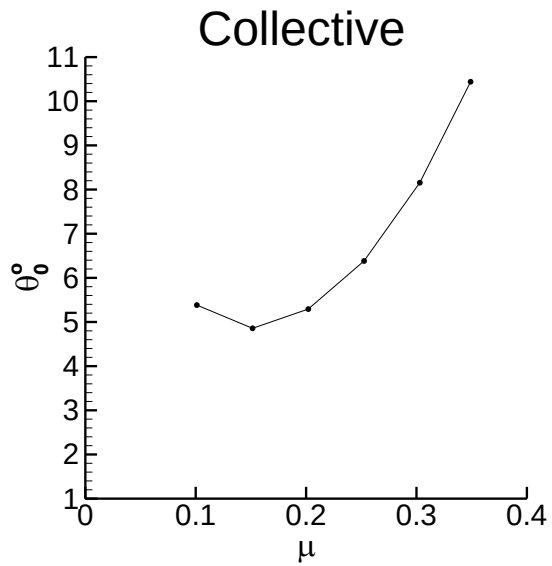
Trim Variables: Collective, Lateral and Longitudinal Cyclic

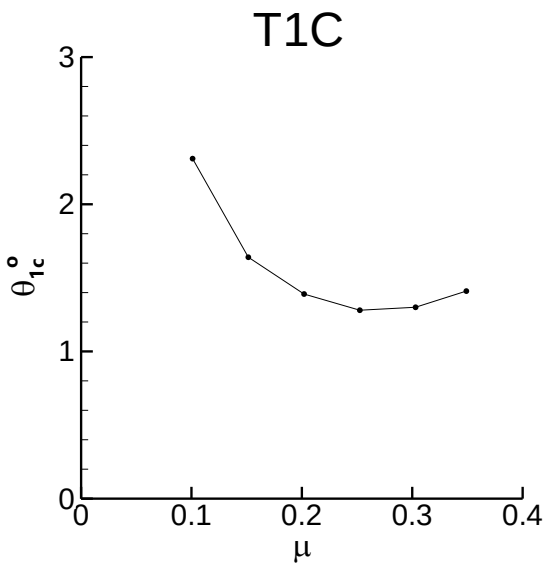
CAMRAD II:

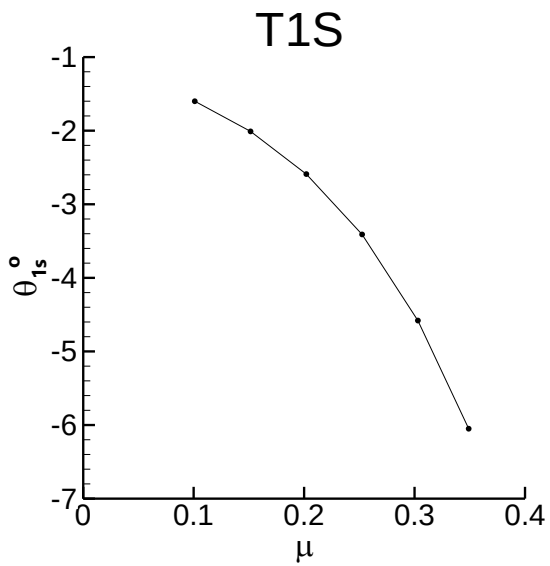
- 23 aerodynamic panels
- Free wake
- Core size = 0.8c [from correlations with HART II BVI SPL]
- Post trim azimuthal resolution = 1.5º

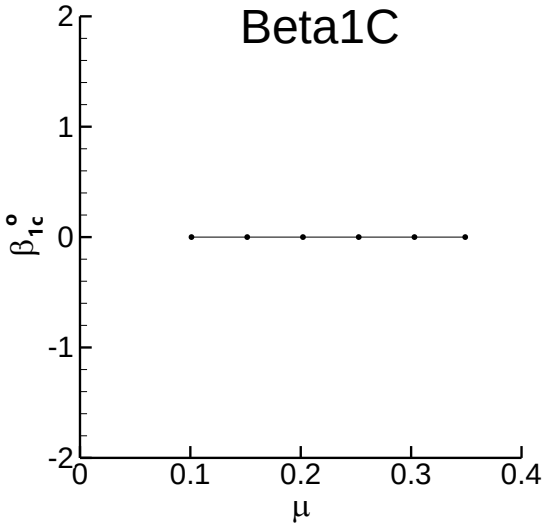
Controls

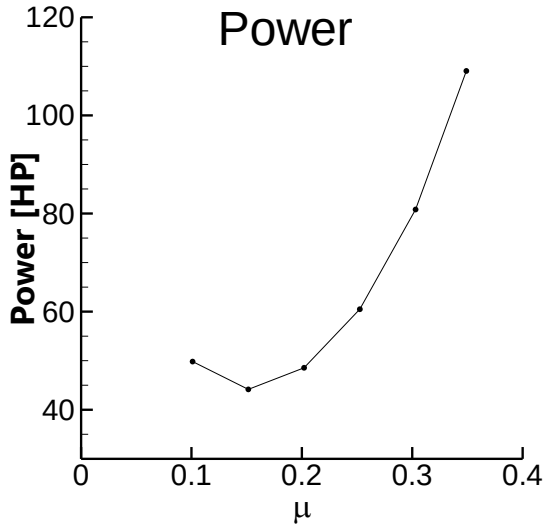
Controls, Long. Flap, Power vs. Advance Ratio











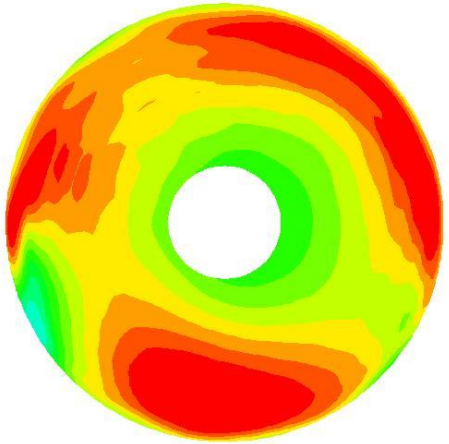
$C_N M^2$ Contours

Low Frequency (0-10 BPF) $C_N M^2$ vs. Advance Ratio

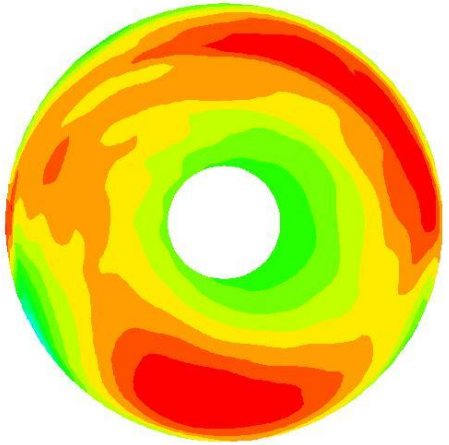
Advance Ratio

V

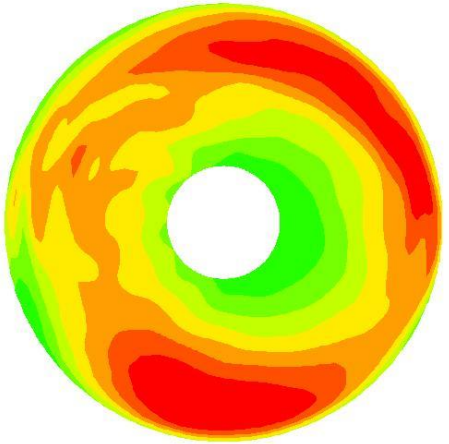
0.1010



0.1515



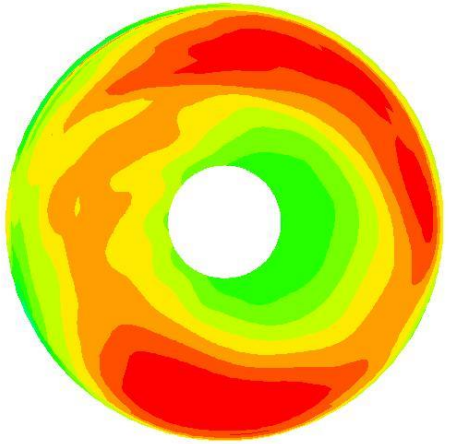
0.2020



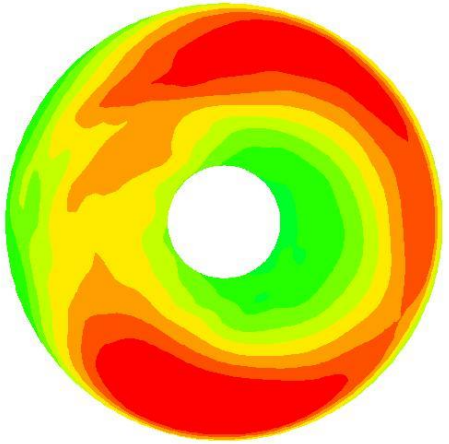
Advance Ratio

V

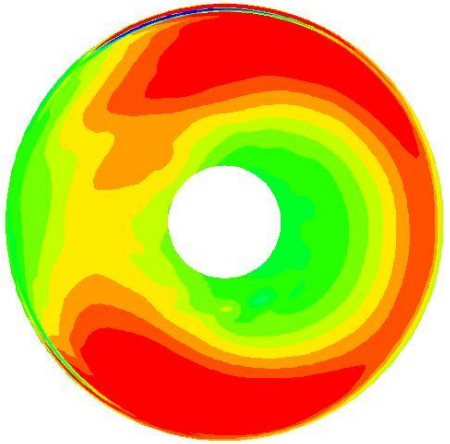
0.2525

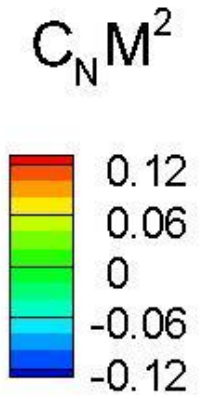


0.3030

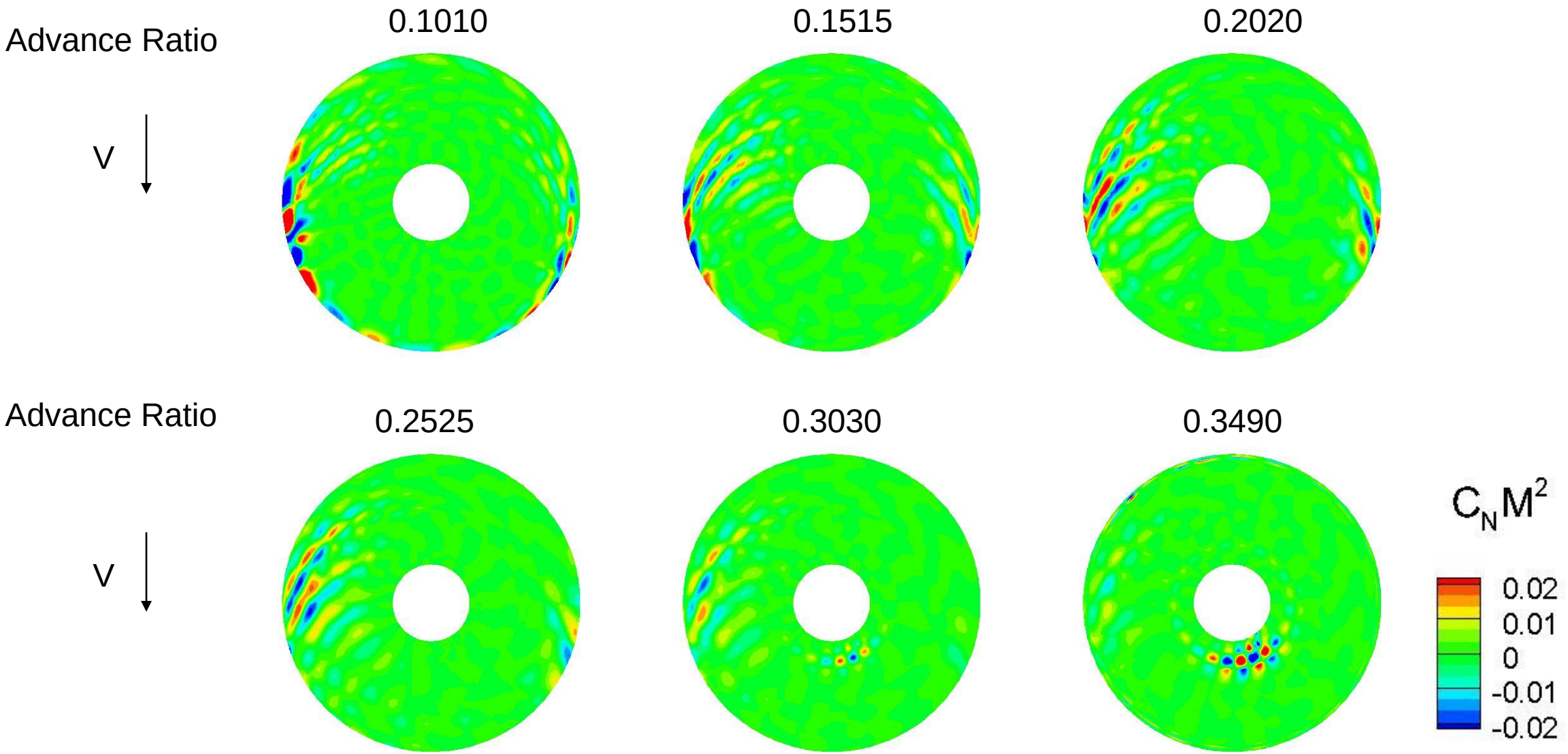


0.3490





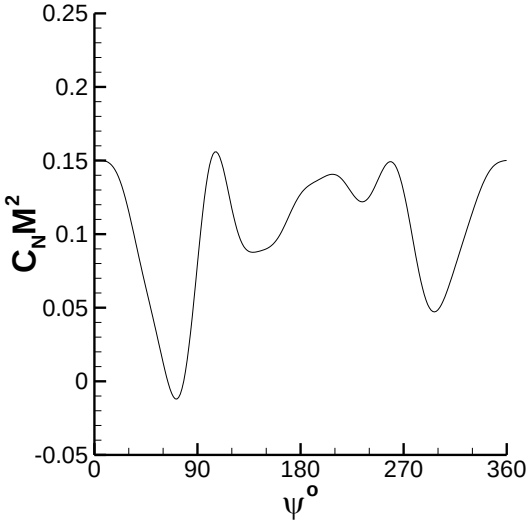
Mid Frequency (> 10 BPF) $C_N M^2$ vs. Advance Ratio



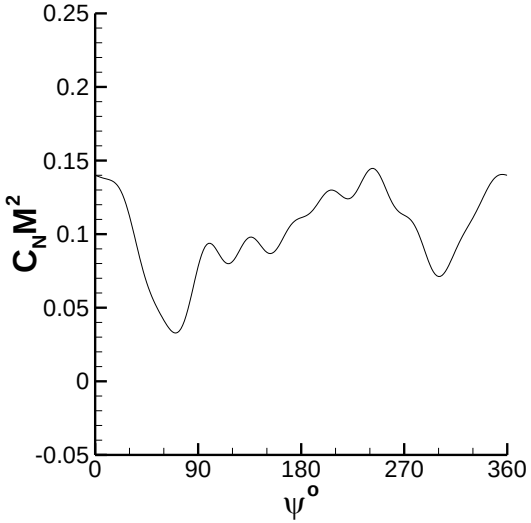
$C_N M^2$ Contours

Low Frequency (0-10 BPF) C_NM^2 at 0.875R

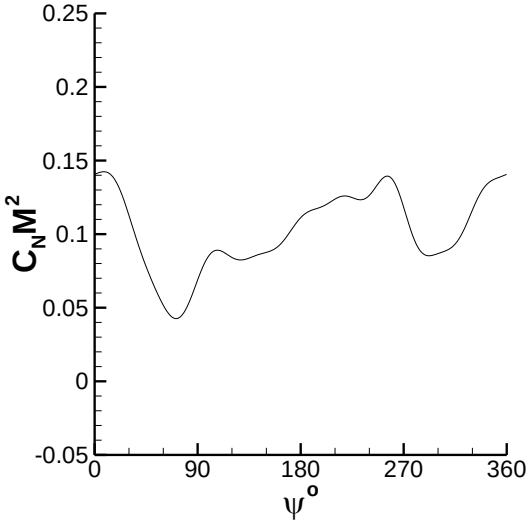
Advance Ratio 0.1010



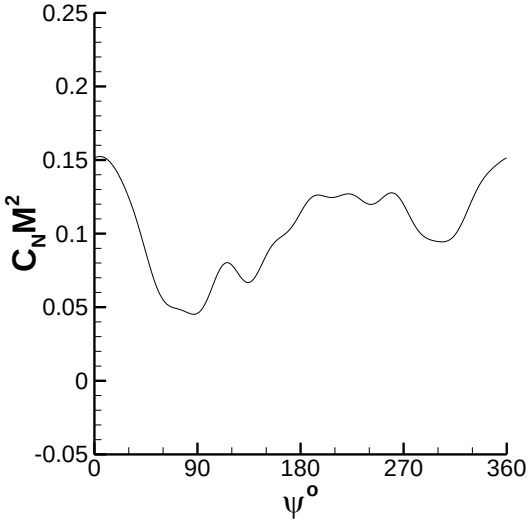
0.1515



0.2020



Advance Ratio 0.2525



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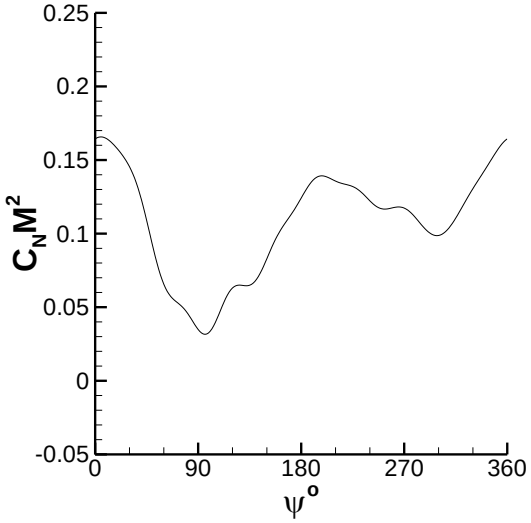

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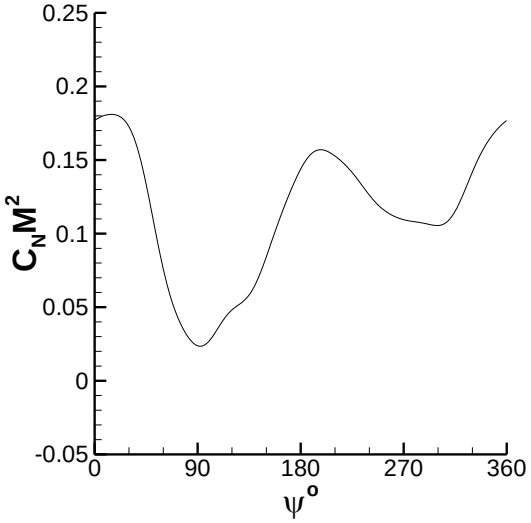
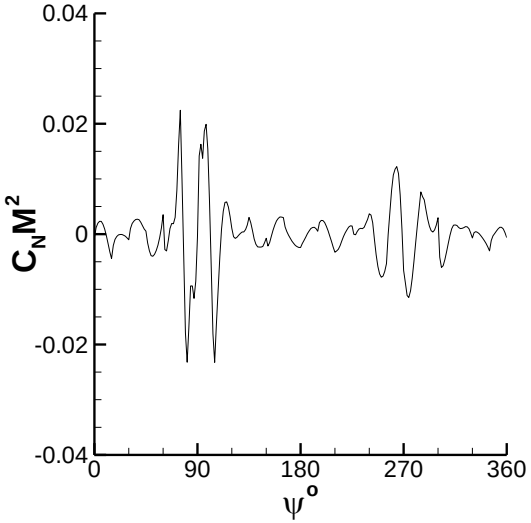


Mid Frequency (> 10 BPF) $C_N M^2$ at 0.875R

Advance Ratio 0.1010



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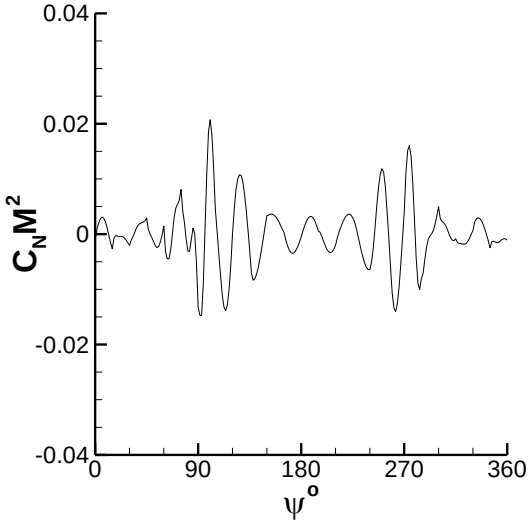

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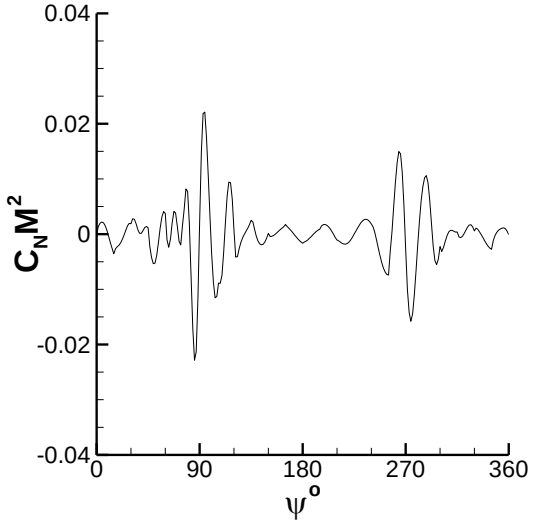
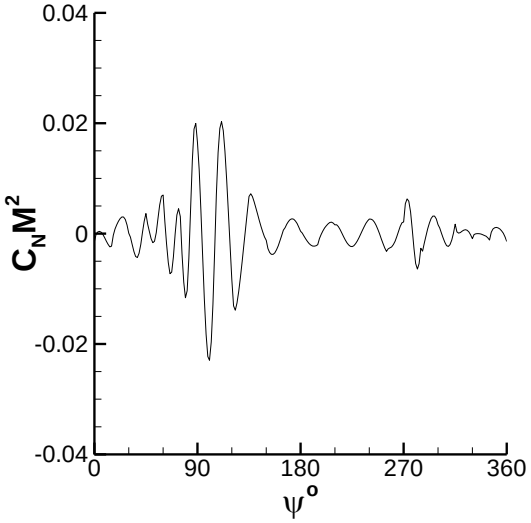


Advance Ratio 0.2525



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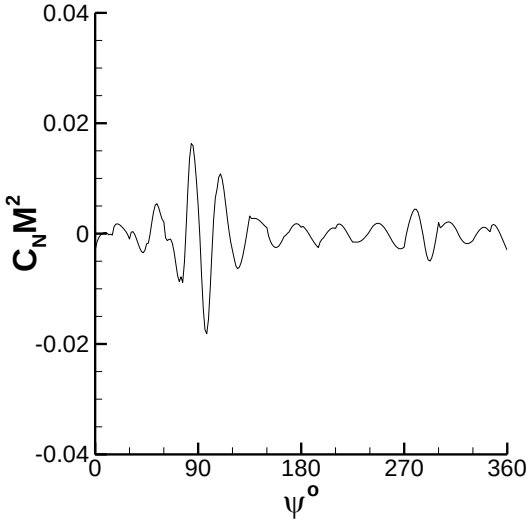

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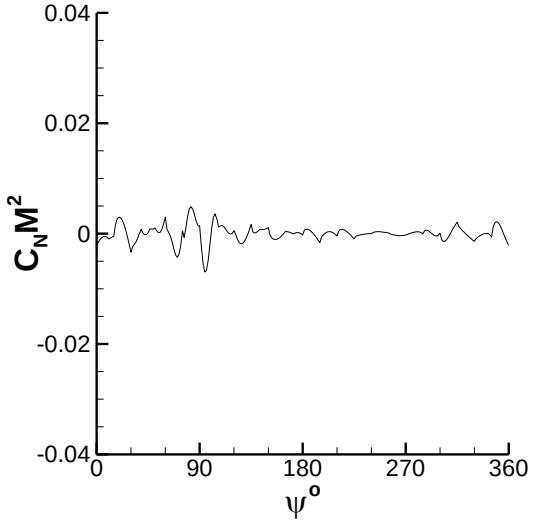
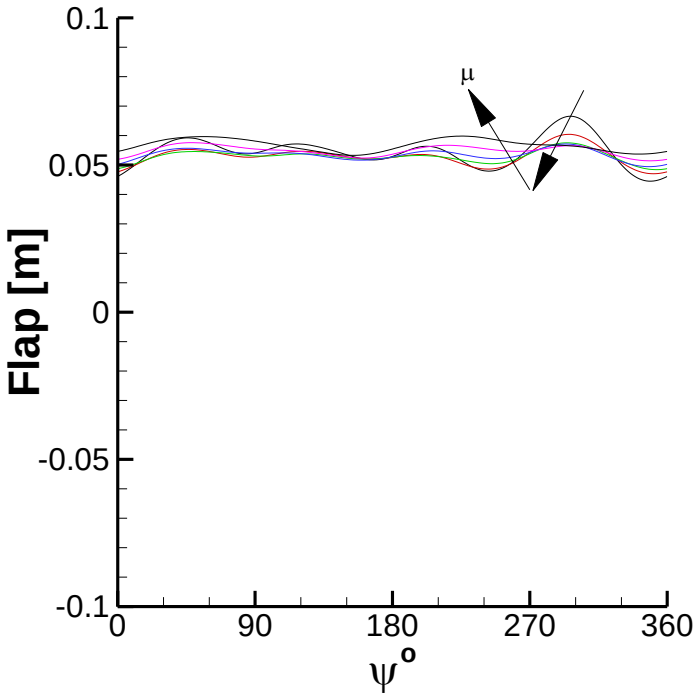
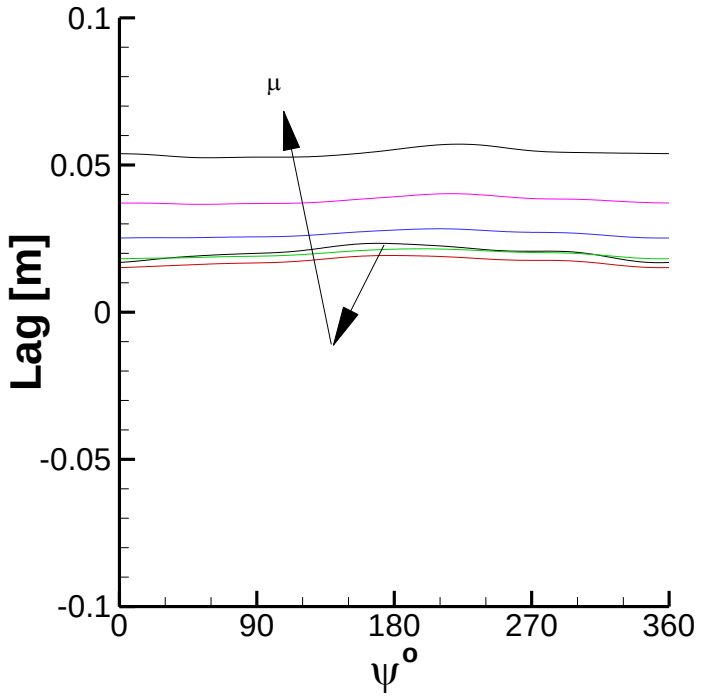
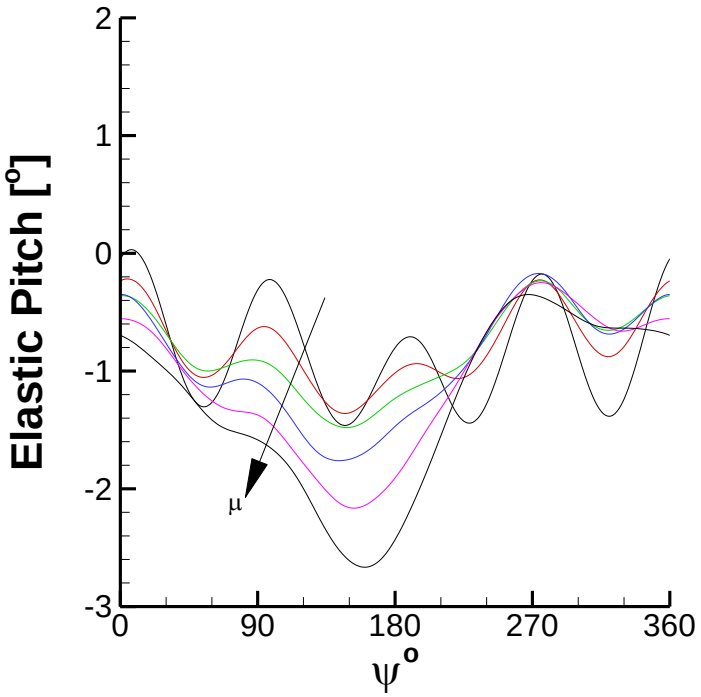


Tip Deflections

Tip Deflections

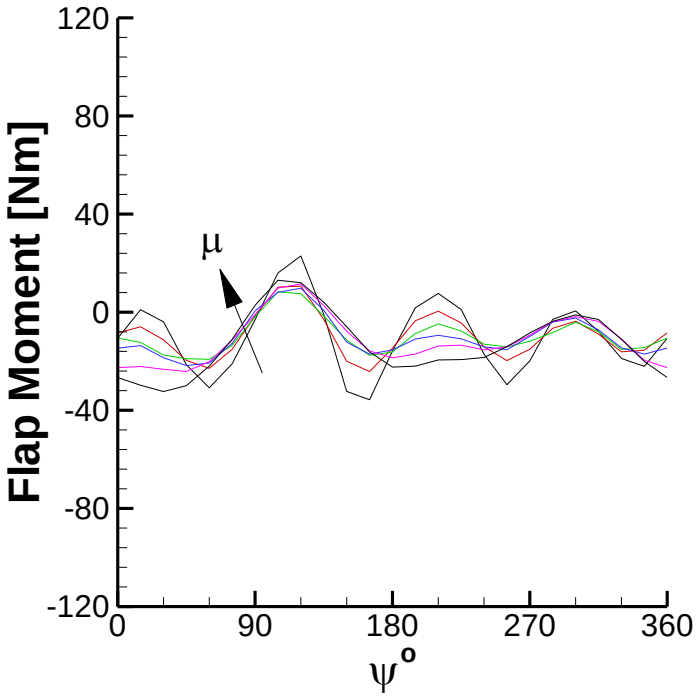


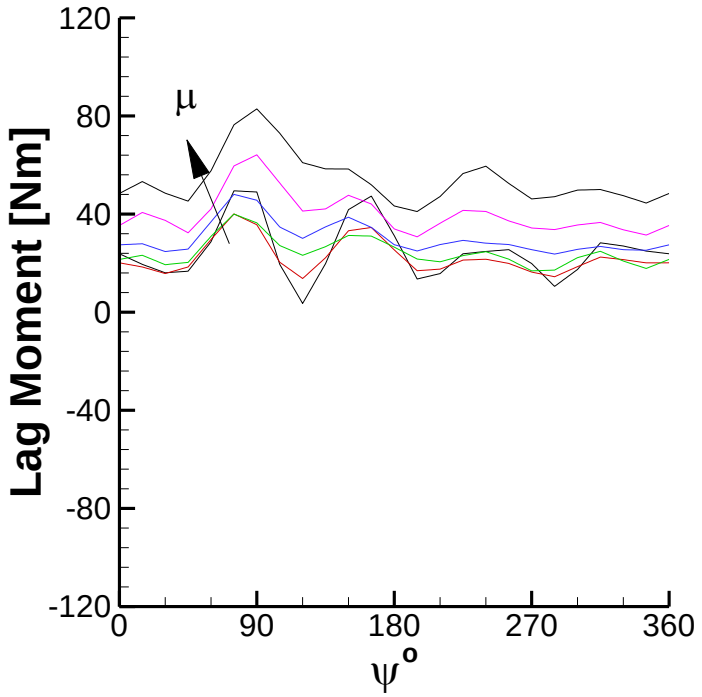


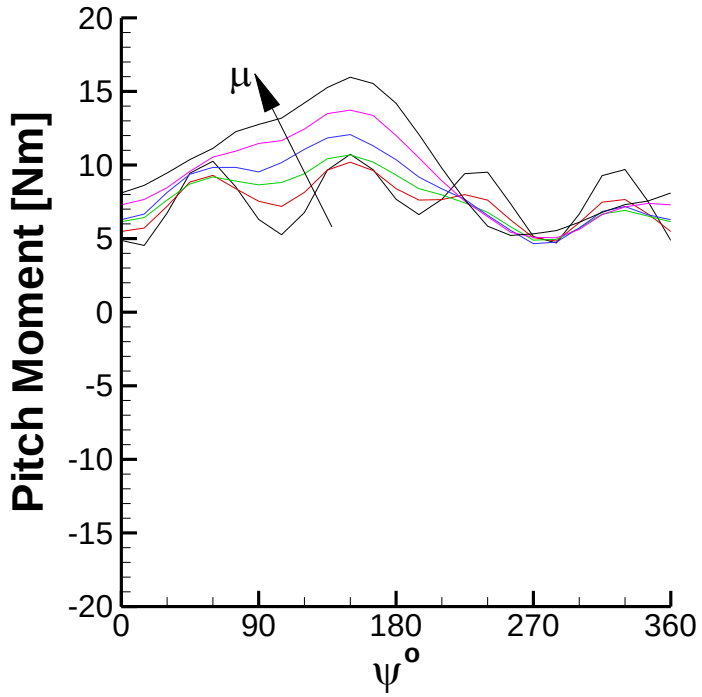


Tip Deflections

Moments at 0.26R



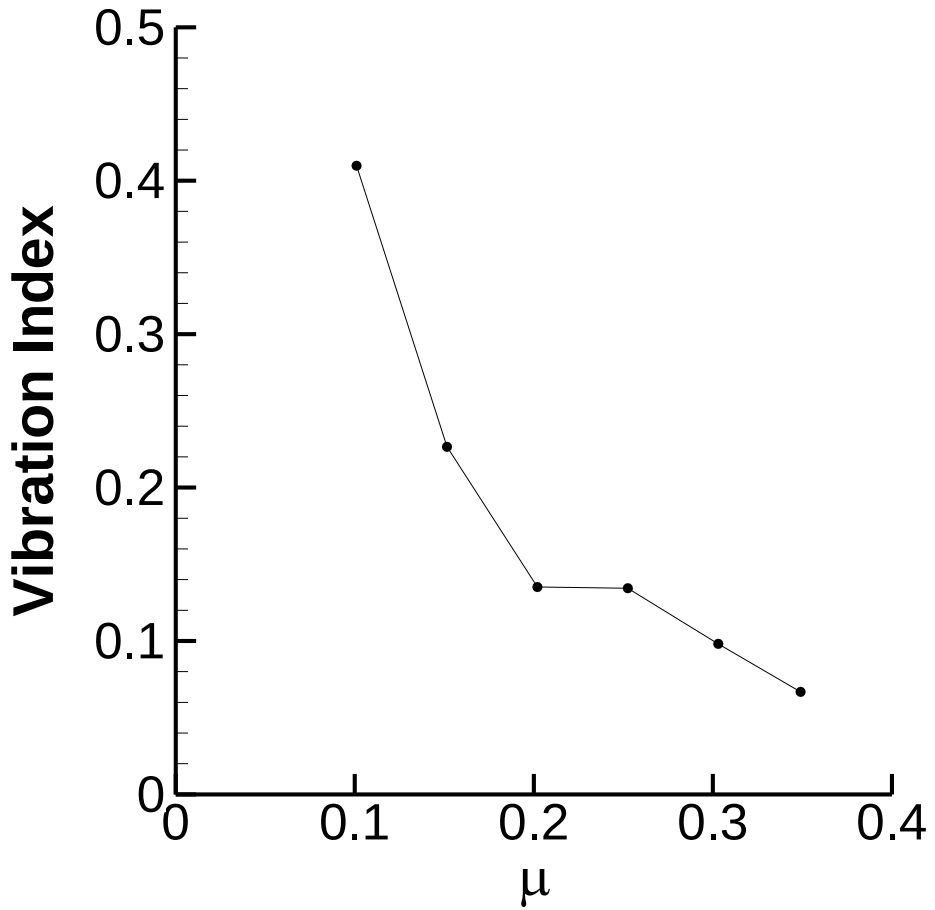




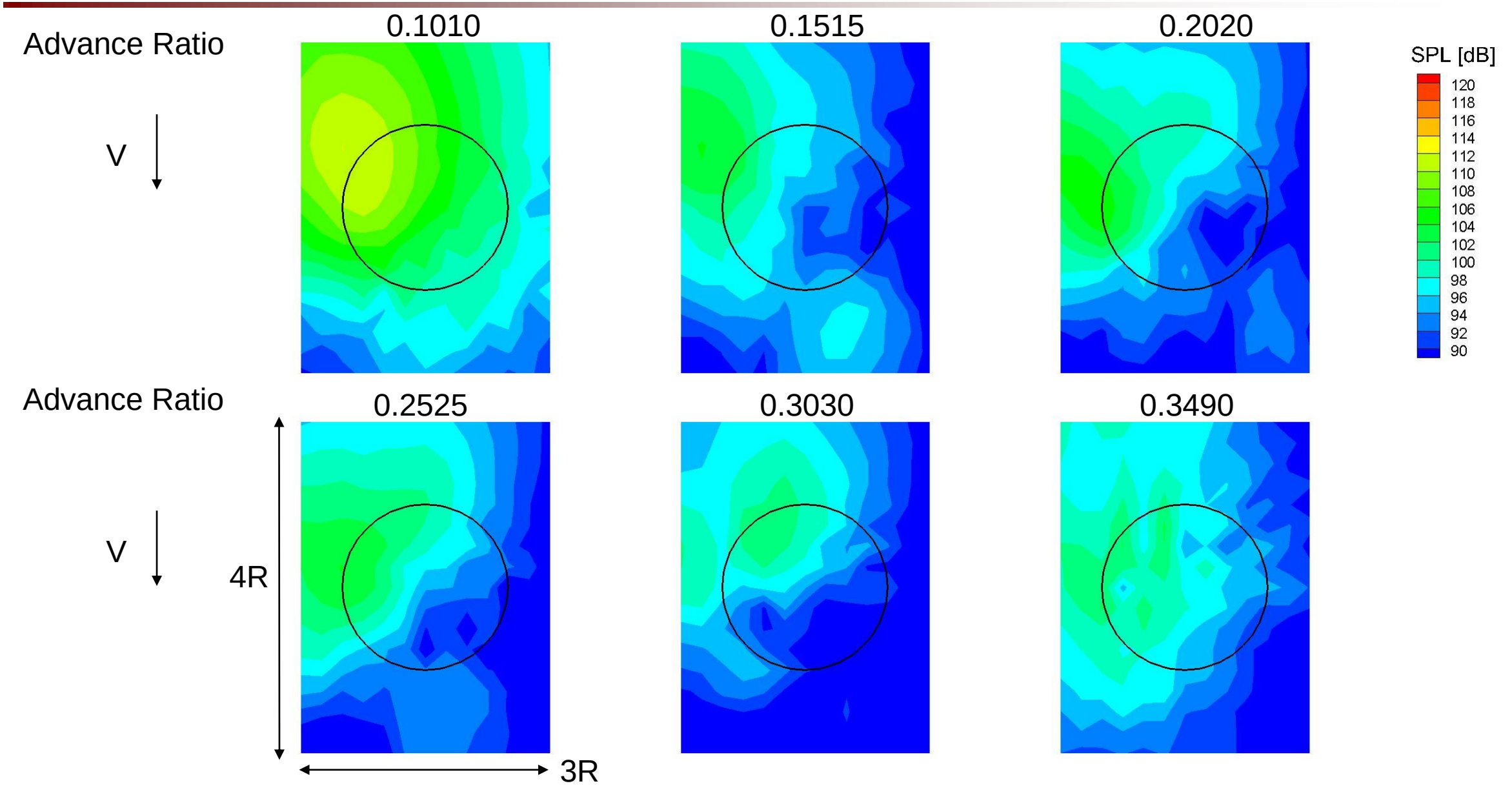
Δ Vibration Index
(% change from baseline)

For 2p and 3p
50% Amplitude

Vibration Index



Mid Frequency OASPL



Observations (1 of 2)

(1) Low Speed Shaft Tilt Sweep

- Lowest BVI SPL noise appears to be at Flight Path Angle = -9º from current analysis.

(2) Descent

- At the -7º Flight Path Angle (chosen previously by STAR2 team):
  - 3p with 50% amplitude at 210º shows:
    - Lowest BVI SPL noise
    - Little effect on the low SPL
    - Highest power increase relative to the baseline
    - Highest increase in Vibration Index relative to the baseline
  - 2p with 50% amplitude:
    - Does not appear effective at noise reduction (BVI SPL or low SPL)
    - Can reduce power at some phase angles
    - Can reduce Vibration Index at other phase angles

Observations (2 of 2)

(3) Level flight μ sweep

- Hard to draw any conclusions.
- Vibration Index appears to reduce with increasing μ
- BVI SPL noise appears to decrease a little with increasing μ

- No active twist has been applied to any of the level flight cases.

Lingering Questions (1 of 2)

(1) Need to settle on a trim strategy.

- Trimming to lift and drag just result in the TPP in the same place, regardless of the shaft tilt.
- Trimming to thrust and zero flapping locates the TPP. Articulated rotor, so the hub moments are still relatively small.

(2) Inconsistent conditions?

- Low speed case: $\gamma = 0^o$, $\mu = 0.1510$ indicates $\alpha_s = -2.120^o$
- Level flight: $\gamma = 0^o$, $\mu = 0.1515$ indicates $\alpha_s = -7.275^o$

(3) Shaft tilt for max BVI SPL?

- HART II: 4.5^o aft
- STAR: 4.5^o aft, essentially based on HART II
- STAR2: Analysis here shows that 6.89^o aft (-9^o flight path)

Lingering Questions (2 of 2)

(4) What level flight speed for application of active twist?

(5) This presentation has covered just 2 flight regimes covering only 3 of the test plan categories.

- This is too much to track during a short presentation.
- Essentially, this has been an exercise in setting up and running cases… this generates a huge number of plots, BUT:
- The STAR2 Team needs to decide what on items specifically to focus.