FIFTH INTERNATIONAL WORKSHOP
COMPUTATIONAL EXPERIMENT IN AEROACOUSTICS
CEAA
September 19-22, 2018, Svetlogorsk, Russia

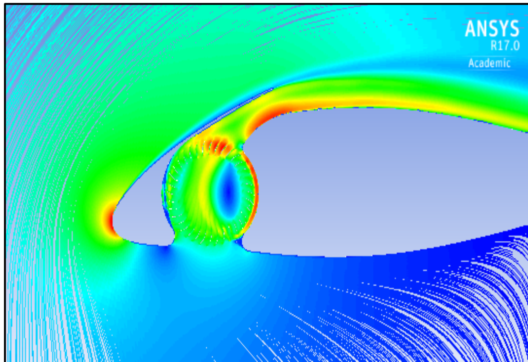
A Peculiar Case of Fan-Wing Acoustics

Vladimir Golubev, Stanislav Karpuk, Marina Kazarina, Florent Colomb

Department of Aerospace Engineering

Embry-Riddle Aeronautical University

Daytona Beach, FL, USA



Outline

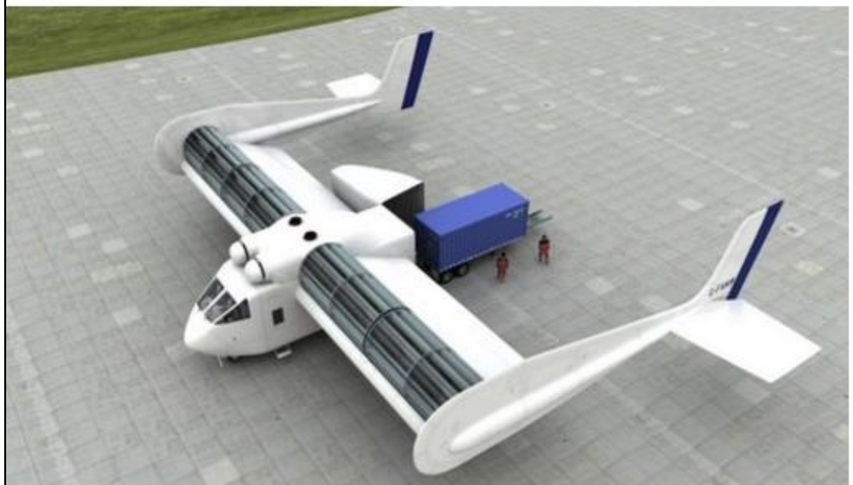
- **Motivation: Preliminary Feasibility Analysis Of A Multi-purpose Fan-Wing Aircraft Concept**
  - Competition analysis
  - Mission/ Requirements and constraints
  - Baseline aircraft conceptual design
  - Aerodynamic analysis of a fan-wing airfoil
- **Fan-Wing Acoustic Radiation Analysis**
  - Selection of numerical model for fan-wing airfoil acoustic analysis
  - Results for baseline, fan-off and fan-on cases
- **Conclusions**

Outline

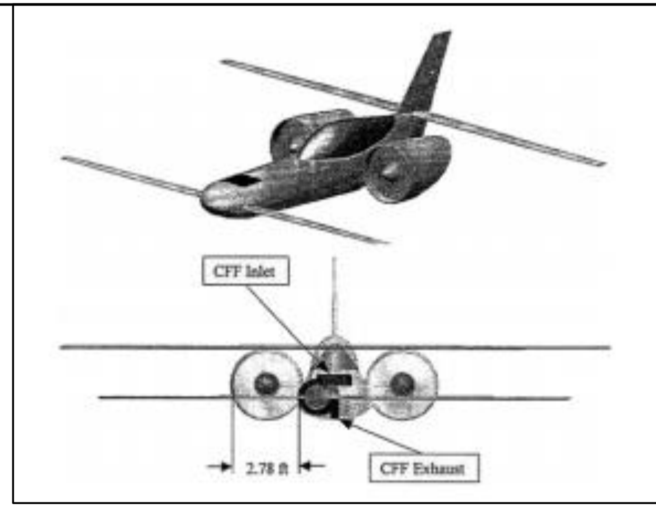
- **Motivation: Preliminary Feasibility Analysis Of A Multi-purpose Fan-Wing Aircraft Concept**
  - Competition analysis
  - Mission/ Requirements and constraints
  - Baseline aircraft conceptual design
  - Aerodynamic analysis of a fan-wing airfoil
- **Fan-Wing Acoustic Radiation Analysis**
  - Selection of numerical model for fan-wing airfoil acoustic analysis
  - Results for baseline, fan-off and fan-on cases
- **Conclusions**

Karpuk, S., Kazarin, P.S., Gudmundsson, S., Golubev, V.V., (2018) “Preliminary Feasibility Study of a Multi-Purpose Aircraft Concept with a Leading-Edge Embedded Cross-Flow Fan,” *AIAA Paper 2018-1744*, AIAA Aerospace Sciences Meeting, 8-12 January, 2018, Kissimmee, FL.

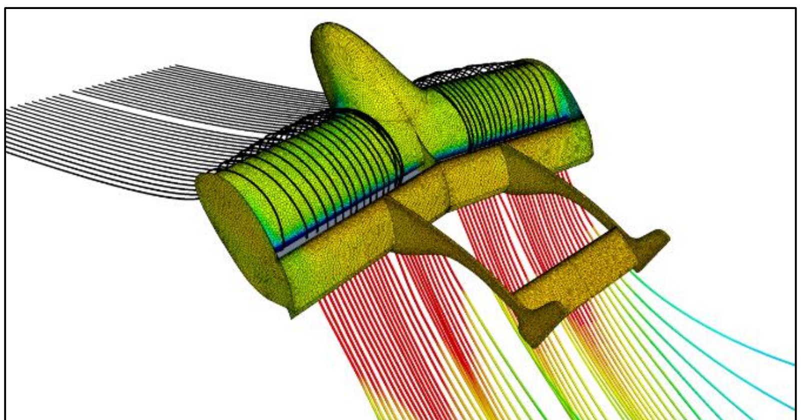
Existing aircraft concepts featuring *cross-flow fan* (CFF) as a propulsion device



Fan-Wing transport concept rendering (Peebles)



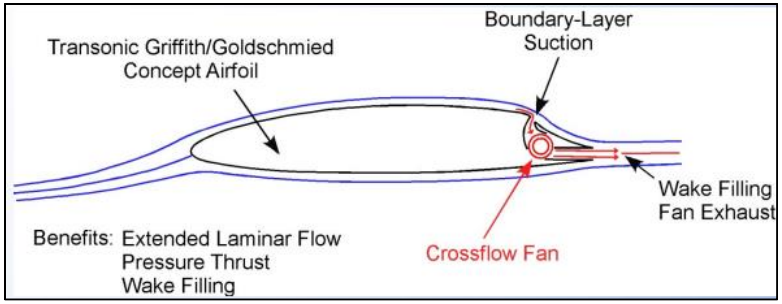
VTOL Fan-Wing Aircraft Concept (Gossett)



Propulsive Wing Concept (Kummer, Dang)

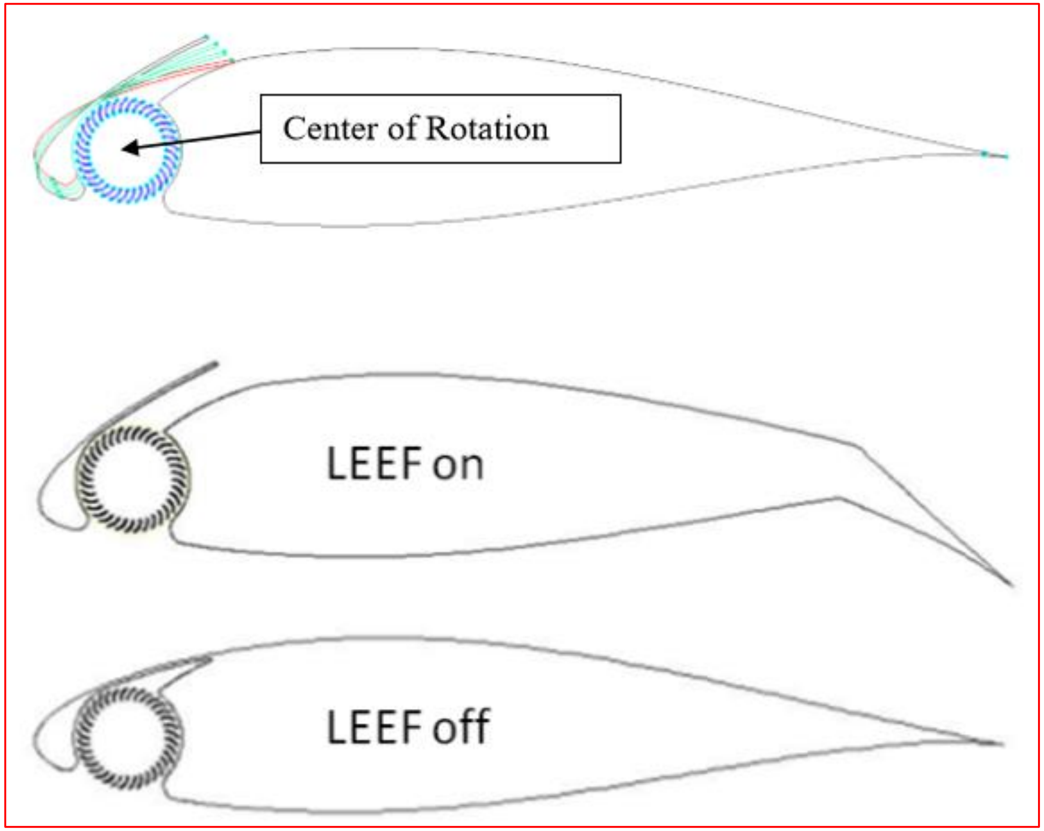
https://www.youtube.com/watch?v=QlXNEefLXz8

CFF as an Active Circulation Control Device for ESTOL Aircraft



CFF as a laminar flow device (Kramer et al.)

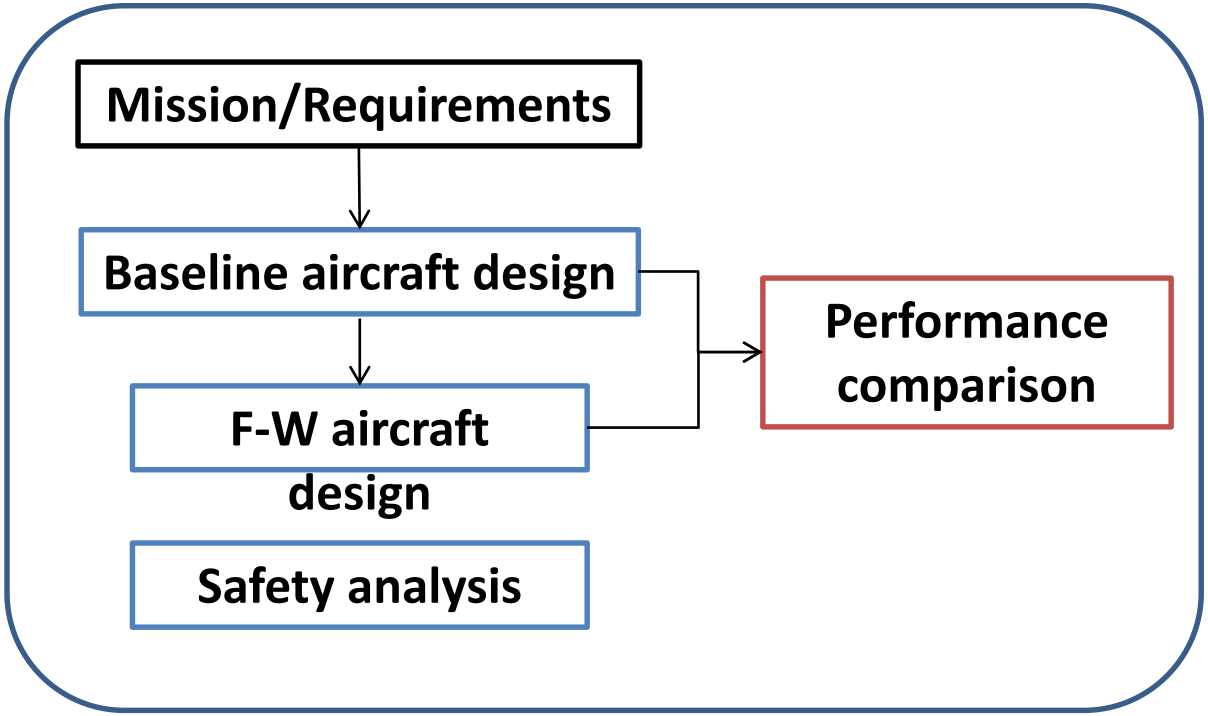
The Bauhaus Luftfahrt regional jet concept (Goland et al.)



CFF as high-lift device reduced the ground roll of a PA-18 by 4 times (Phan)

Fan-Wing Aircraft Design Study Objectives

To perform a feasibility analysis of F-W as a high-lift device for a multi-purpose ESTOL aircraft



Competition Analysis

	Gross Weight (lb)	Payload Weight (lb)	Empty weight (lb)	Max Cruise speed (KTAS)	Rate-of-Climb (fpm)	Power loading (lb/hp)	Wing loading (lb/ft^2)	Max Power (SHP)
IAI Arava	15000	4080	8816	176	1290	10.00	31.90	1500
CASA-212	16975	4080	8333	200	1630	9.43	38.49	1850
DHC-6 Twin-Otter	12500	3230	6881	170	1600	8.33	29.76	1500
Dornier Do-228	14550	3230	8243	223	1870	10.17	42.30	1552
Evector Ev-55	10141	1530	5860	220	-	9.39	39.77	1070
Harbin Y-12	11684	2890	6621	177	1595	9.42	31.67	1240
Average	**14142**	**3502**	**7779**	**189.2**	**1597**	**9.47**	**35.65**	**1452**


Evektor EV-55


IAI Arava

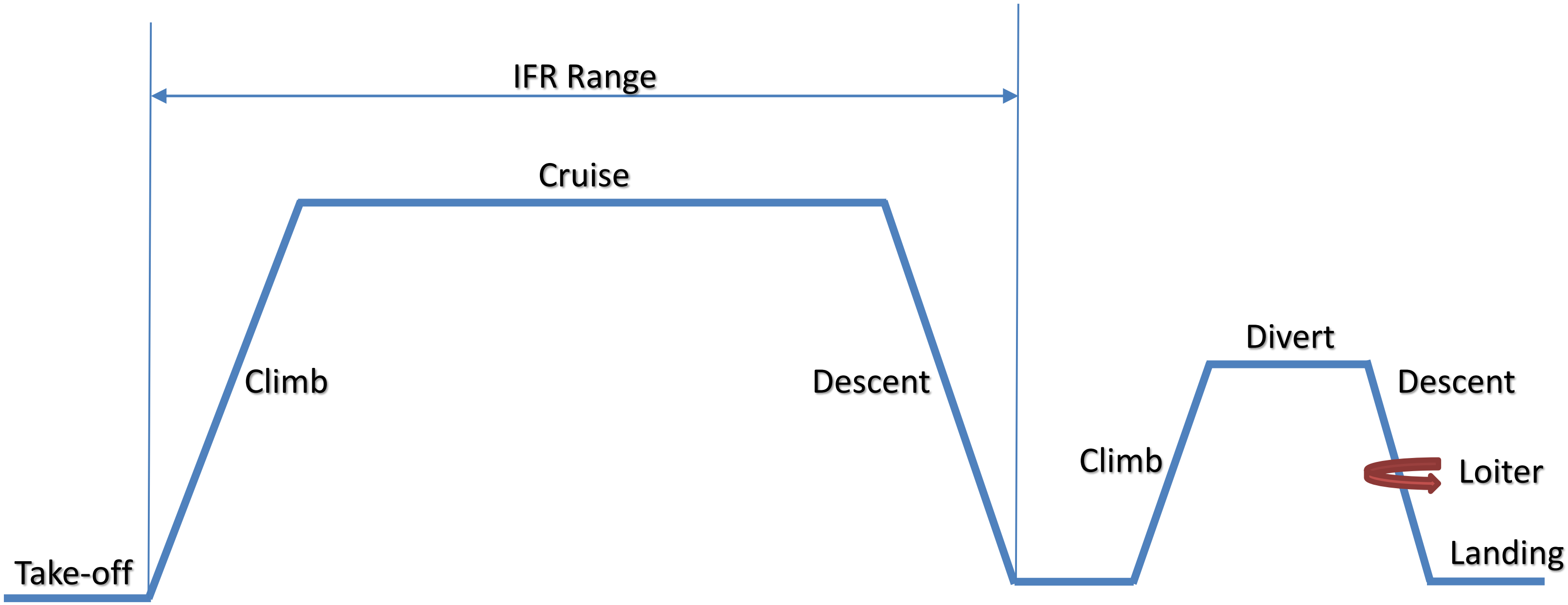

Dornier Do-228


CASA-212


Harbin Y-12

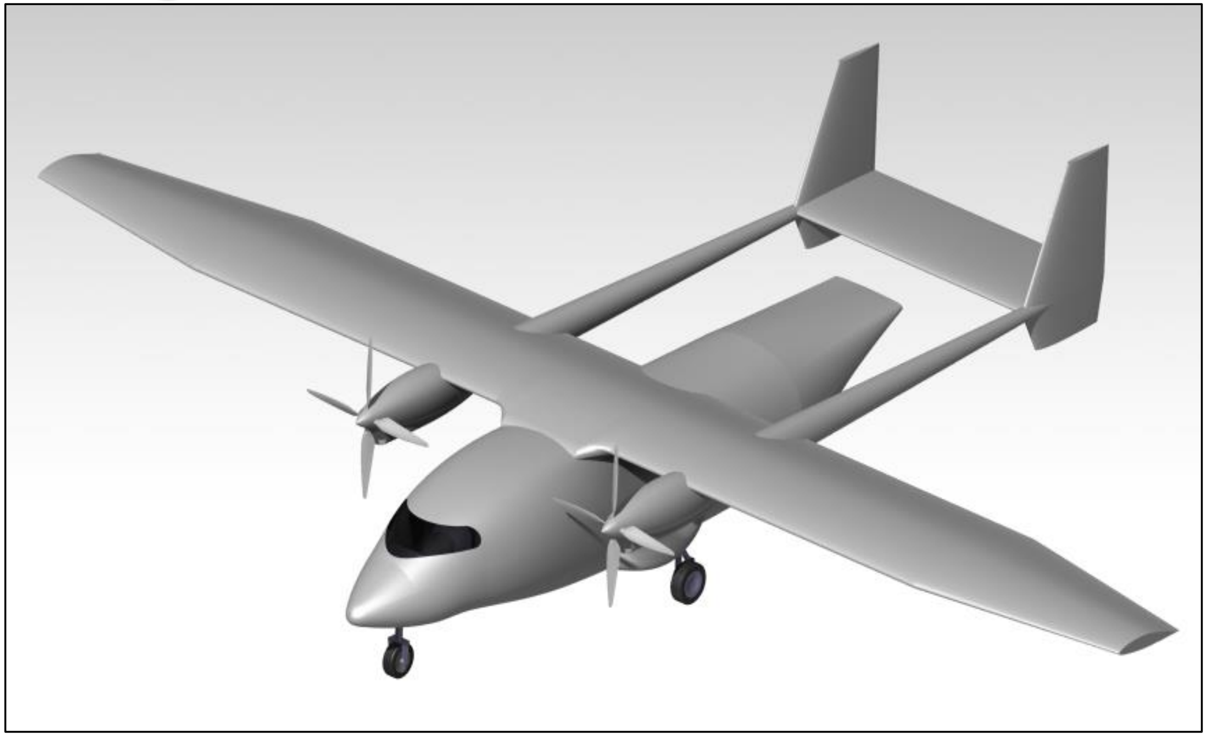

DHC-6 Twin-otter

Mission definition



Payload (lb)	4200
Rate-of Climb (fpm)	≥1600
Maximum Cruise speed (KTAS)	≥200
Mission profile	VFR and IFR

Concepts Competition: Final ESTOL baseline configuration



Description	Value
Length (ft)	42.55
Height (ft)	14.25
Span (ft)	66
AR	10.00
Root Chord (ft)	7.20
Taper Ratio	0.50
Incidence (deg)	3.00
LE Sweep (deg)	0.00

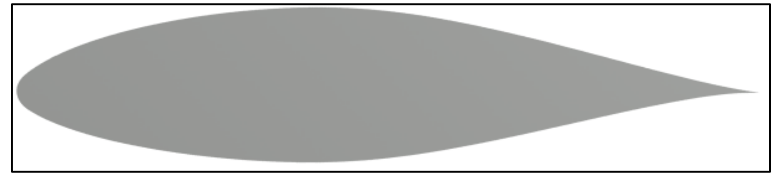
Features:

- Twin-boom configuration to have a large aft door
- Semi-tapered wing based on the research analysis of F-W

Baseline Aerodynamics: Airfoil selection

Airfoil selection criteria

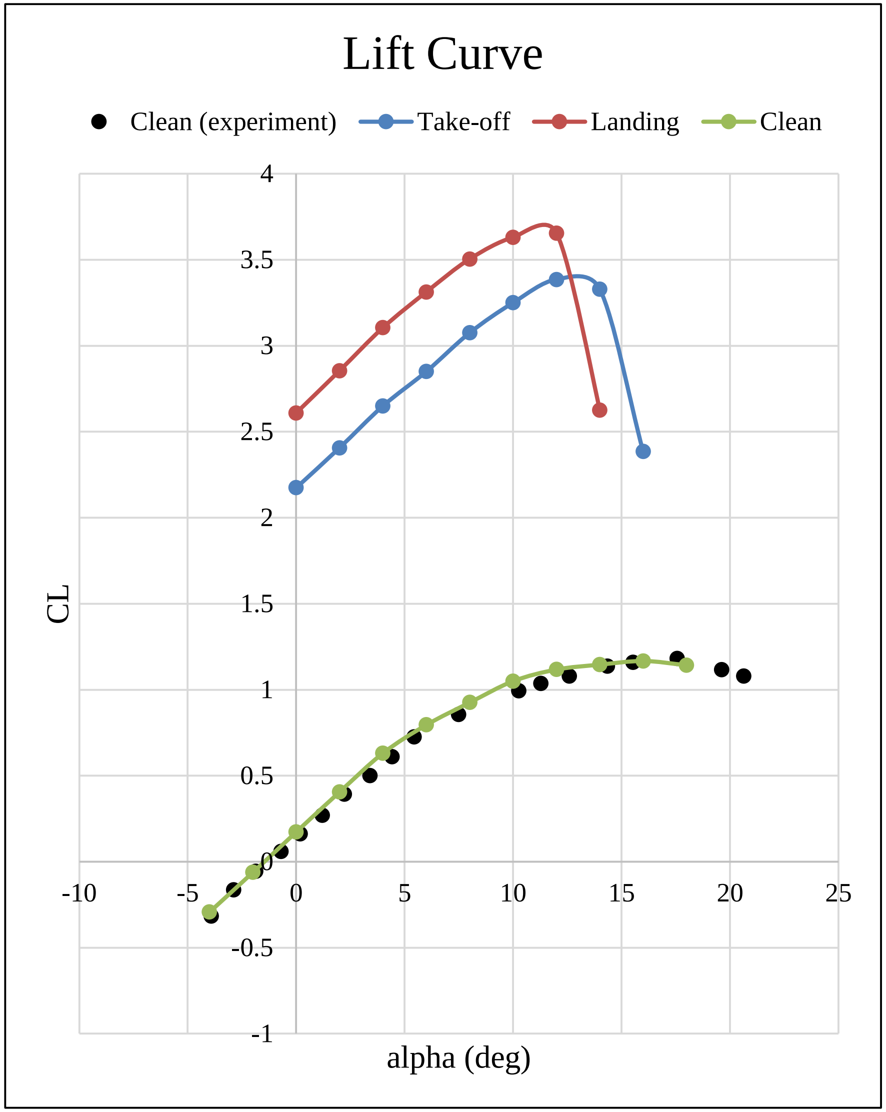
- Large thickness to embed CFF
- NLF airfoil
- Cruise, climb, high AOA airfoil performance

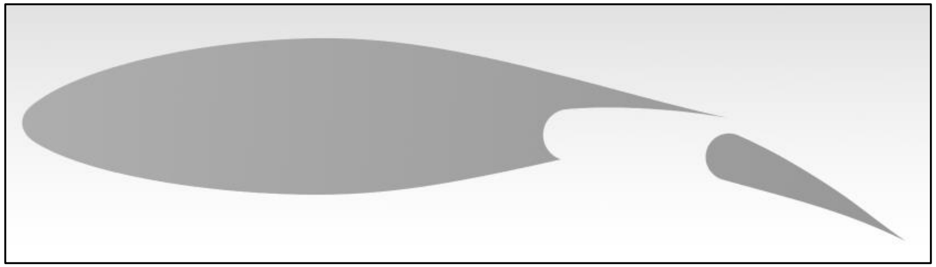


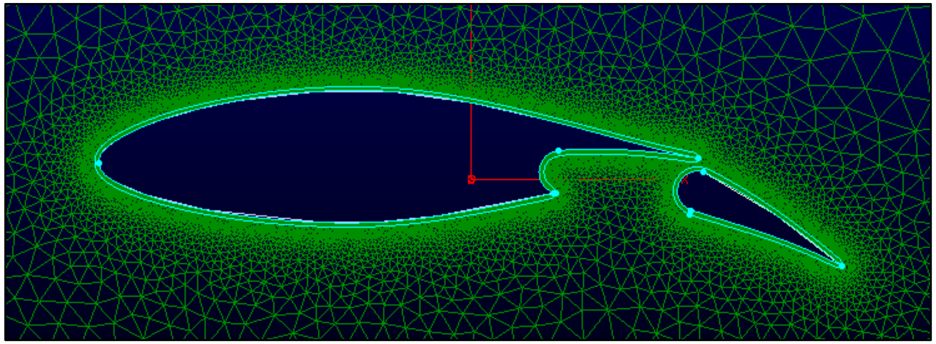
NACA 65221

	Characteristics			Score		
Parameters\Airfoil	**NACA63(4)-221**	**NACA65(4)-221**	**NACA66(4)-221**	**NACA63(4)-221**	**NACA65(4)-221**	**NACA66(4)-221**
thickness (%)	21	21	21			
Cl0	0.16	0.16	0.15	1	1	
AOA for Cl=0	-1.5	-1.6	-1		1	
Clmax	1.45	1.48	1.5			1
AOA for Clmax	18	20	19		1	
Cdmin	0.0053	0.0045	0.0037			1
Cl at Cdmin	0.2	0.28	0.2	1		1
(Cl/Cd)max	116.7	100	125			1
Cl of (Cl/Cd) max	0.7	0.6	0.5			1
cruise Cm	-0.05	-0.025	-0.026		1	
drag bucket start at Cl	-0.2	-0.2	-0.1			
drag bucket end at Cl	0.6	0.6	0.5			
CL_ROC in drag bucket	Y	Y	N	1	1	
CL_Cruise in drag bucket	Y	Y	Y	1	1	1
				4	**6**	**6**

Aerodynamics: Conventional High-Lift Devices Study







NACA 65221 airfoil at the take-off

Stability and control

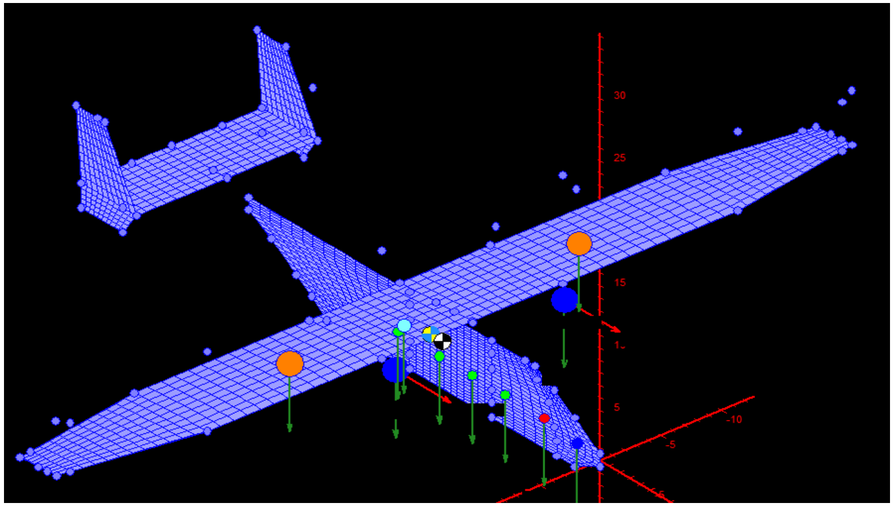
Longitudinal	Value	Lateral	Value
$C_{L\alpha}$	4.94	$C_{N\beta}$	0.132
$C_{L\delta e}$	0.568	$C_{N\delta r}$	-0.114
$C_{M\alpha}$	-0.625	$C_{N\delta a}$	-0.015
C_{Mq}	-9.06	$C_{l\beta}$	-0.052
$C_{M\delta e}$	-1.95	$C_{l\delta a}$	0.219
		$C_{l\delta r}$	0.024
		C_{lp}	-0.601

Mode	Parameter	MIL-STD Cat. B Level 1	Baseline
Short Period	Damping	$0.30<\zeta_{SP}<2.00$	0.44
	Natural frequency (rad/s)	$1.10<\omega_{NSP}<6.00$	3.44
Phugoid	Damping	$\zeta_{PH}>0.04$	0.322
Dutch Roll	Damping	$\zeta_{DR}>0.08$	0.145
	Natural frequency (rad/s)	$\omega_{NDR}<4.00$	2.27

	Neutral point location from the aircraft nose (ft)	% MAC
Theory	15.11	46
SURFACES	15.06	45

The Neutral point validation

Description	Horizontal Tail	Vertical Tail
Span (ft)	15.00	9
AR	3.50	4.20
Root Chord (ft)	5.50	5.50
Taper Ratio	1.00	0.50
Incidence (deg)	-1.00	0.00
LE Sweep (deg)	0.00	20.00
Volume coefficient	0.67	0.067



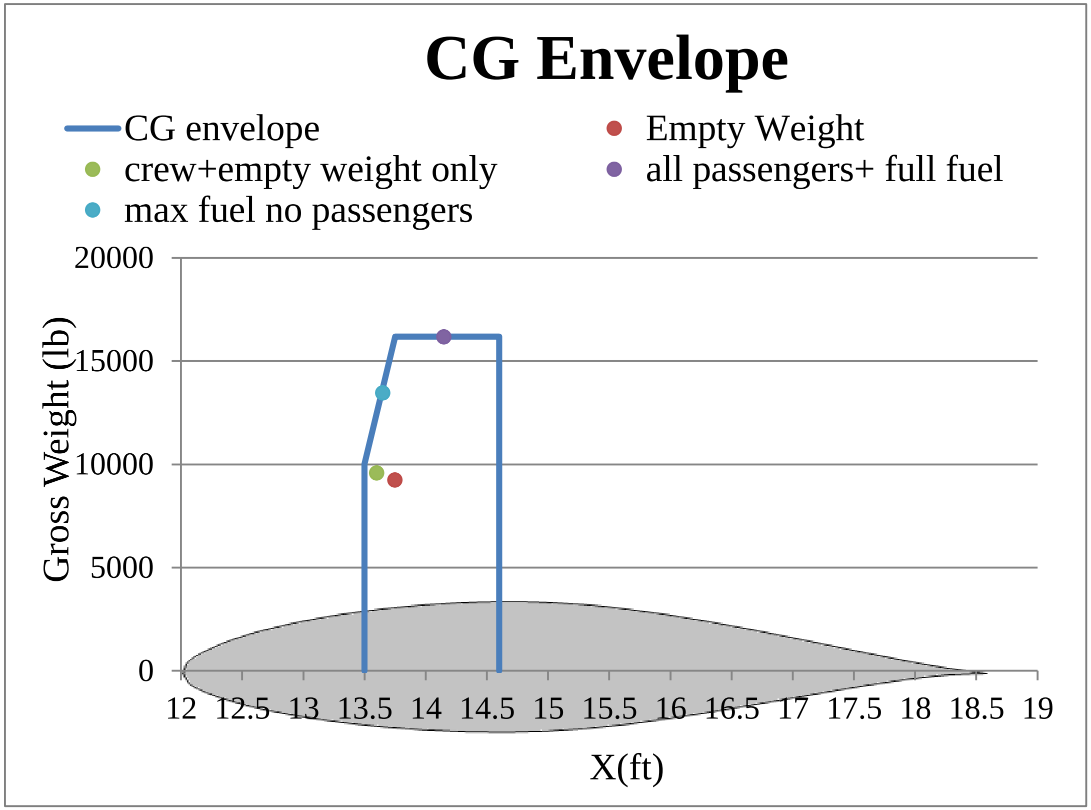
The SURFACES Model

Weights

Baseline aircraft weights

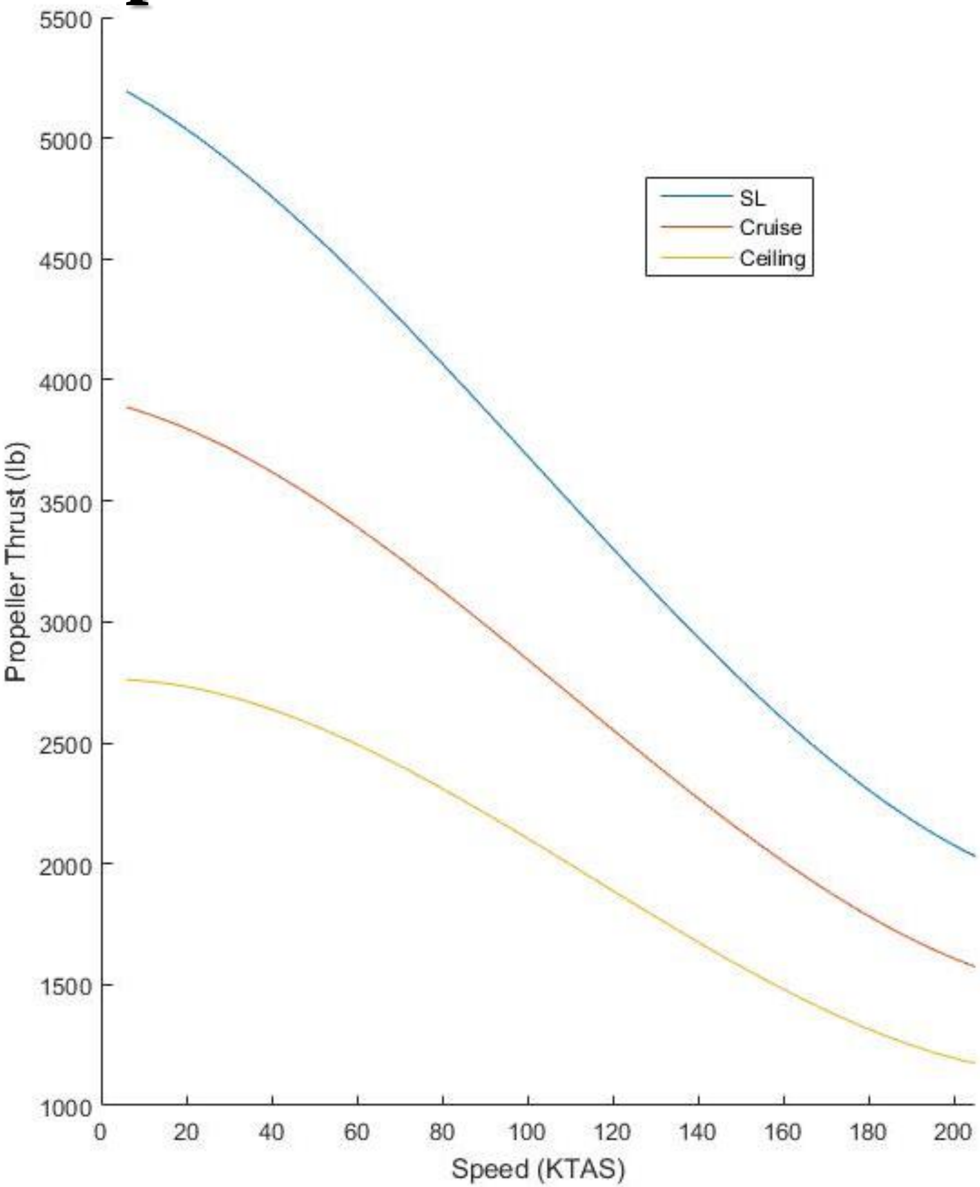
Maximum Take-off Weight (lb)	16187
Maximum Landing Weight (lb)	15701
Maximum Fuel Weight (lb)	3457
Payload Weight (lb)	4200
Empty Weight (lb)	9684

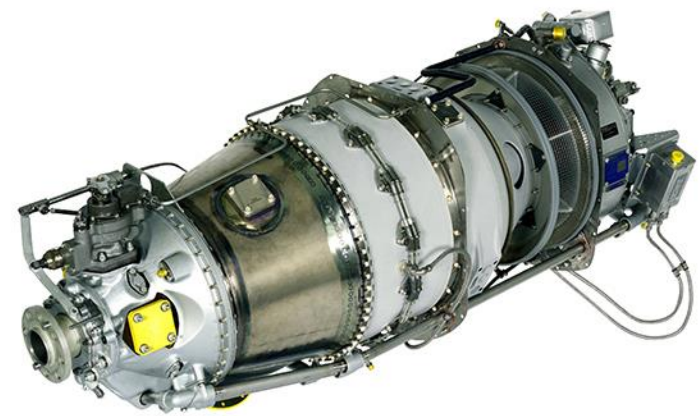
Estimations Used:
Raymer, Nicolai, Torenbeek, Niu



CG range: 16% MAC

Propulsion

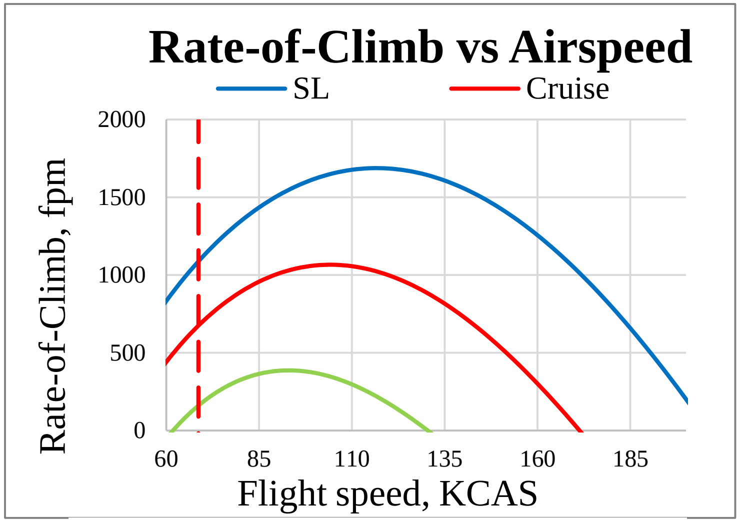




PT6A-135 Engine

Parameter	Value
Engine Model	PT6A-135
Engine Power (SHP)	750
Dry Weight (lb)	338
SFC(lb/hp h)	0.585

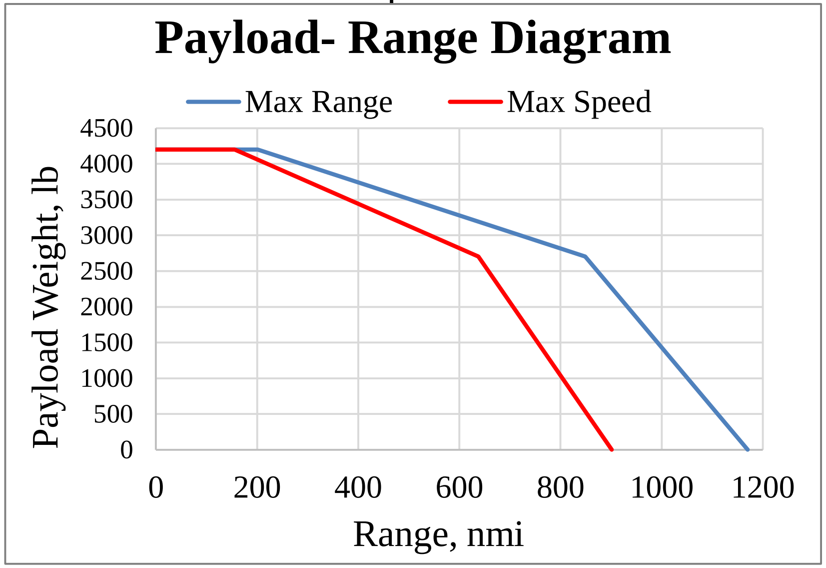
Performance



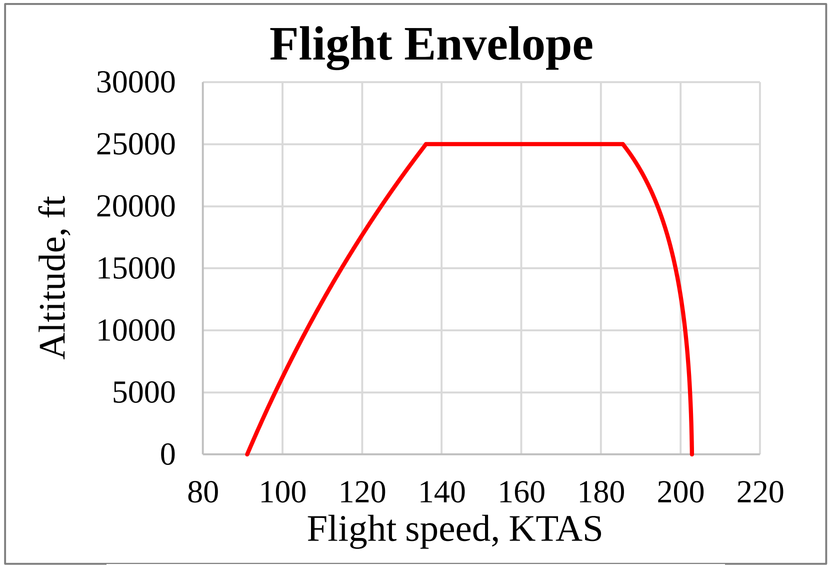
Climb performance

Description	Value
Take-off ground run (ft)	1212
Take-off distance with 50ft obstacle (ft)	1912
Landing approach distance (ft)	659
Flare distance (ft)	113
Free-roll distance (ft)	197
Breaking distance (ft)	576
Total landing distance (ft)	1498

Take-off performance



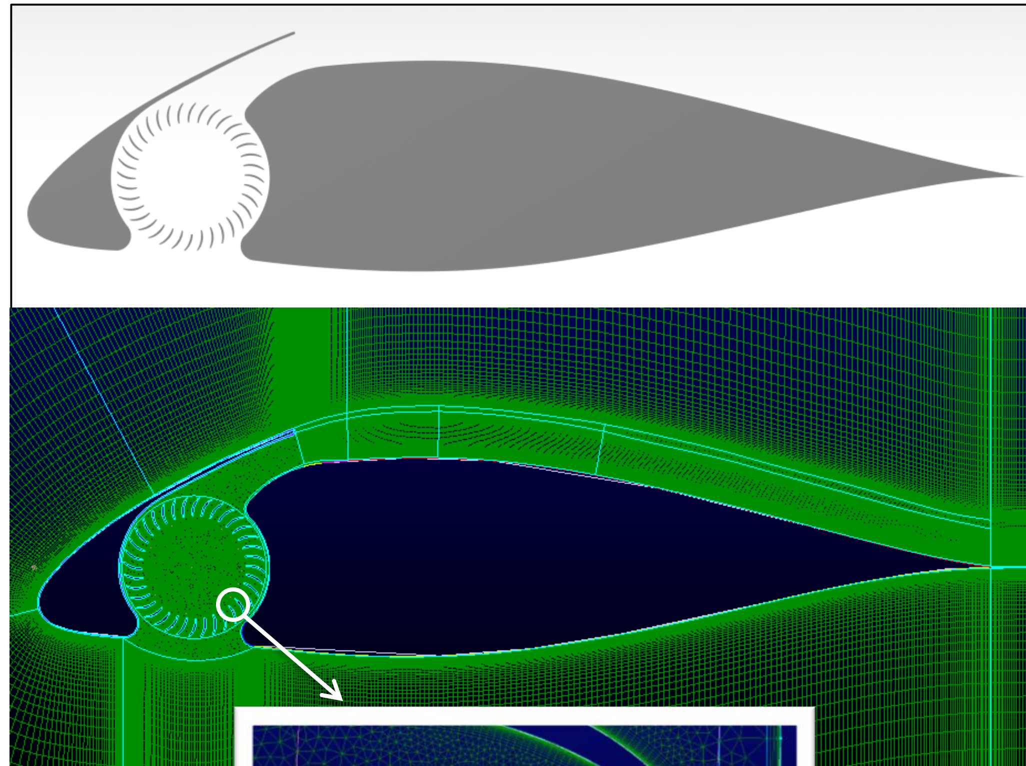
Payload- Range diagram

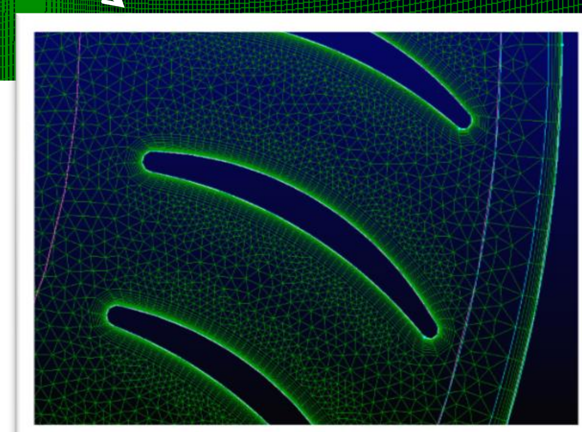


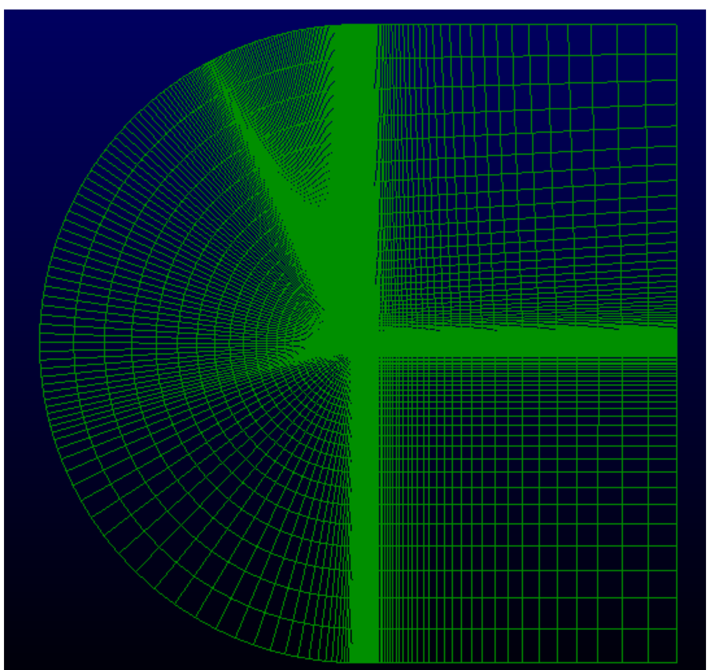
Flight envelope

Fan-wing airfoil configuration analysis

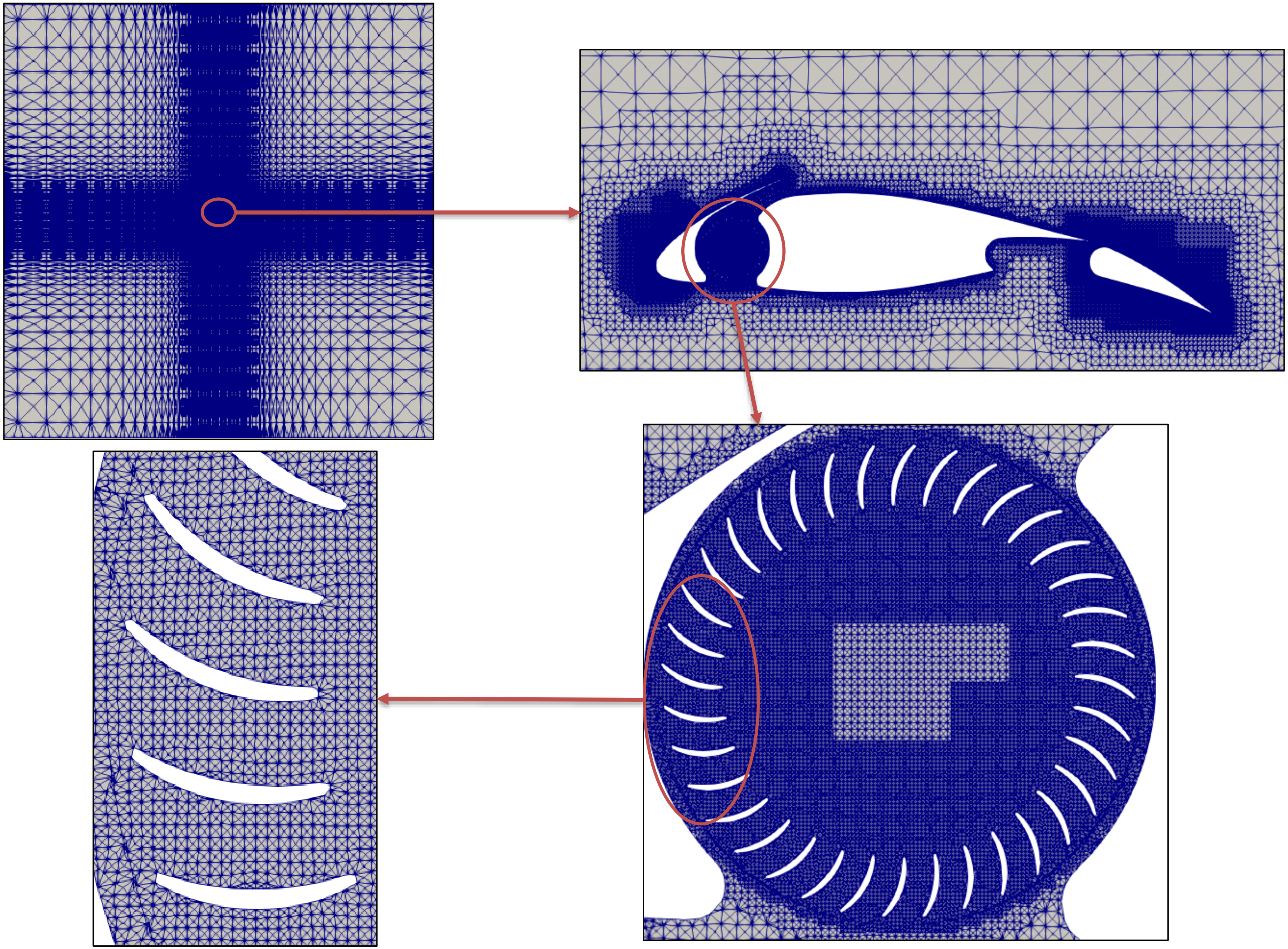
Airfoil	NACA65221
Fan diameter-to-chord ratio	0.11
Fan gap-to-diameter ratio	0.1
Number of blades	36
Fan blade-to-diameter ratio	0.15
Fan gap clearance (% diameter)	5
Slat deflection (deg)	15



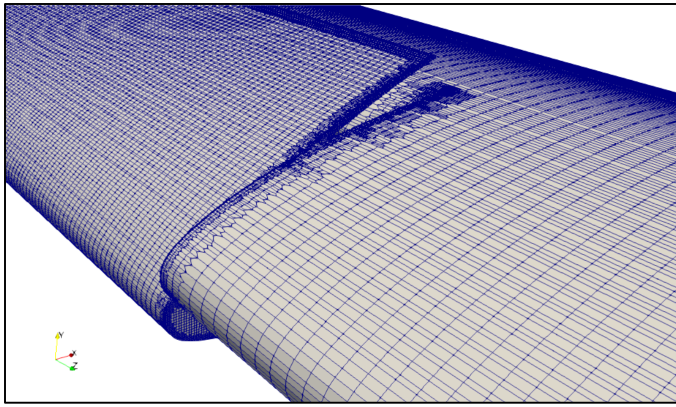




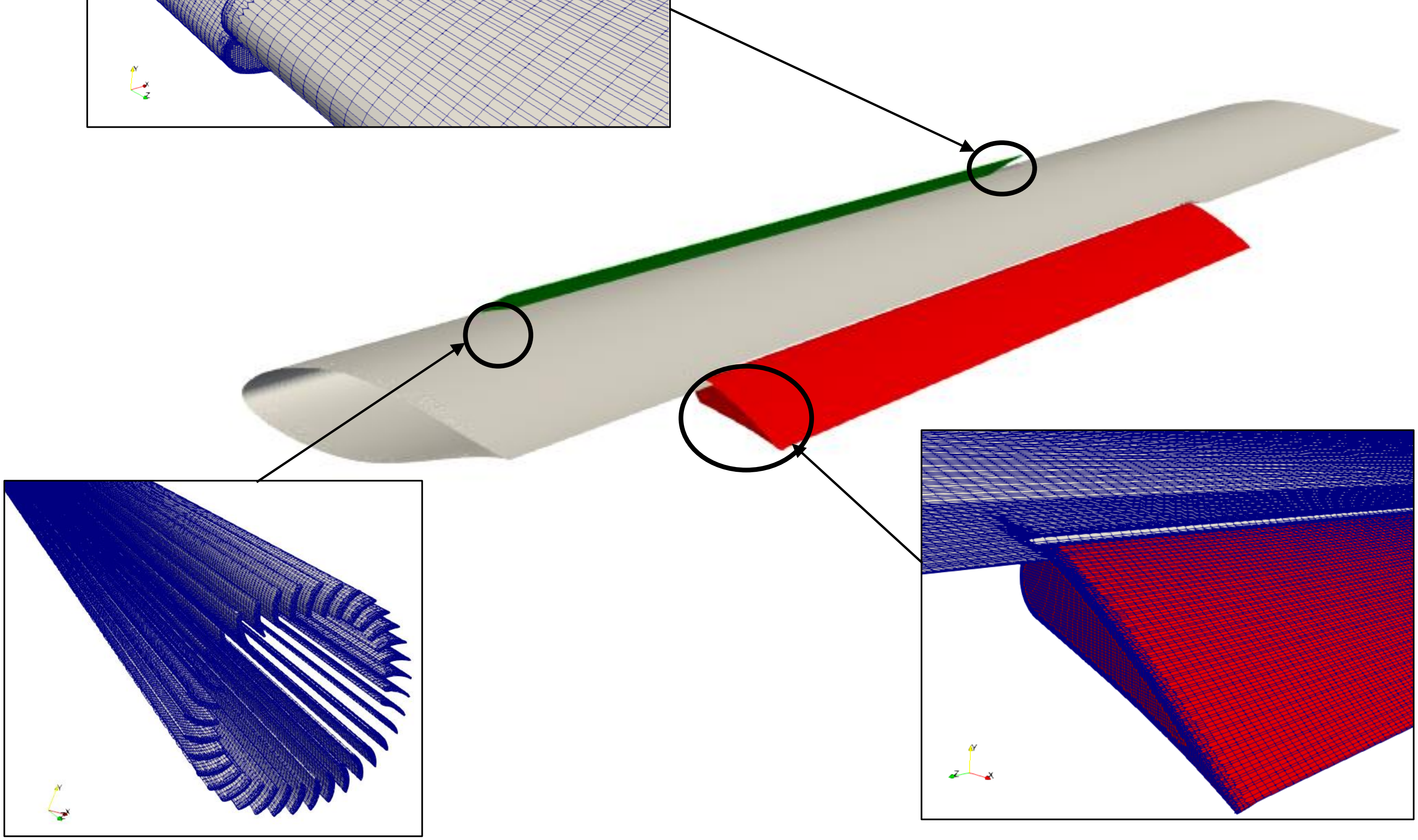
3-D Wing Mesh generation (Taper ratio =1, flap ratio=0.5)



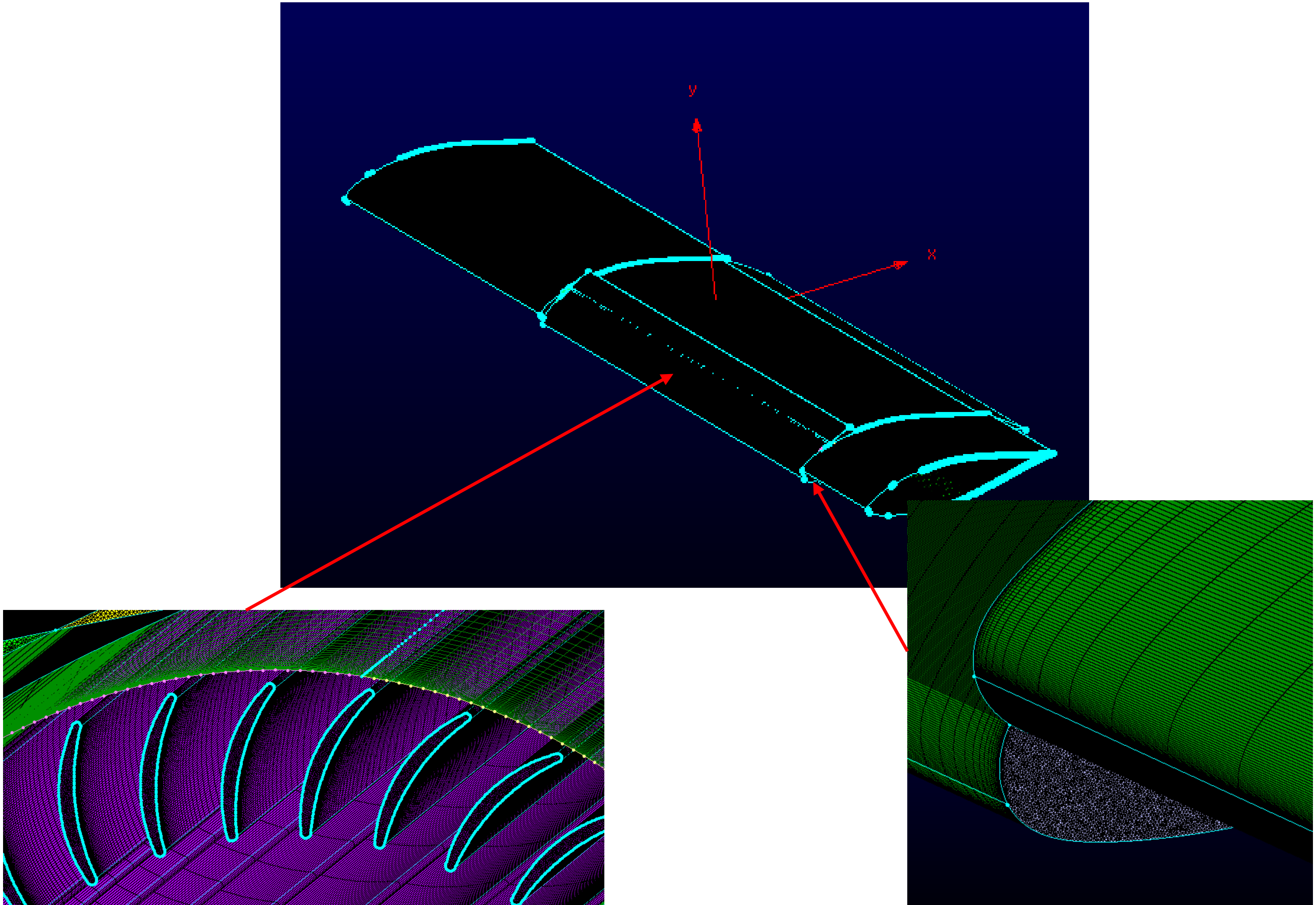
3-D Wing Mesh generation (Taper ratio =1, flap ratio=0.5)



Mesh generator: SnappyHexMesh
Number of cells: 14x 10E6 cells



CFF Mesh with Pointwise

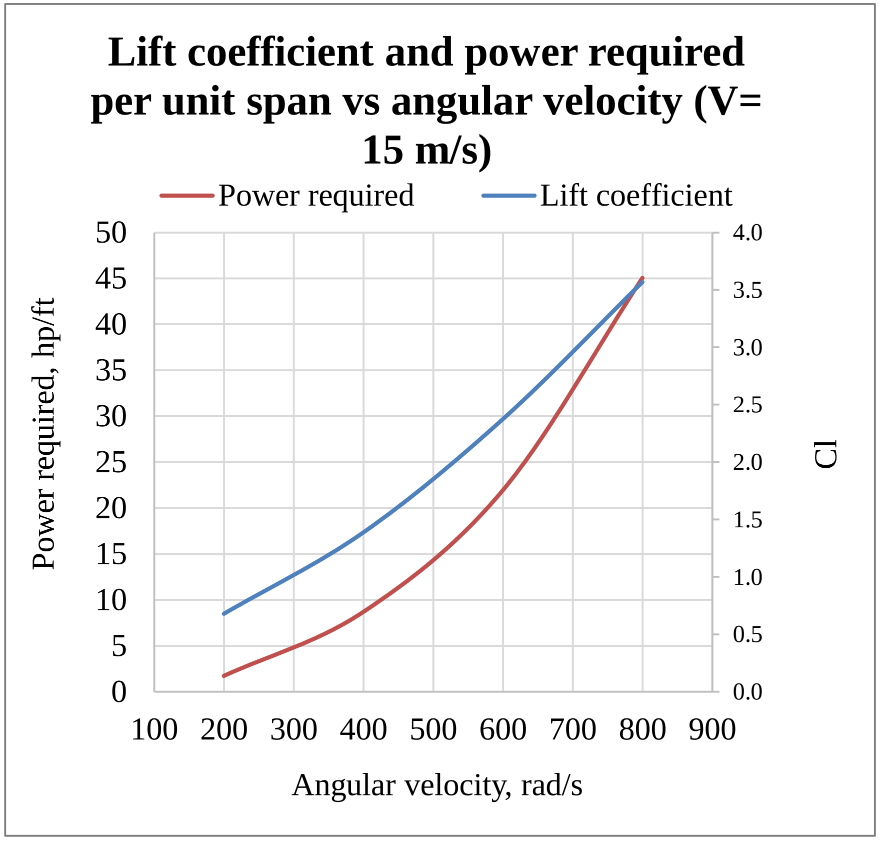


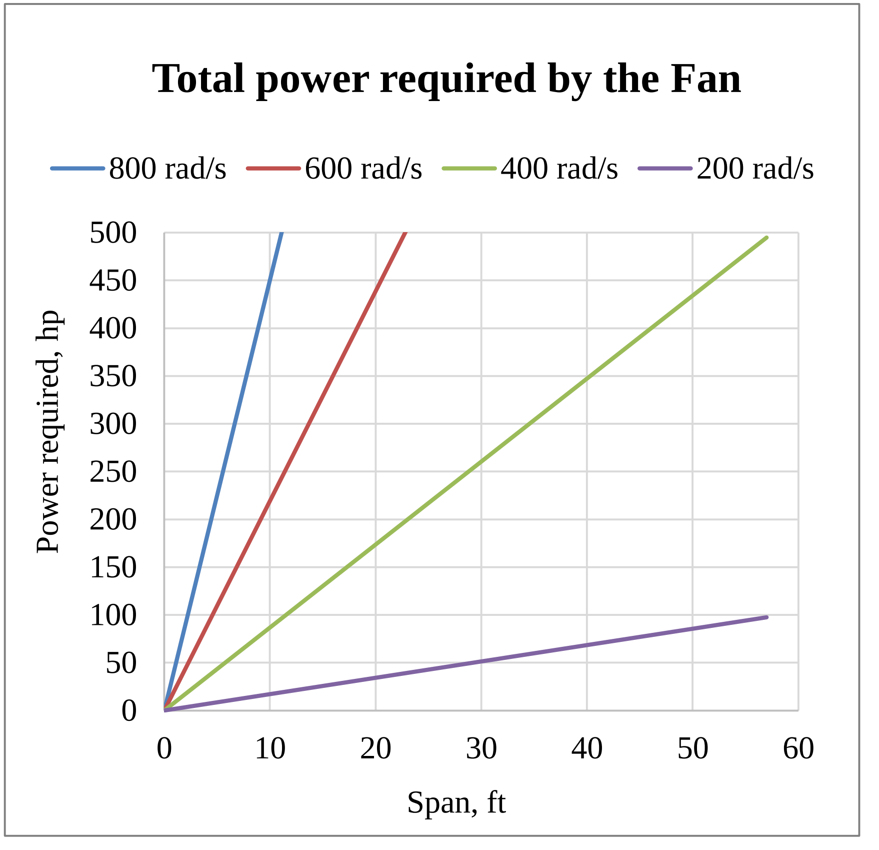
Fan-wing airfoil configuration analysis: Power required for the fan

$$\tau/b = C_\tau q_\infty c^2$$ Torque per unit span

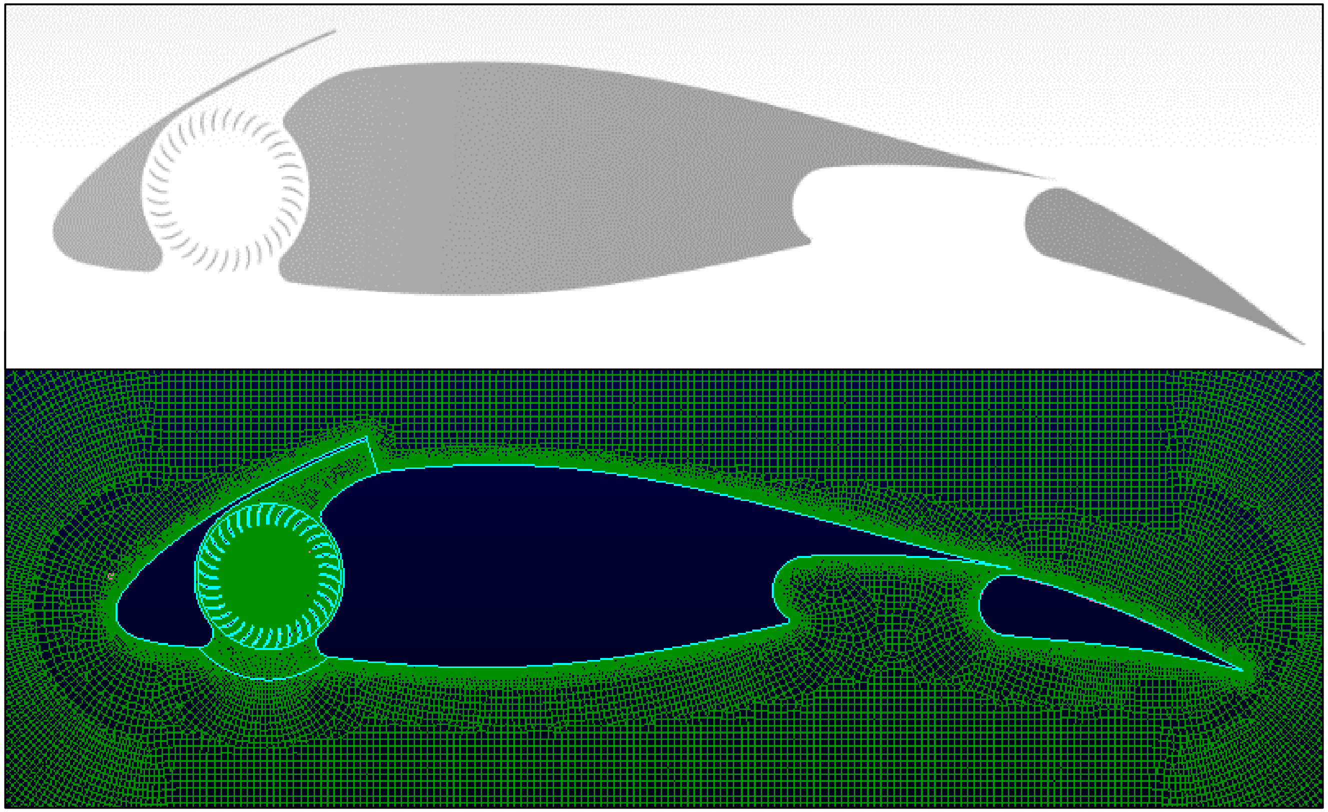
$$P/b = \tau\,\omega/b$$ Power peer unit span

400 rad/s was chosen as a compromise between efficiency and power required





Flapped fan-wing airfoil configuration analysis

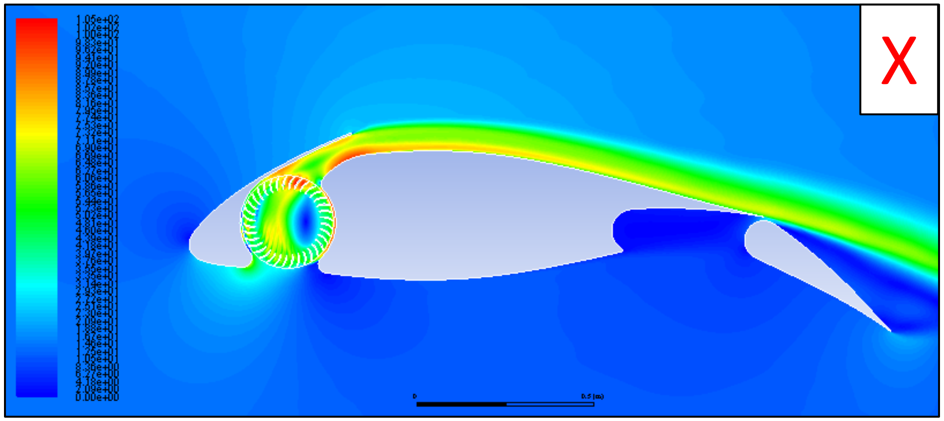


Fan-wing mesh for the CFF airfoil with Fowler flaps

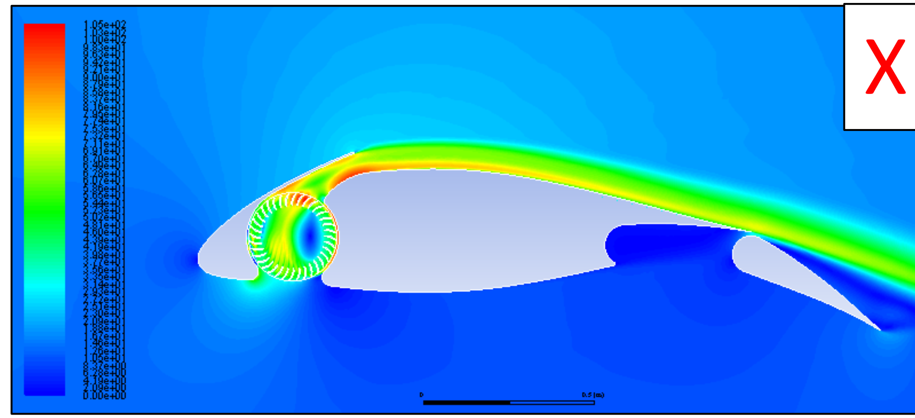
Airfoil	NACA65221
Flap type	Single-slotted Fowler
Flap-chord ratio	0.3
Gap-chord ratio	0.06

Hybrid structured/unstructured mesh
Number of cells: 291892
Far-field: 70 chord away
Y+=1

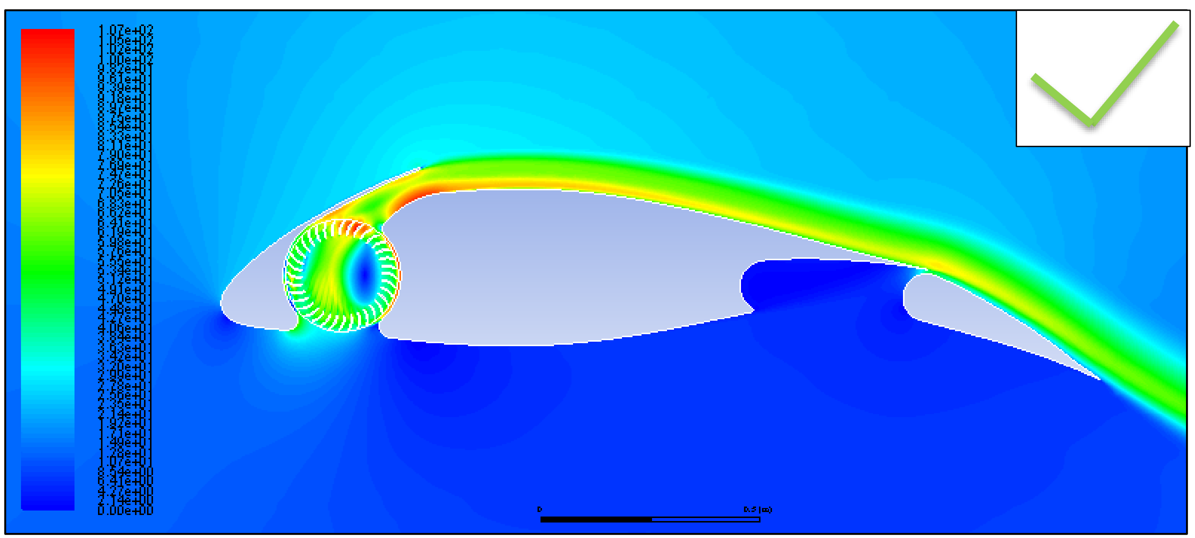
Flapped fan-wing airfoil configuration analysis: Flap deflection trade study



Flap deflection: 40 deg



Flap deflection: 35 deg



Flap deflection: 30 deg

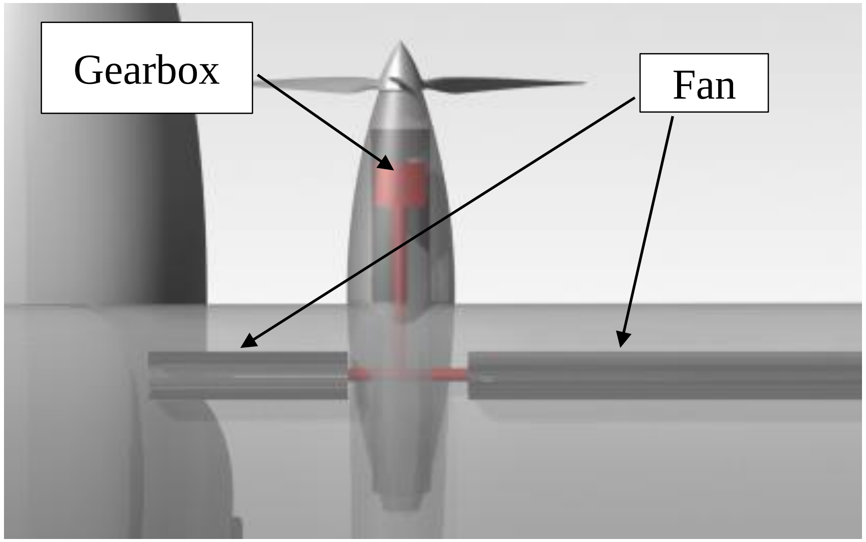
Flap deflection of 30 deg was chosen for the flapped airfoil

Aircraft CFF modifications. Power system variants

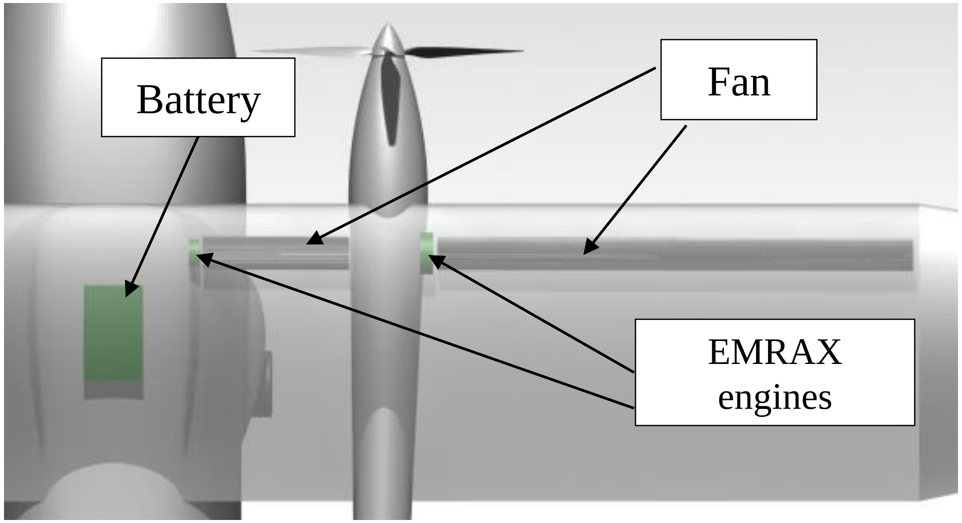
Flow Coeff $\varphi = \left.\frac{V_\infty}{\omega D}\right|_{CFD} = \left.\frac{V_\infty}{\omega D}\right|_{Aircraft}$

Additional 446 hp are required to run the fan during take-off and landing

Model 1 and 2



Model 3



Model	Model Description
Baseline	Baseline configuration
Model 1	Baseline engines
Model 2	Increased engine power
Model 3	Baseline engines and additional electric engines for the fan

F-W aircraft modifications: Payload/ Take-off trade study

Gross Weight:

$$W_0 = \frac{W_{crew} + W_{payload} + W_{misc}}{1 - \frac{W_f}{W_0} - \frac{W_e}{W_0}}$$

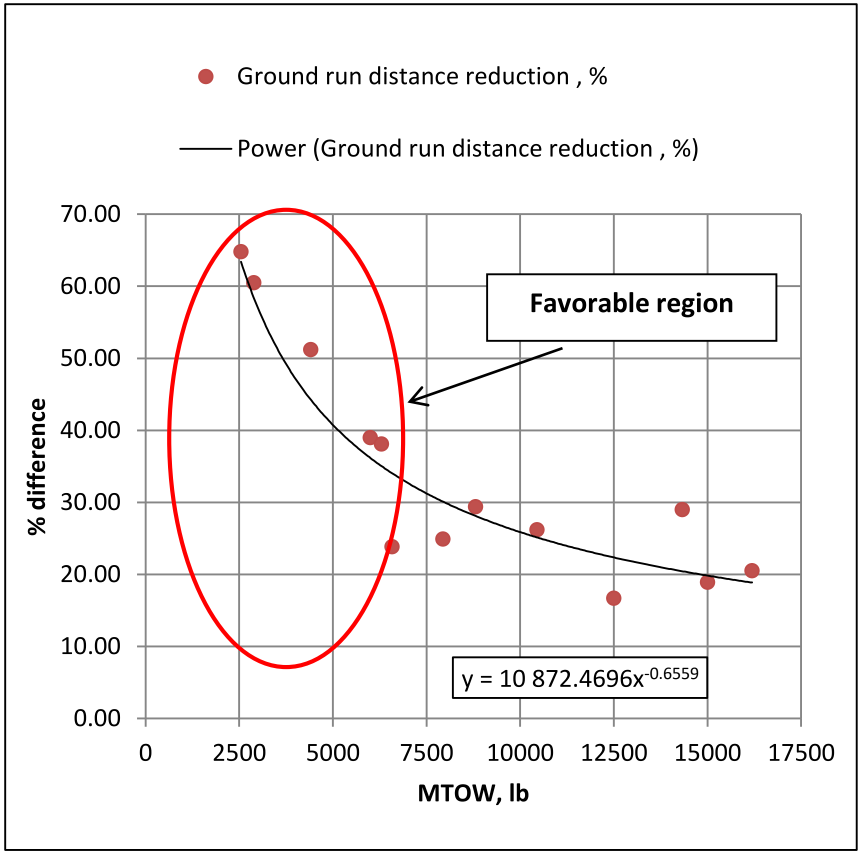
	Baseline	Model 1	Model 2	Model 3
Maximum Take-off Weight, lb	16187	16187	16187	16187
Empty Weight, lb	9684	10064	10424	10254
Maximum Payload Weight, lb (% diff-ce)	4200 (0)	3820 (9.0)	3460 (17.6)	3630 (13.6)

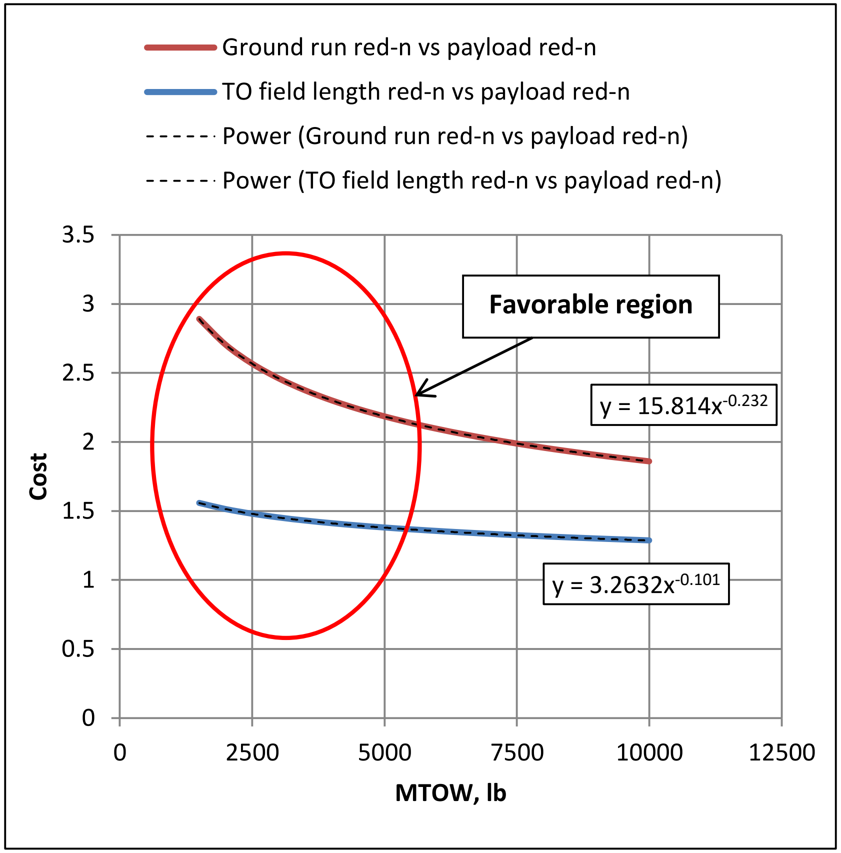
- Model 2 has the smallest possible payload among other concepts
- Model 1 shows the best payload capabilities

	Baseline	Model 1	Model 2	Model 3
Ground Roll, ft (% diff-ce)	1212 (0)	1395 (15.1)	900 (-25.7)	971(-19.9)
Take-off distance ft (% diff-ce)	1912 (0)	2106 (10.1)	1493 (-21.9)	1570 (-17.9)

- **Model 1** has more payload comparing to other competitors but significantly loses in take-off distance even comparing to the Baseline
- **Model 2** has superior take-off performance with more weight penalty. **Note: The Engine Is Overpowered**
- **Model 3** has opposite effect comparing to the Model 3 with the same required power

Scaling study of potential fan-wing aircraft: Payload vs. take-off length cost function analysis





$$Cost = \frac{f(MTOW)}{g(MTOW)}$$

$f(MTOW)$ – take-off distance % difference function

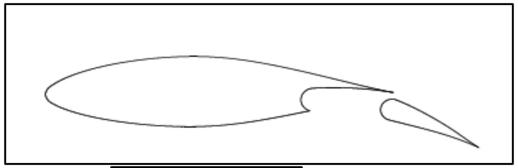
$g(MTOW)$ – payload weight % difference function

Outline

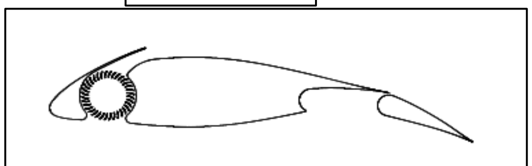
- **Motivation: Preliminary Feasibility Analysis Of A Multi-purpose Fan-Wing Aircraft Concept**
  - Competition analysis
  - Mission/ Requirements and constraints
  - Baseline aircraft conceptual design
  - Aerodynamic analysis of a fan-wing airfoil
- **Fan-Wing Acoustic Radiation Analysis**
  - Selection of numerical model for fan-wing airfoil acoustic analysis
  - Results for baseline, fan-off and fan-on cases
- **Conclusion**

A Holy Grail / "dream-come-true" for an aeroacoustician:
A combination/interaction of turbomachinery, jet and airframe noise sources

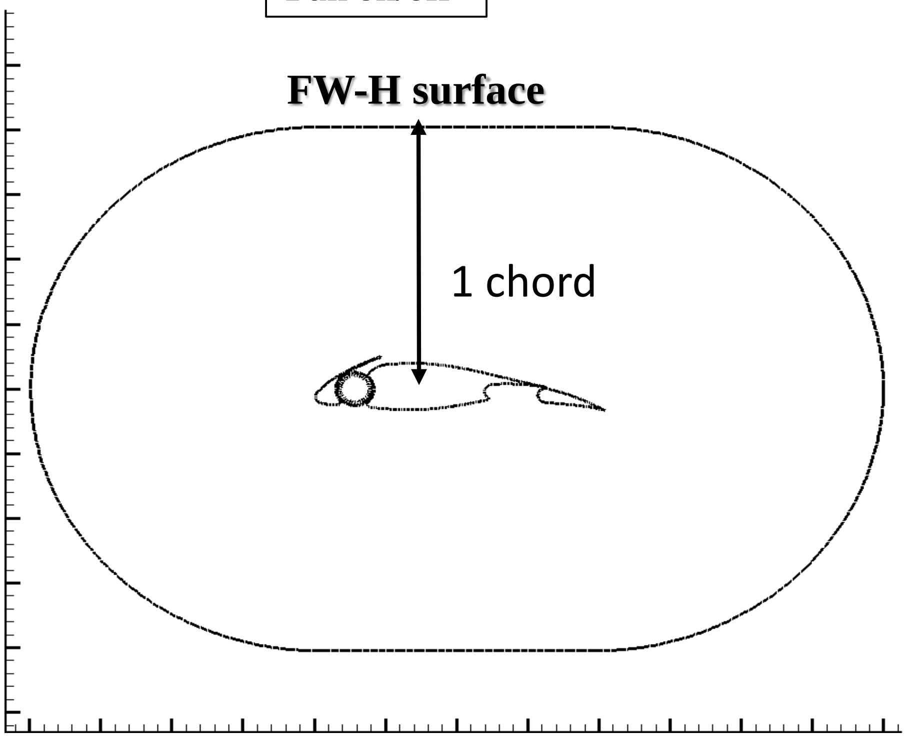
Numerical Modeling Procedure

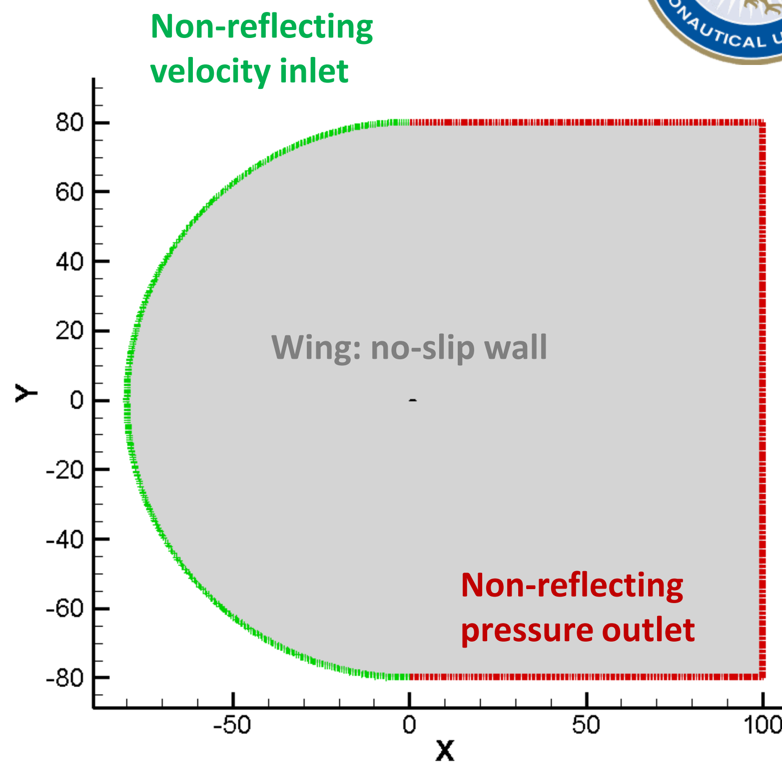


Baseline



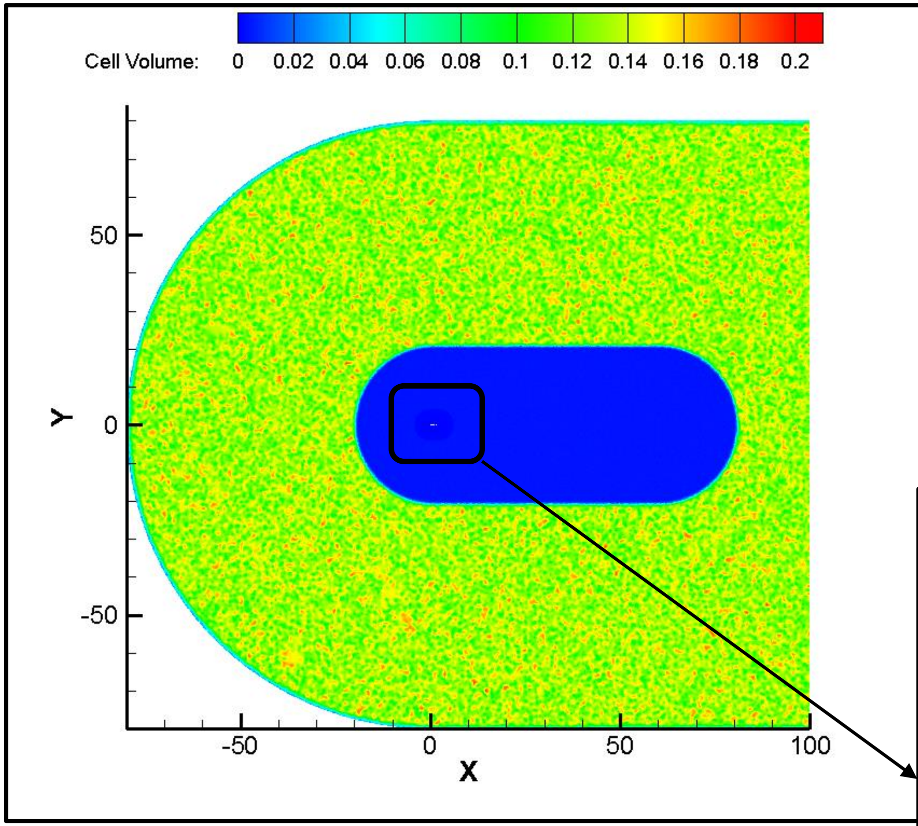
Fan on/off

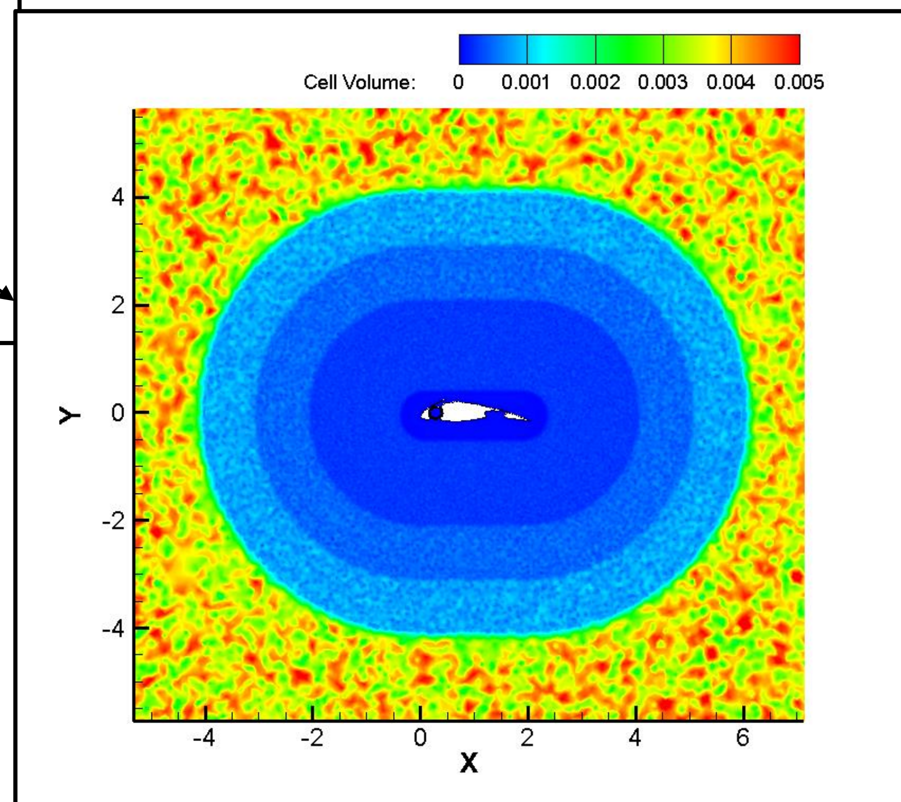




Solver: *Fluent Pressure-based 2nd order*
Turbulence model: *DES*
Free-stream Velocity: *20 m/s*
Angle-off-attack: *0 deg*
Chord length: *1.7 m*
Re= *2.3E6*
Fan rotation: *400 rad/s*

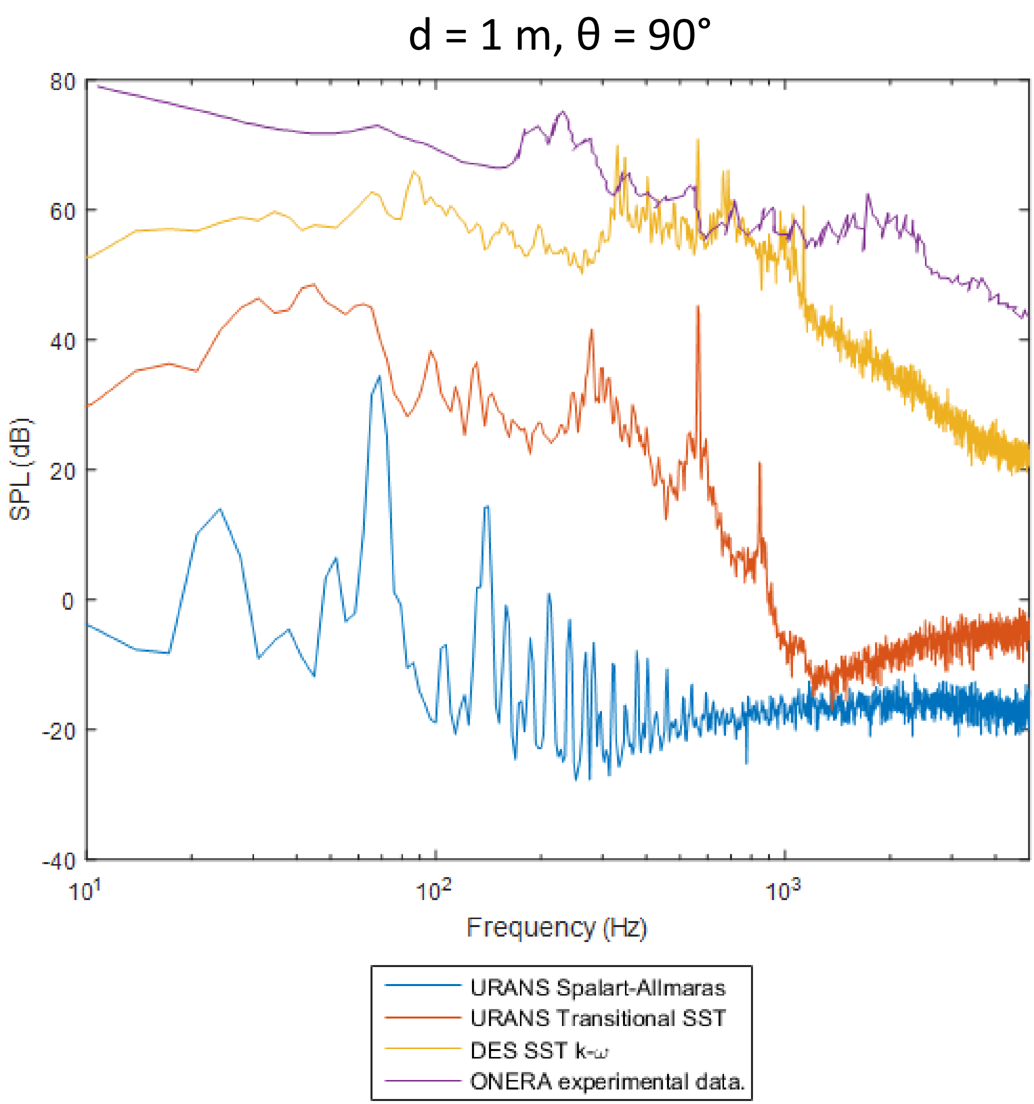
Grid resolution – CFF cases





Unstructured grid
$y^+ = 1$
Max frequency resolution capacity: *400 Hz*
Points per wavelength: *20+*
1.7 M cells / 1 M points

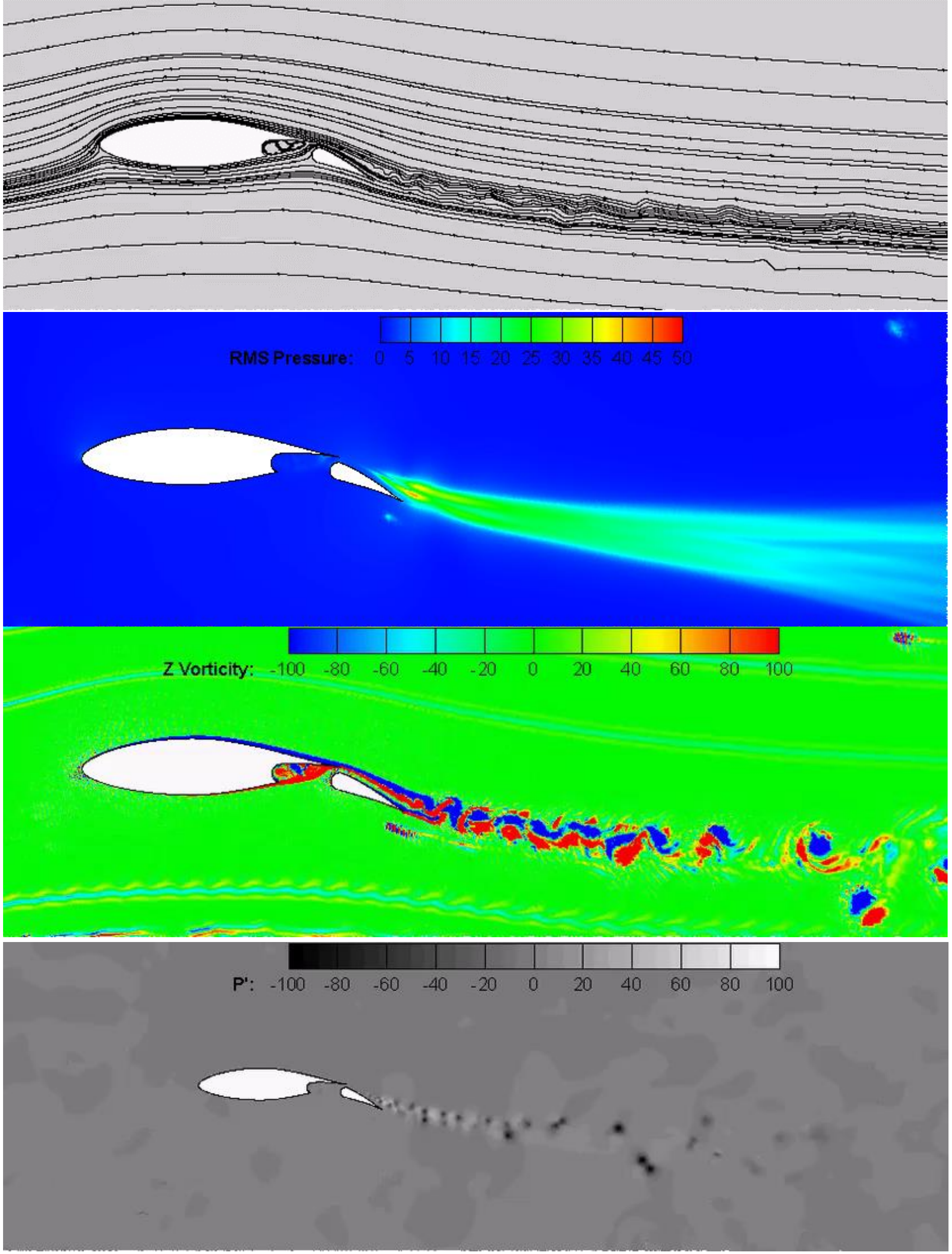
Selection of Numerical Model (Baseline Case)



Comparison between baseline and ONERA experimental data (wing with slat and flap)

- Correlation length for FWH: *0.15c*
- Observation angle: *+90°*
- Computational acoustic results transposed to experimental conditions of distance of observation (1 m) and velocity (30 m/s)

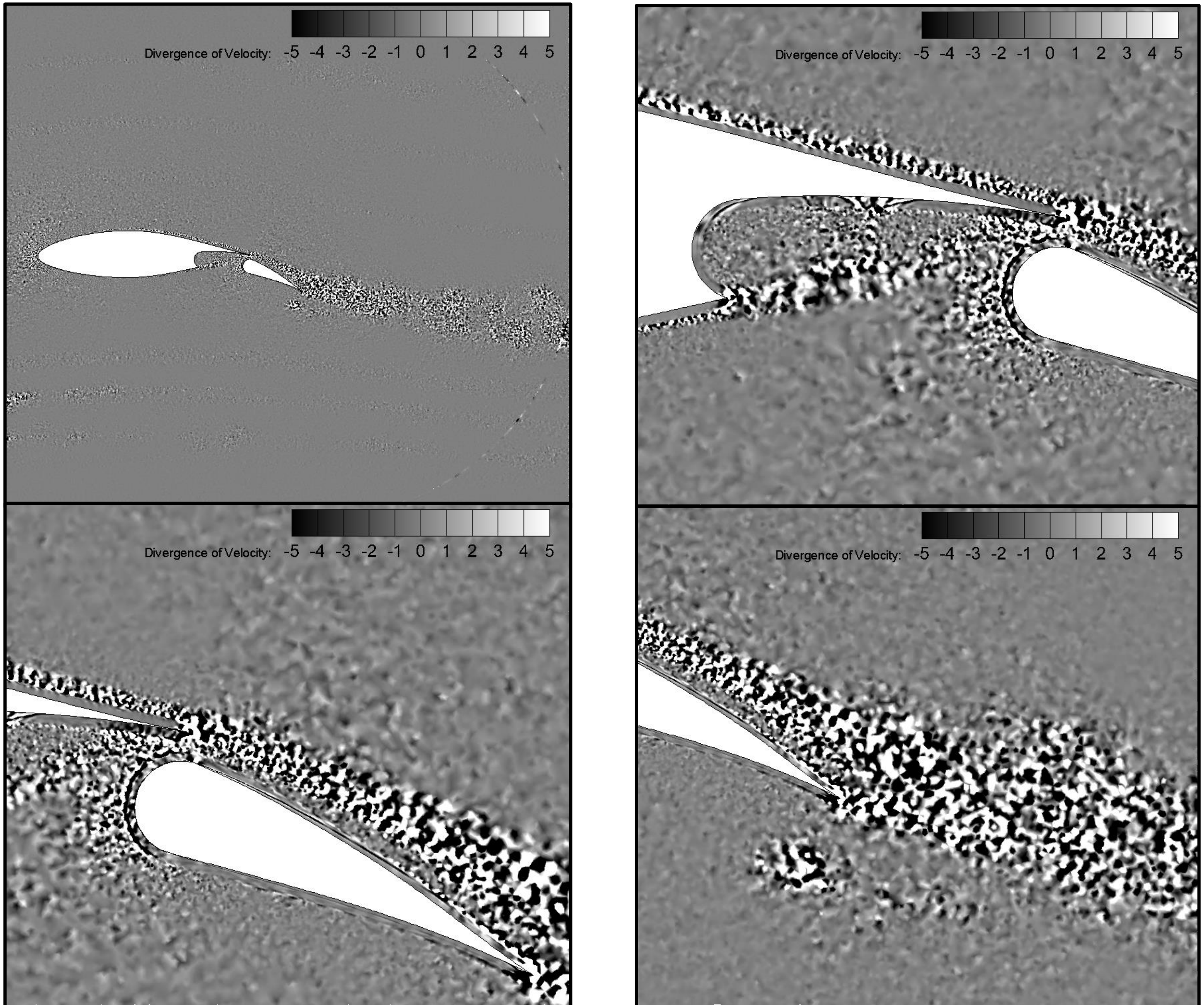
- ***DES simulation produces the most reasonable acoustic levels compared to experiment***
- ***Experiment noisier due to the presence of slat***



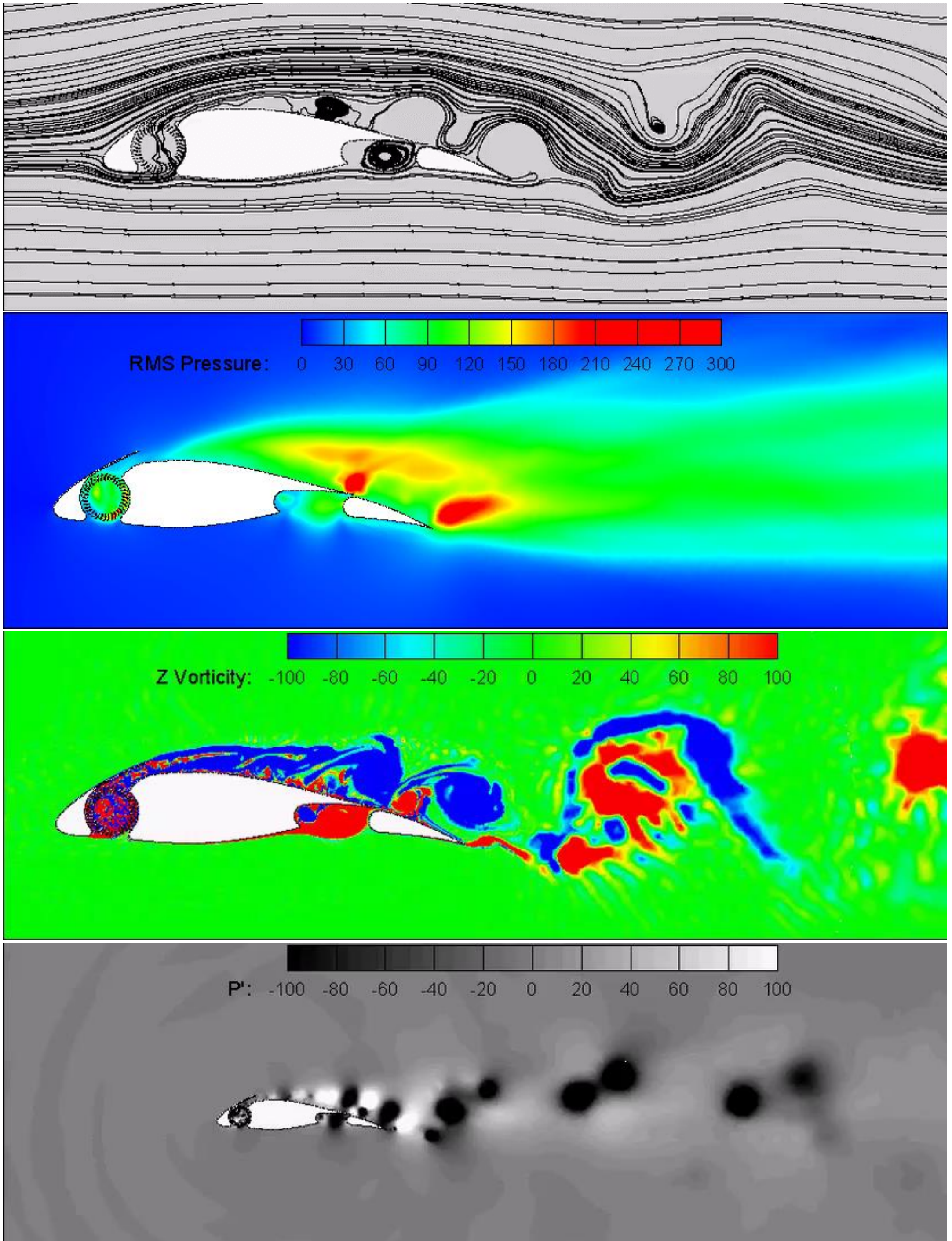
Baseline Case

Streamlines and contours for the baseline airfoil for RMS pressure (top), Z vorticity (middle) and acoustic pressure (bottom)

Baseline – Dilatation Field



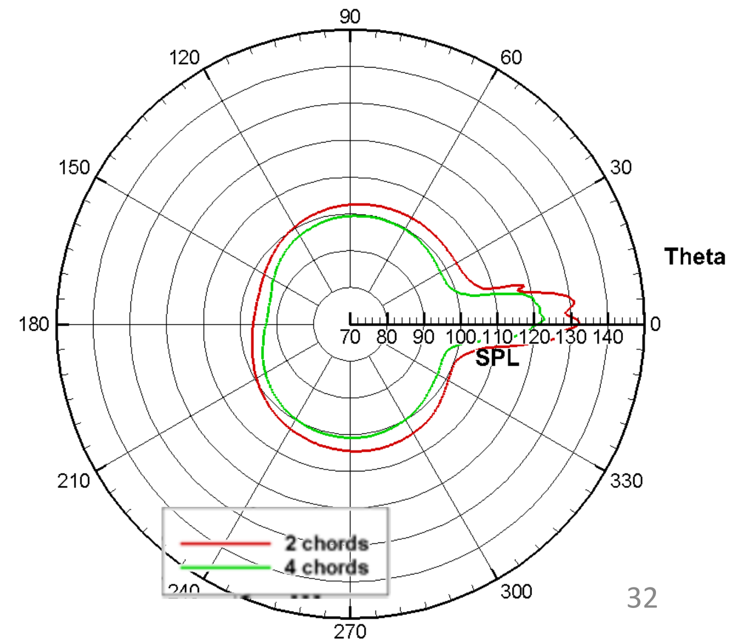
Fan-Off Case

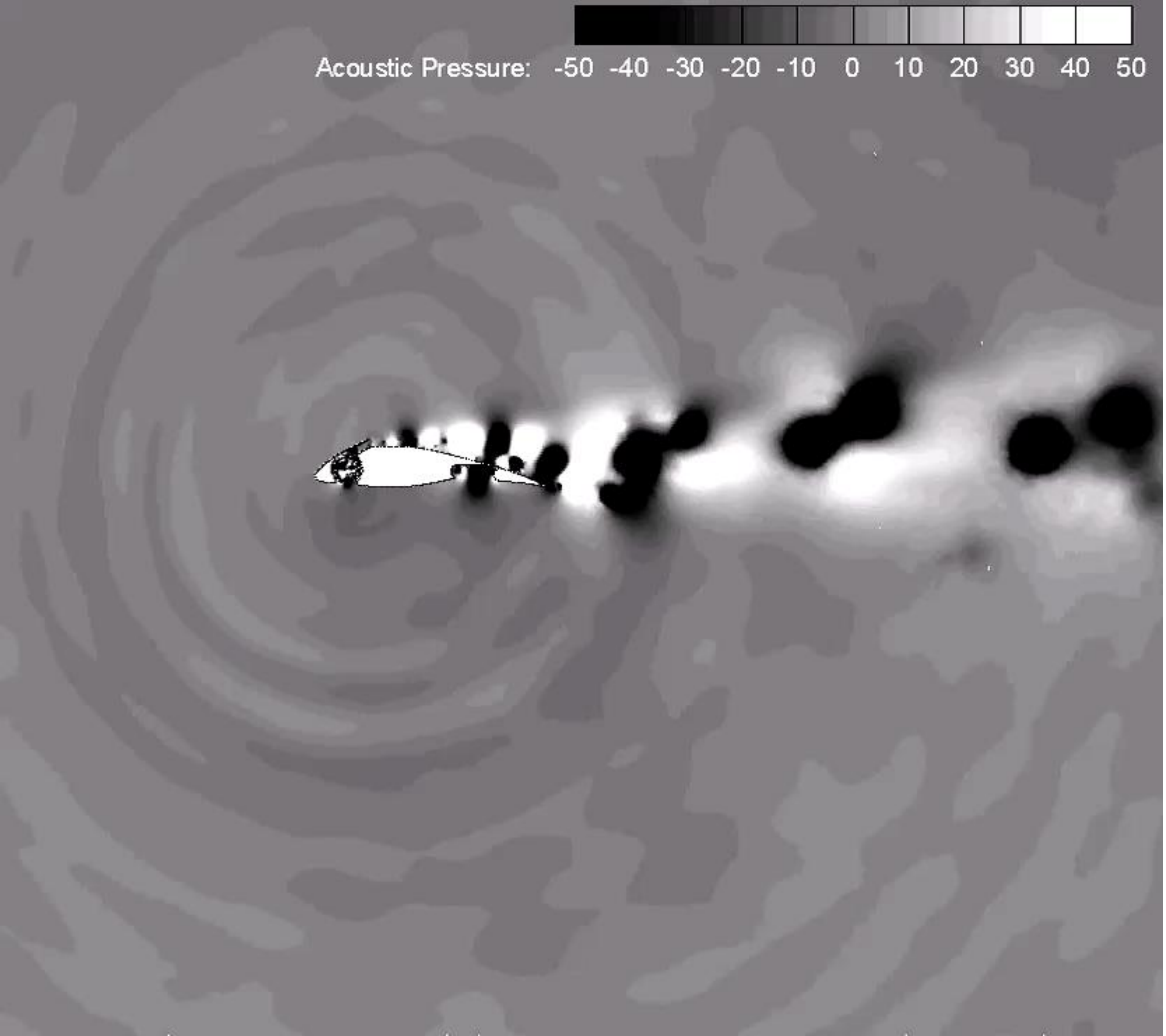


Streamlines and contours of the airfoil with CFF off for RMS pressure (top), Z vorticity (middle) and acoustic pressure (bottom)

RMS pressure directivity in the near field

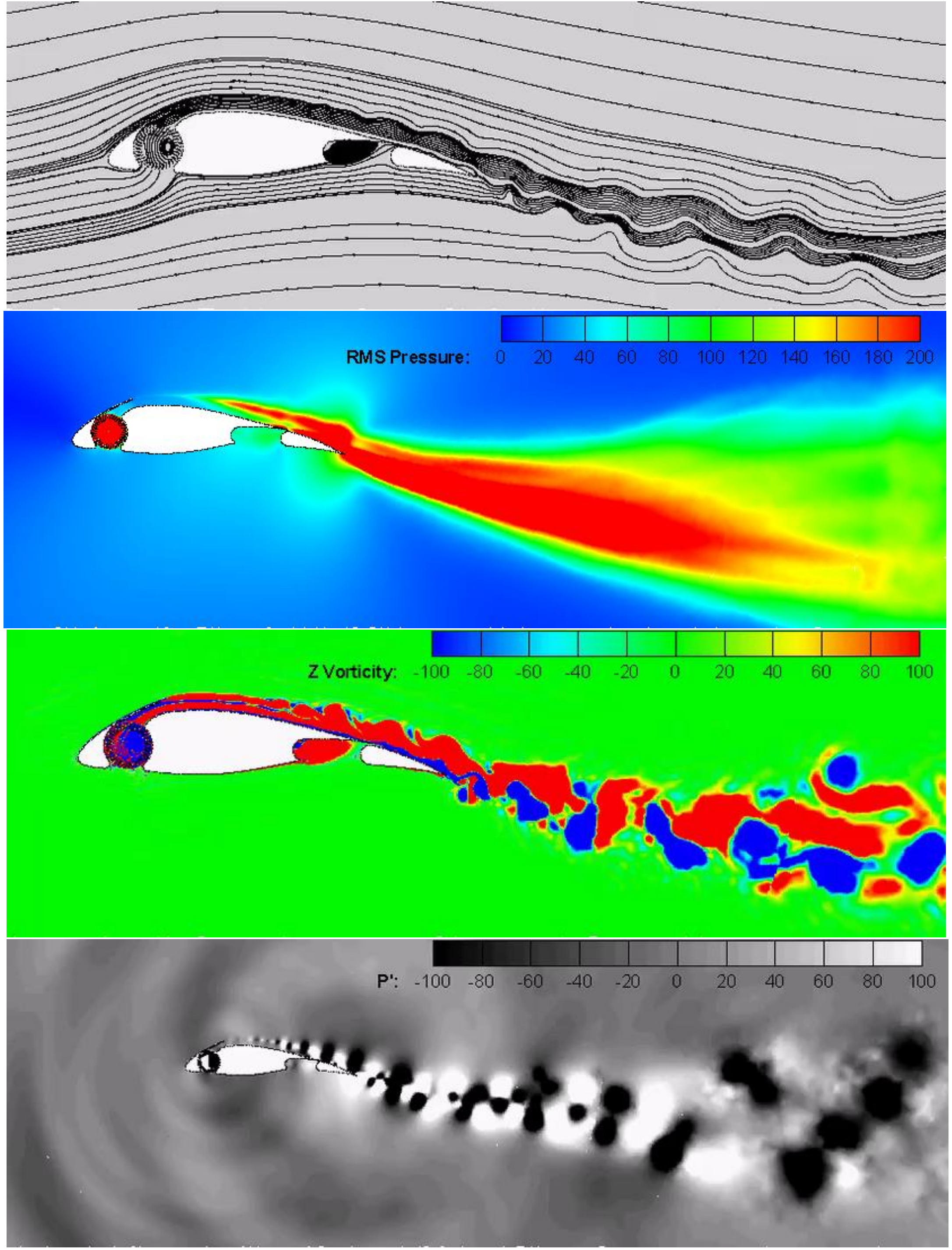
70 – 150 dB




Acoustic Pressure: -50 -40 -30 -20 -10 0 10 20 30 40 50

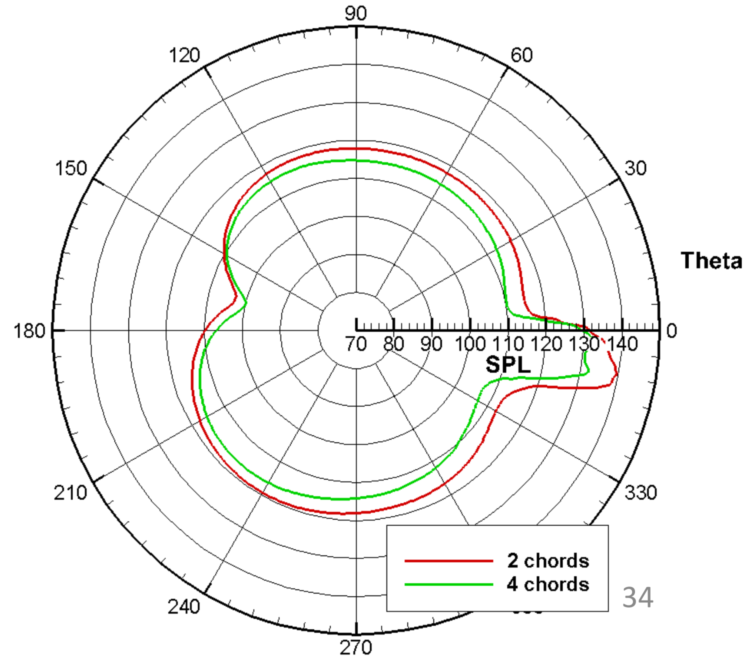
Fan-On Case

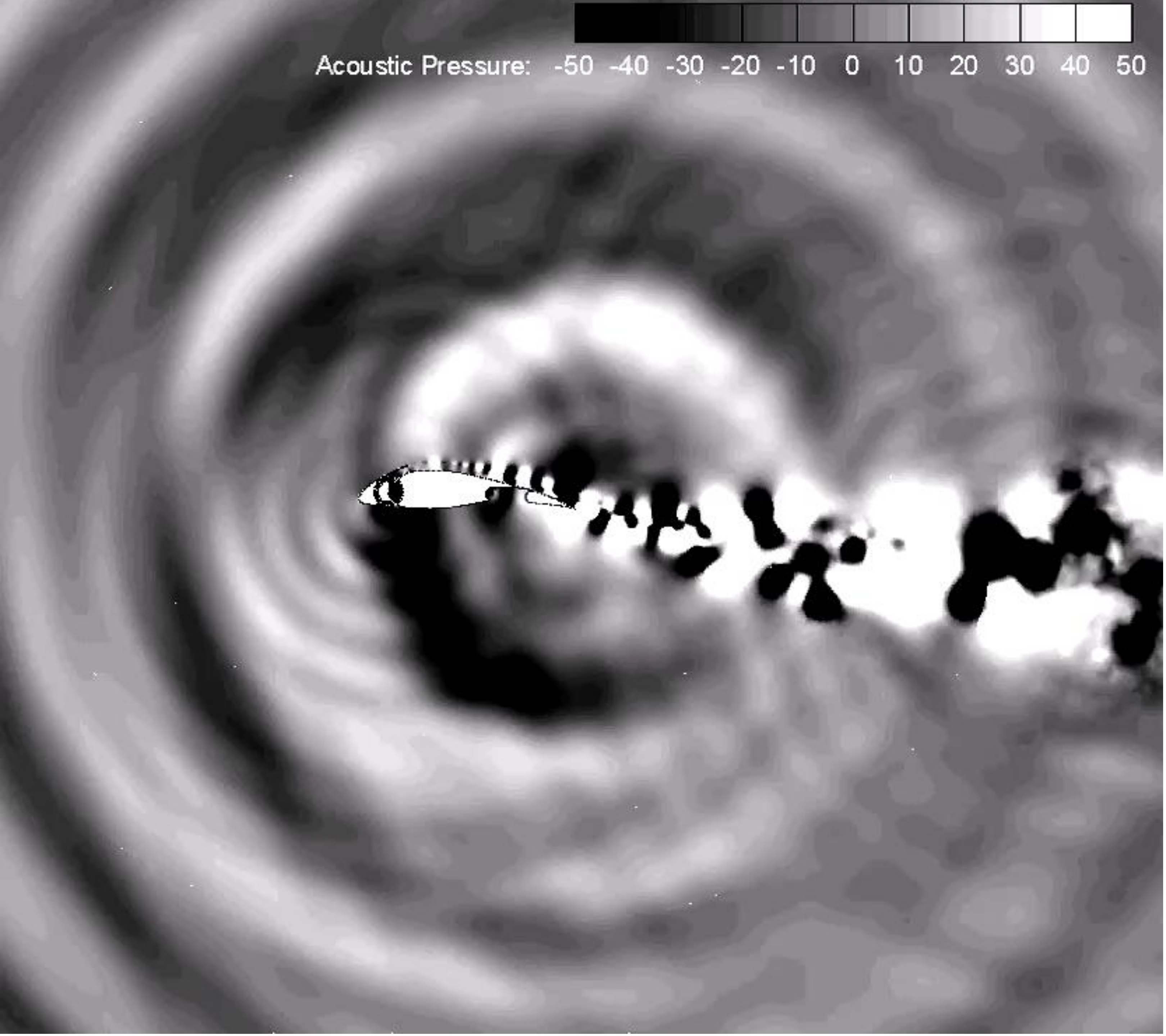
Streamlines and contours of the airfoil with CFF on for RMS pressure (top), Z vorticity (middle) and acoustic pressure (bottom)



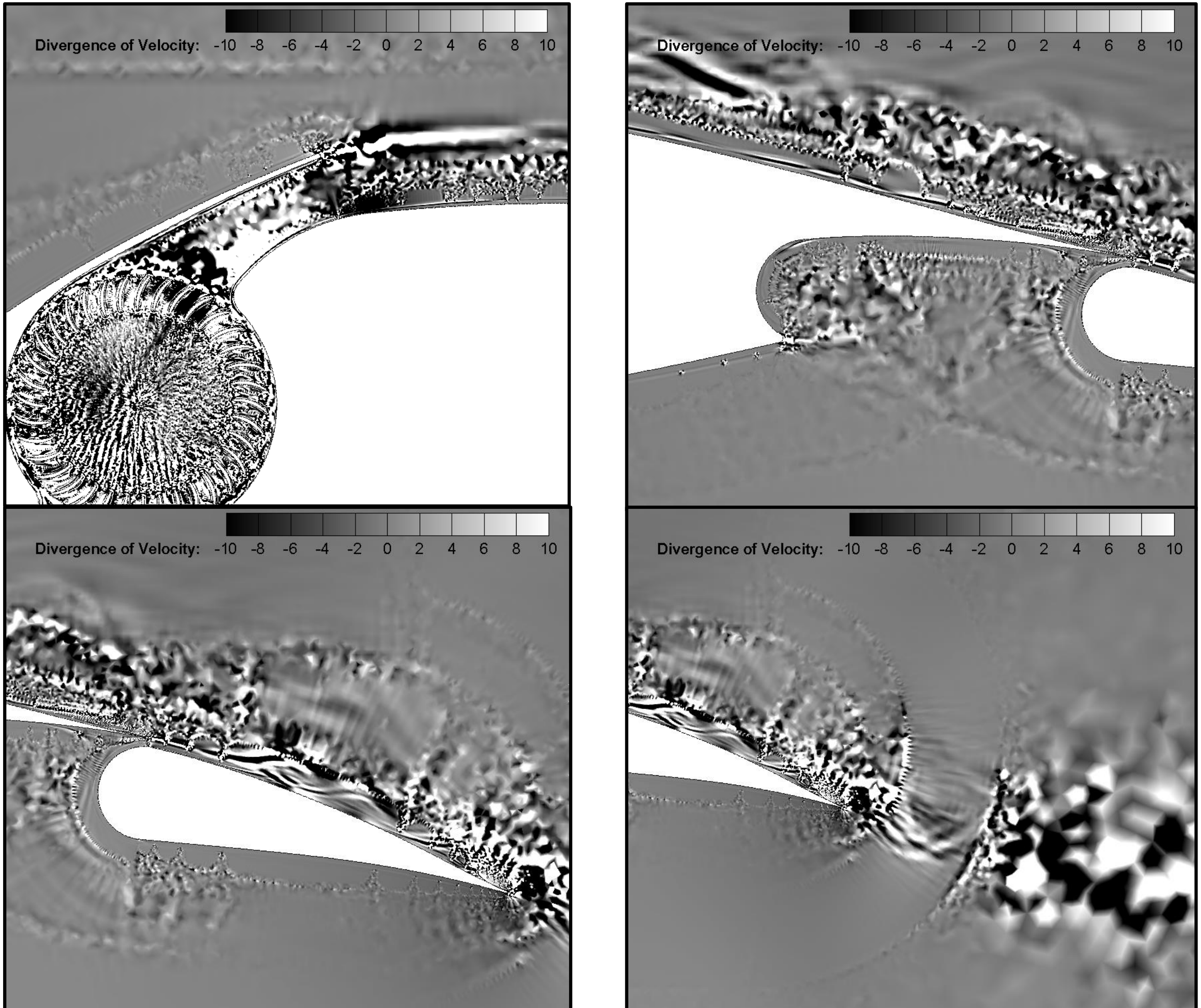
RMS pressure directivity in the near field

70 – 150 dB

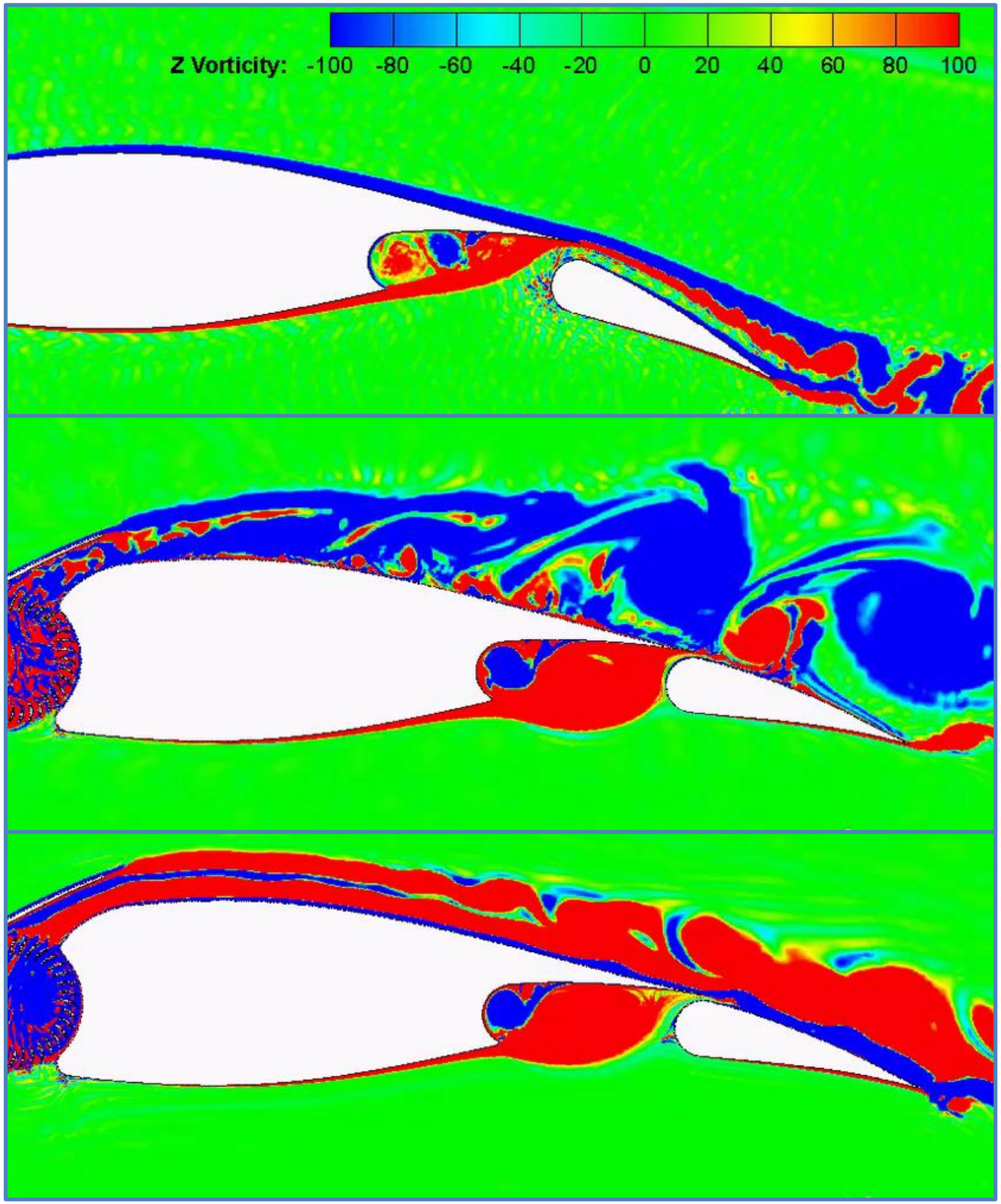



Acoustic Pressure: -50 -40 -30 -20 -10 0 10 20 30 40 50

CFF On – Dilatation Field



Vorticity Contour Comparison



RMS Pressure

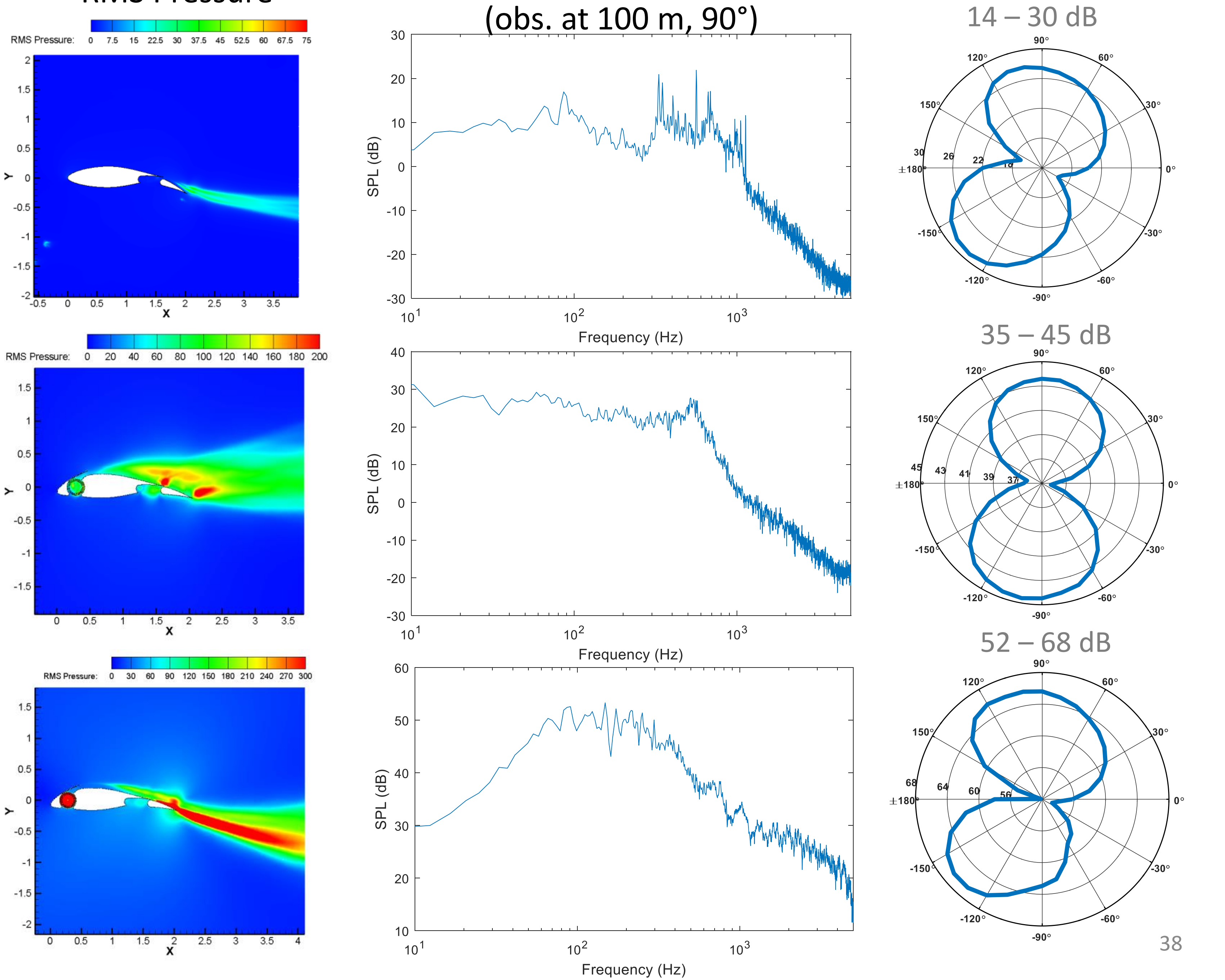
Complete FFT (obs. at 100 m, 90°)

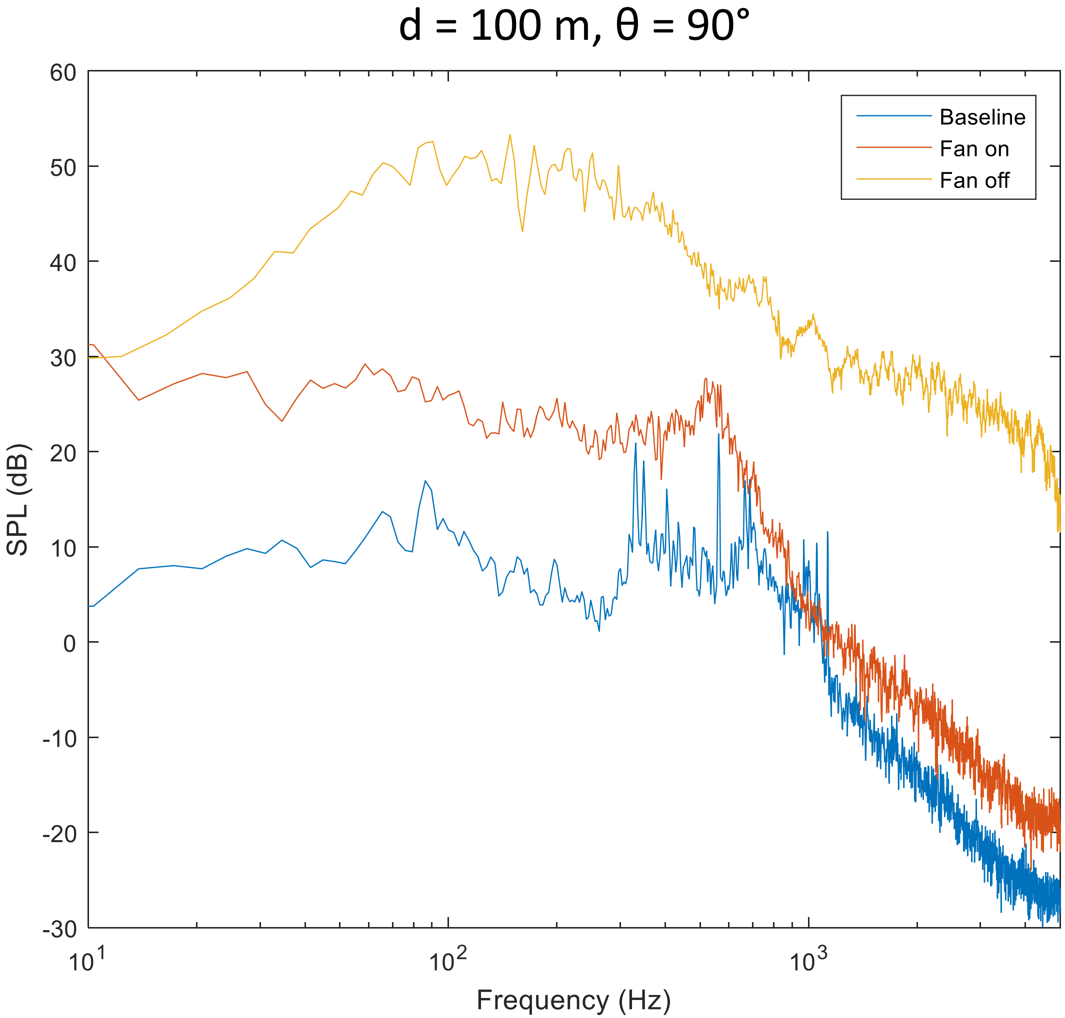
SPL Directivity (f < 200 Hz)

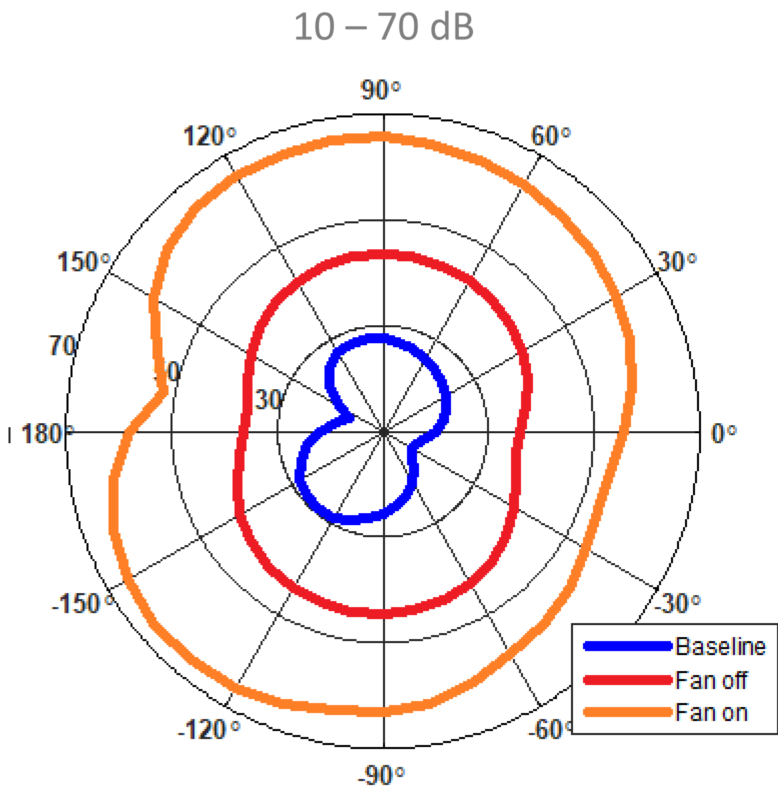
Baseline

Fan off

Fan on



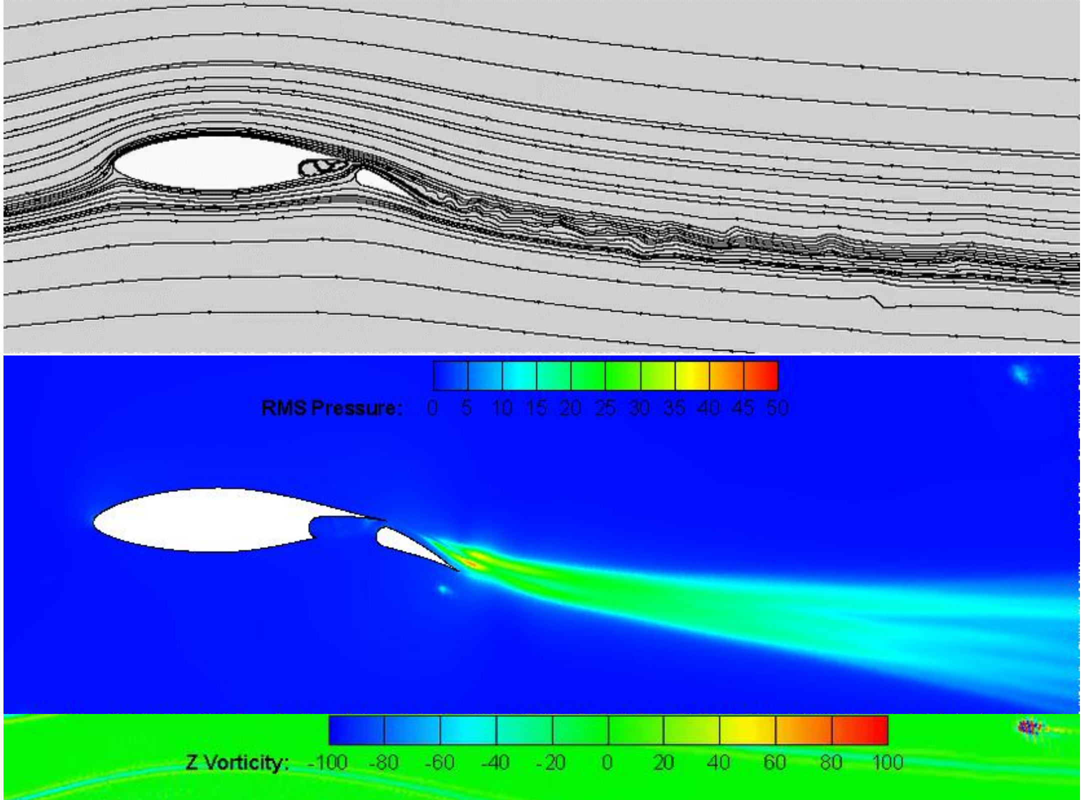

d = 100 m, θ = 90°
SPL (dB)
Frequency (Hz)
Baseline
Fan on
Fan off
60
50
40
30
20
10
0
-10
-20
-30
10^1
10^2
10^3

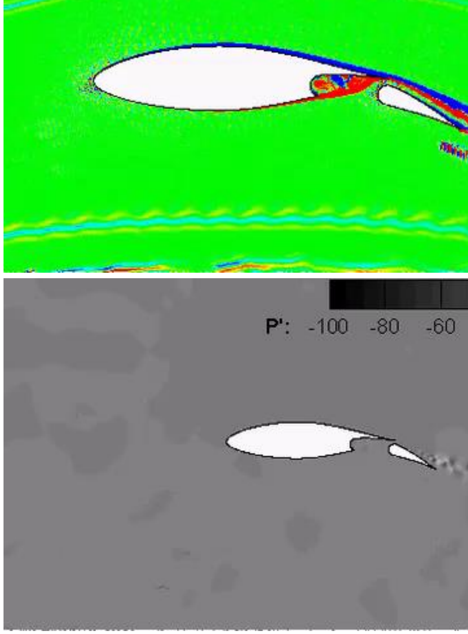

10 – 70 dB
90°
120°
60°
150°
30°
180°
0°
-150°
-30°
-120°
-60°
-90°
70
30
Baseline
Fan off
Fan on

Conclusions

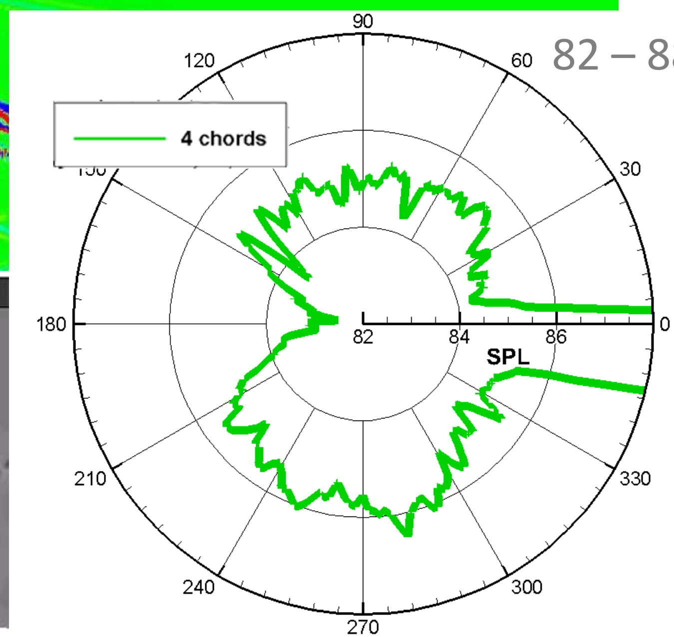
- A feasibility study of a wing with LE-embedded CFF for a multi-purpose ESTOL aircraft concept was performed.
- Scaling study applied to aircraft performance analysis identified a low-to-medium size UAV as the most beneficial configuration for the proposed fan-wing technology.
- Preliminary acoustic analysis employed Fluent DES with FWH formulation for comparative study of acoustic radiation from baseline (flapped airfoil), fan-off and fan-on configurations.
- Fan-on configuration with the highest acoustic signature exhibited suction-side wall jet producing jet self-noise superimposed on the airfoil/flap TE noise from scattered wall jet vorticity.

Streamlines and contours of the baseline airfoil for RMS pressure (top), Z vorticity (middle) and acoustic pressure (bottom)



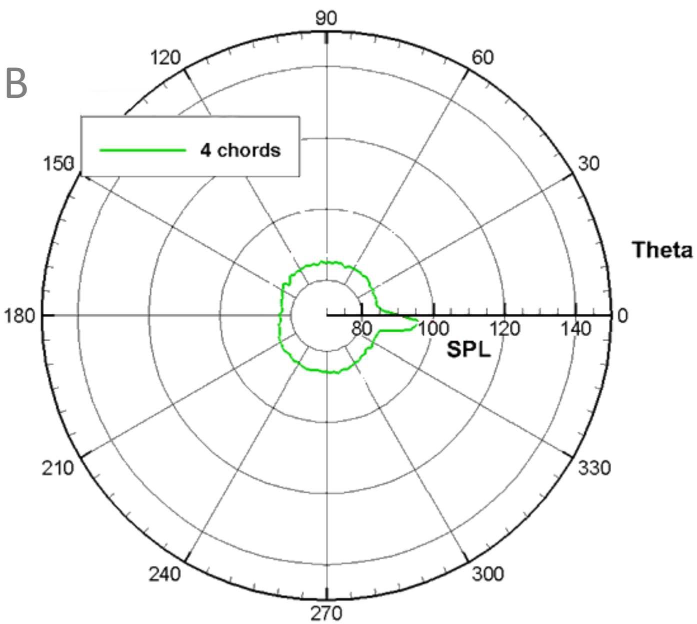


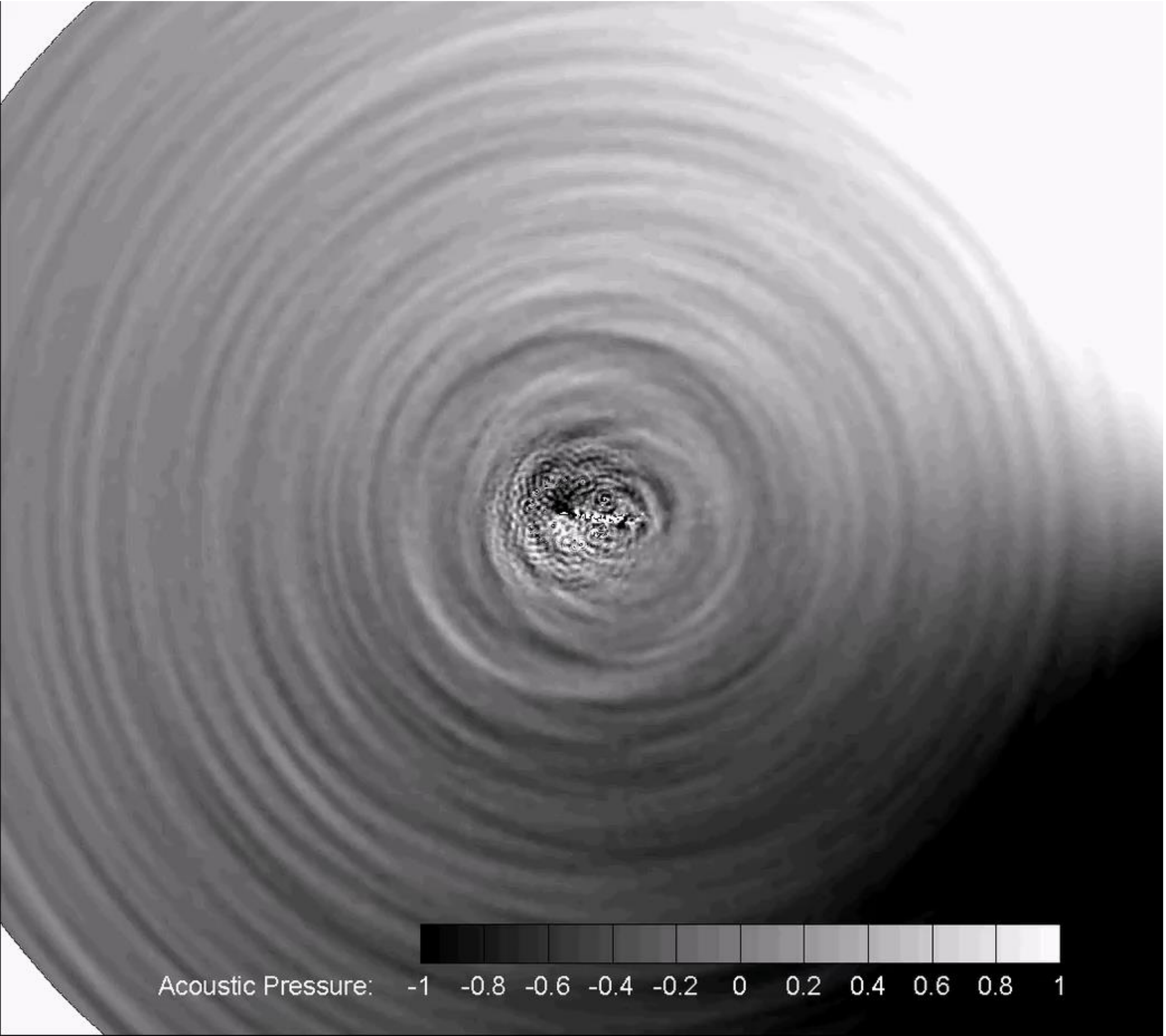
82 – 88 dB



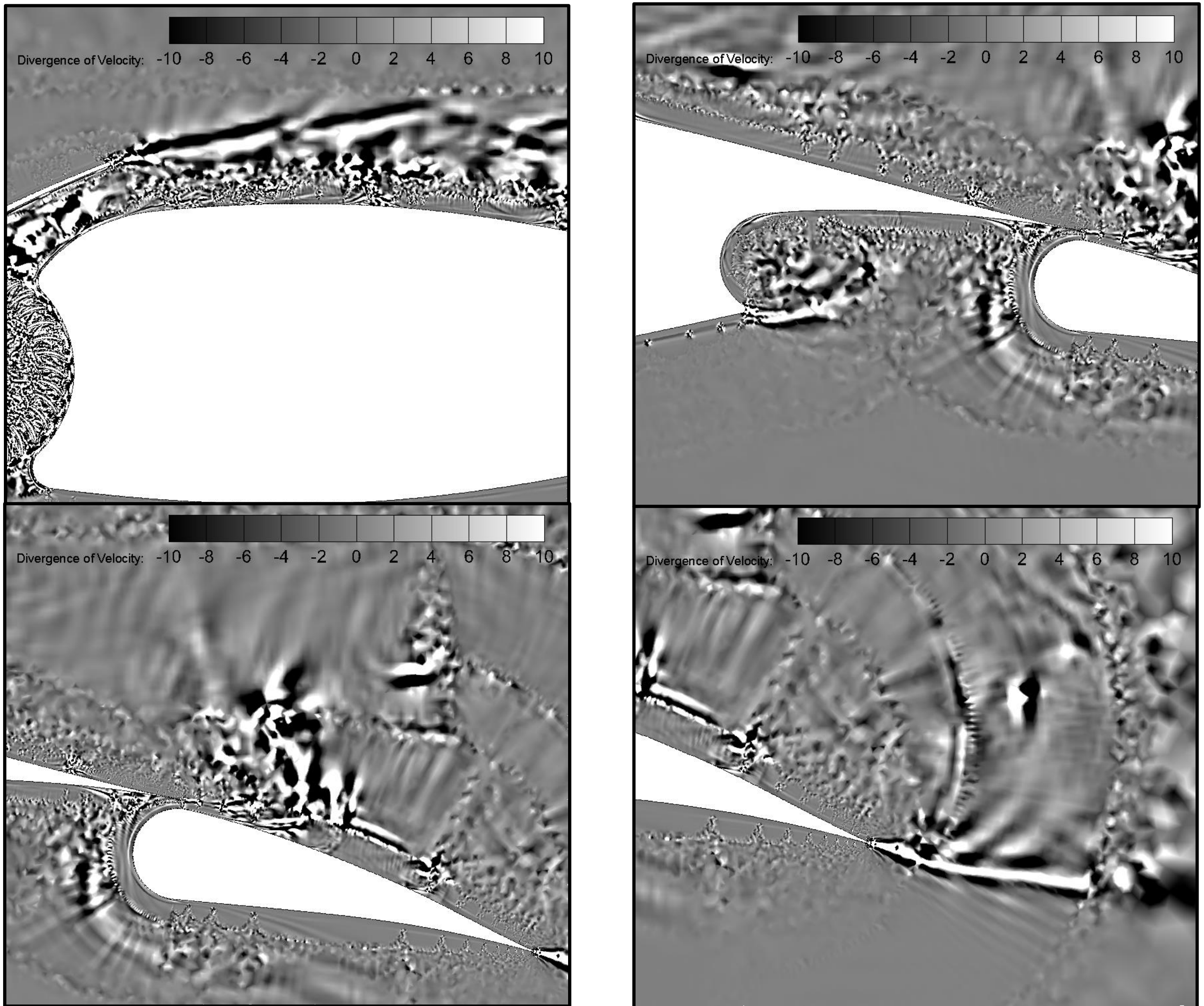
RMS pressure directivity in the near field

70 – 150 dB

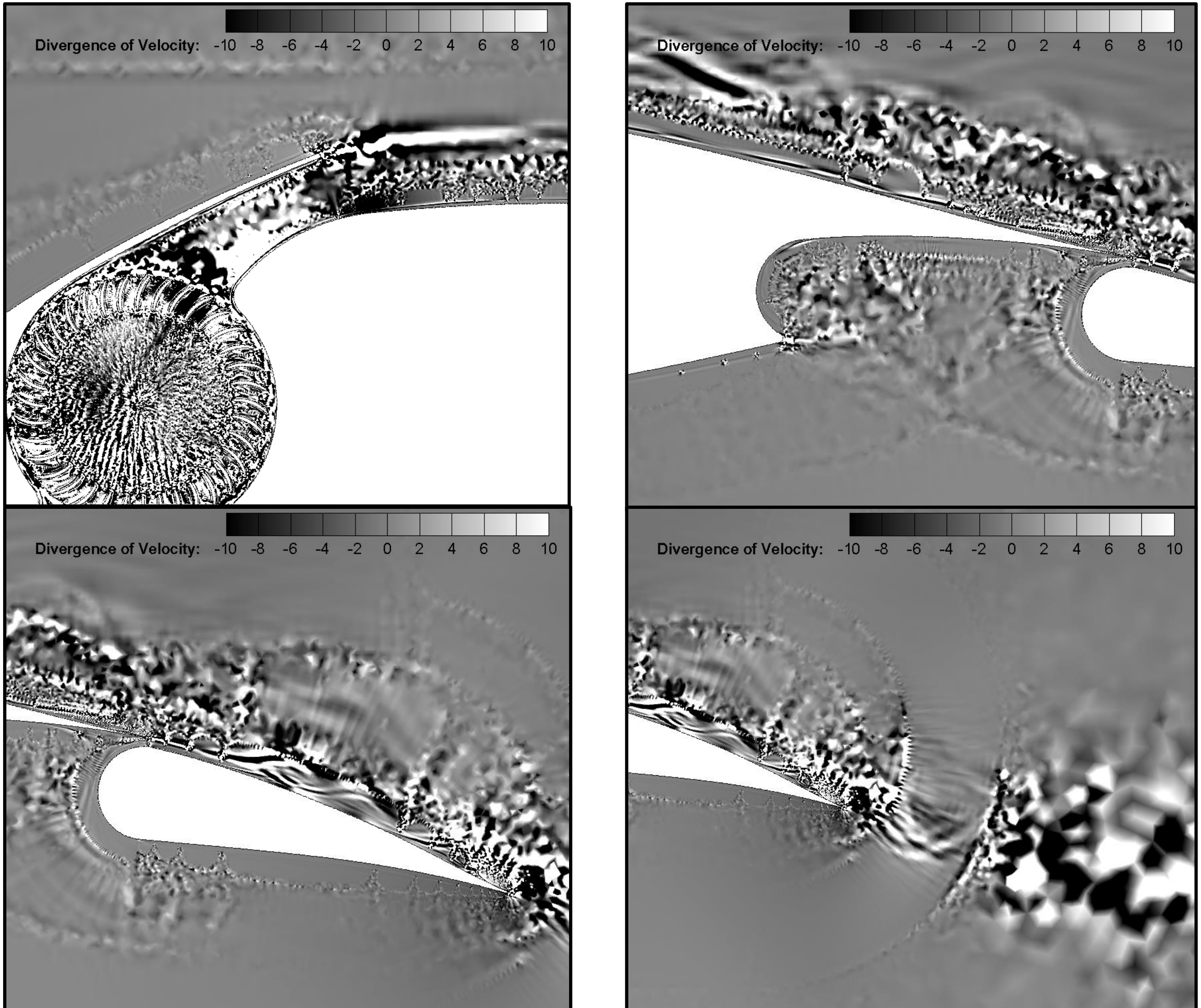



Acoustic Pressure: -1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1

CFF Off – Dilatation Field

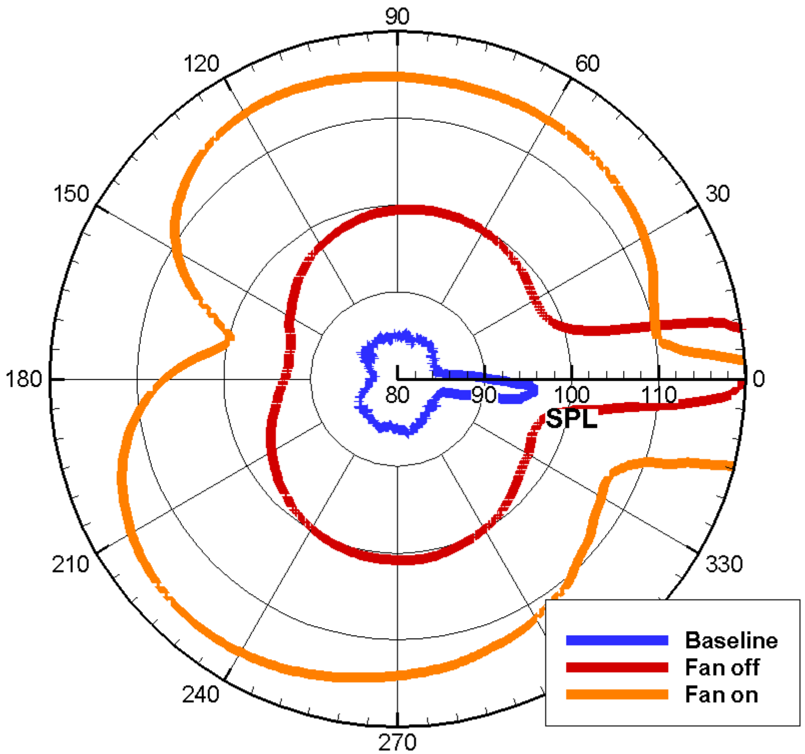


CFF On – Dilatation Field



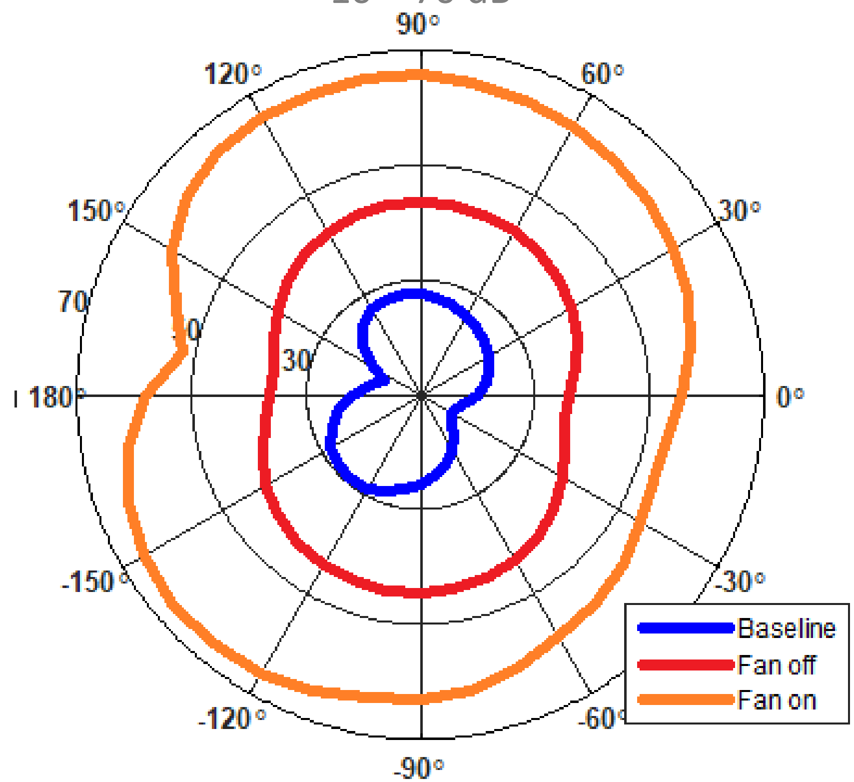
Near field / Far field comparison

80 – 120 dB



Near field (4 chords)

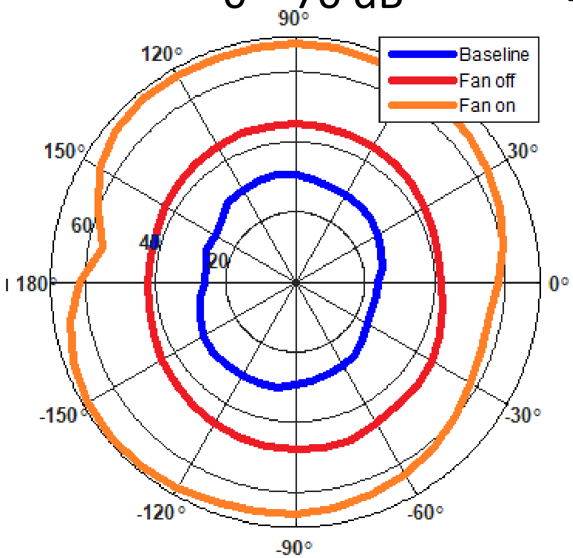
10 – 70 dB



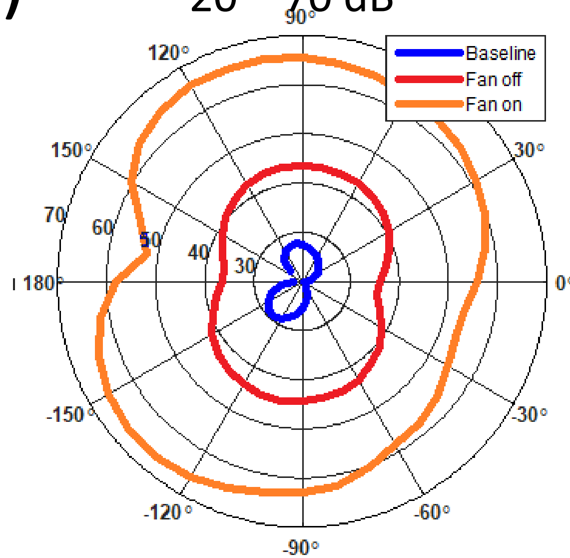
Far field (50 chords)

Directivity comparisons with different scales (f < 200 Hz)

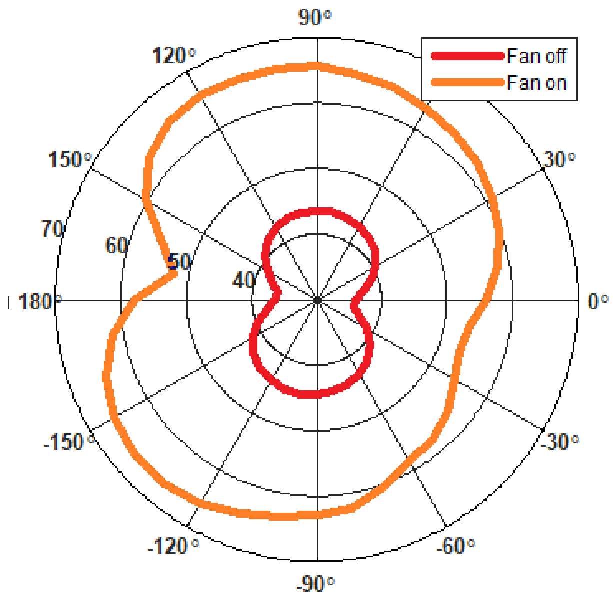
0 – 70 dB



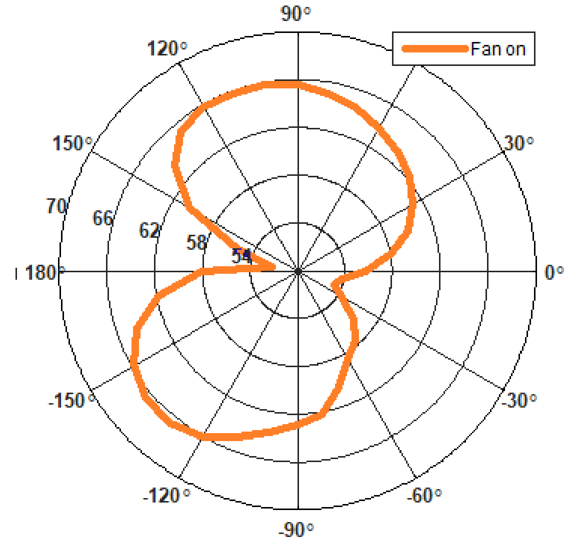
20 – 70 dB



35 – 70 dB

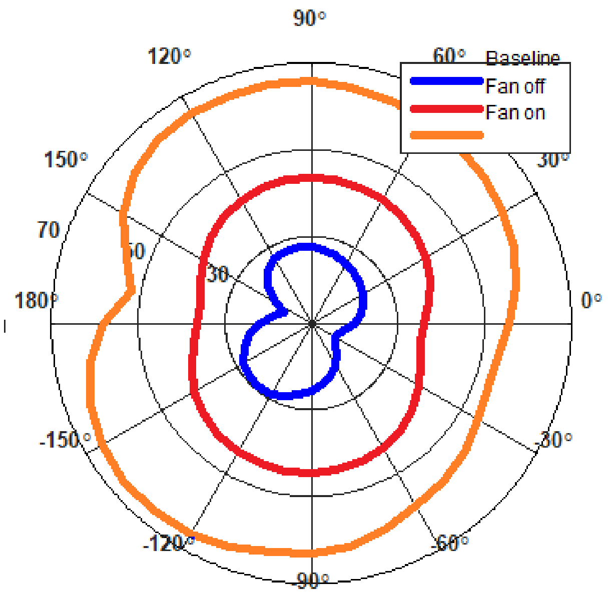


50 – 70 dB

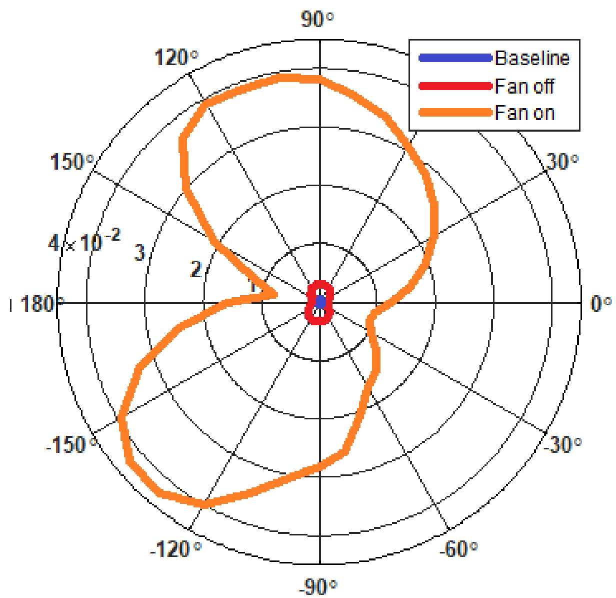


Directivity comparisons with different quantities (f < 200 Hz)

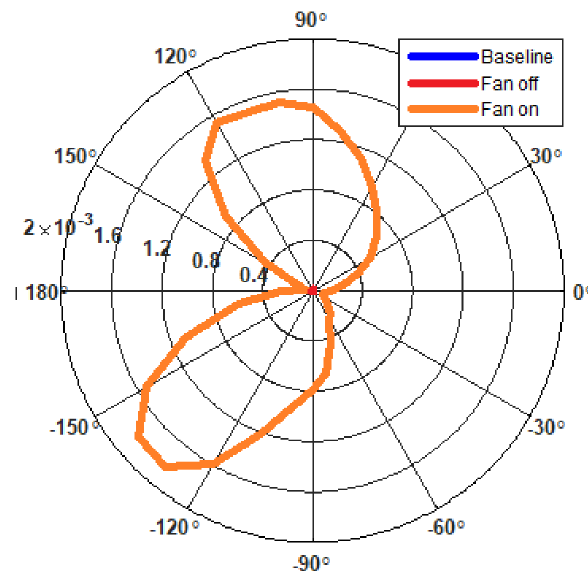
20 log(P/Pref)



P

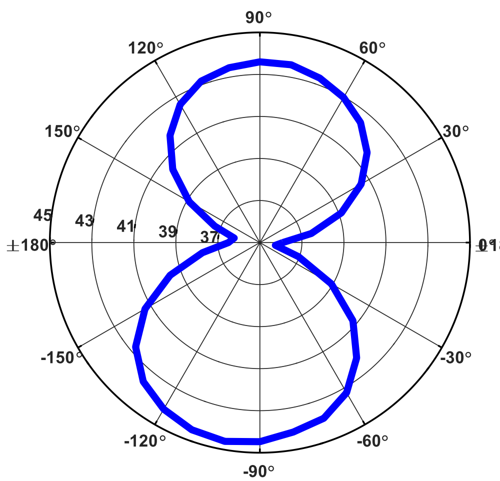


P^2

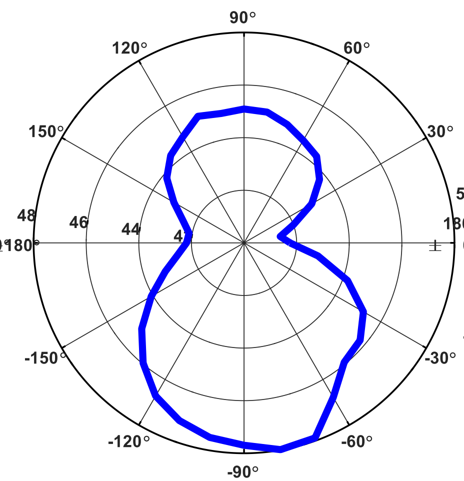


Directivity comparisons with different range of frequencies (fan off)

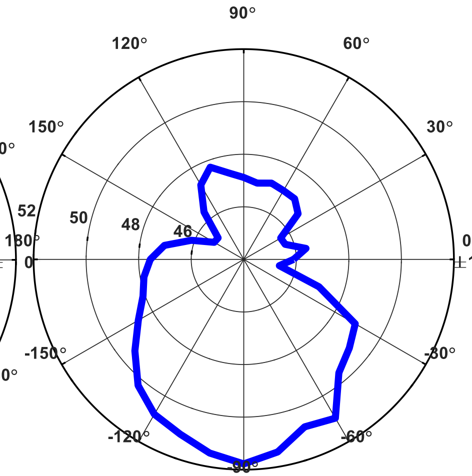
0 – 200 Hz



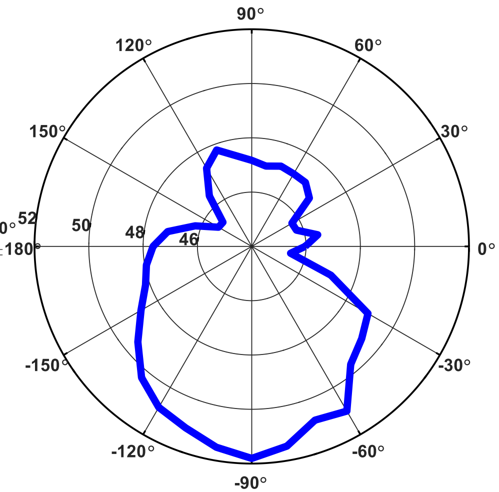
0 – 400 Hz



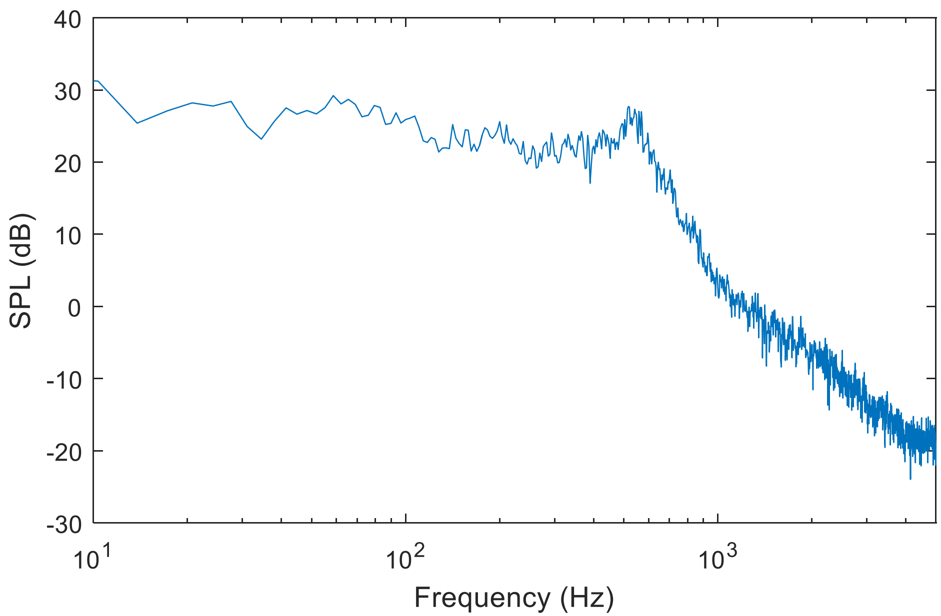
0 – 800 Hz



All frequencies

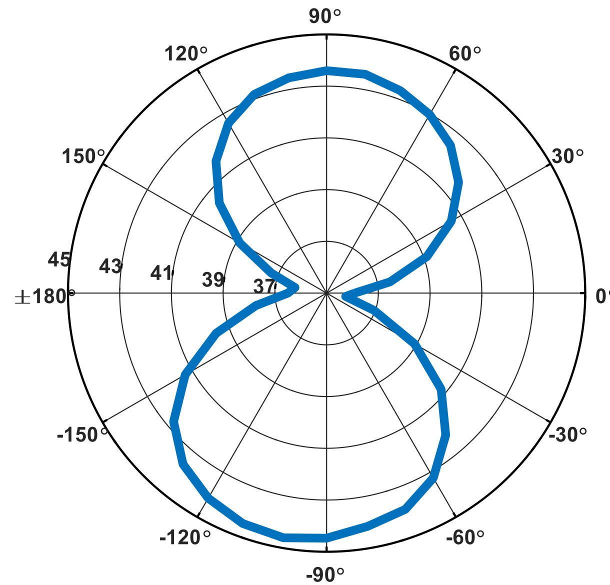


RMS or average ?



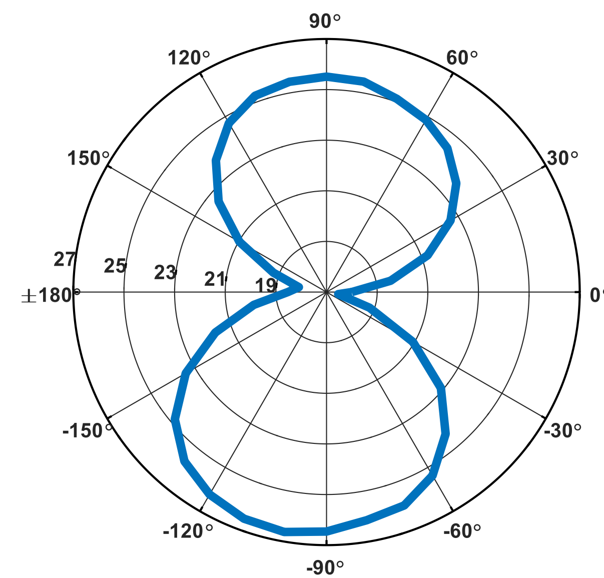
35 – 45 dB

RMS



17 –27 dB

Average



Doing average on low frequencies gives the same shape as RMS but with an amplitude that matches better with spectra

Average would be smaller than highest amplitudes

RMS would be bigger than all the amplitudes

Example of SPL directivity plot in another paper