ENGINE-AIRFRAME INTEGRATION STUDIES FOR FUTURE EFFICIENT PROPULSION SYSTEMS

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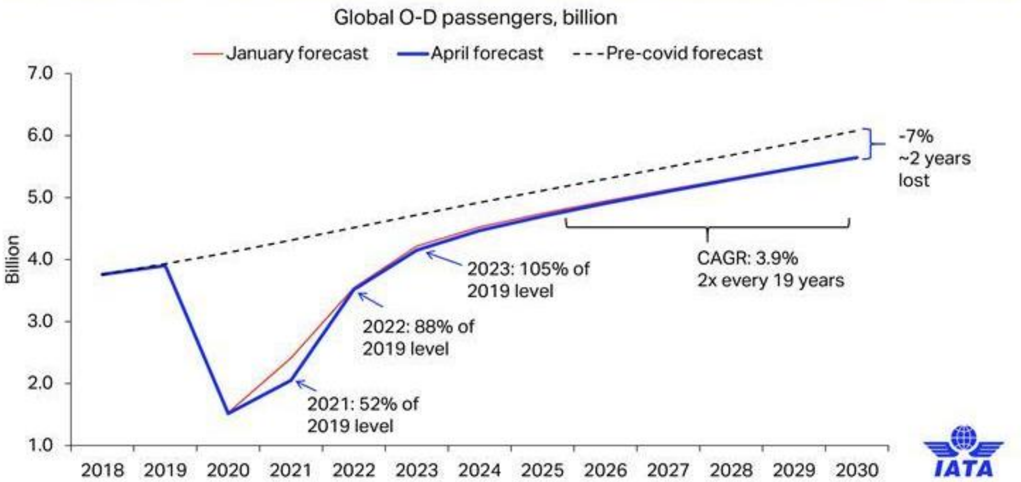
IWACC 8 @ UTIAS, Toronto, ON, CA, May 31-June 2, 2023

Introduction & Motivation:
I have missed views like this in 2020 & 2021

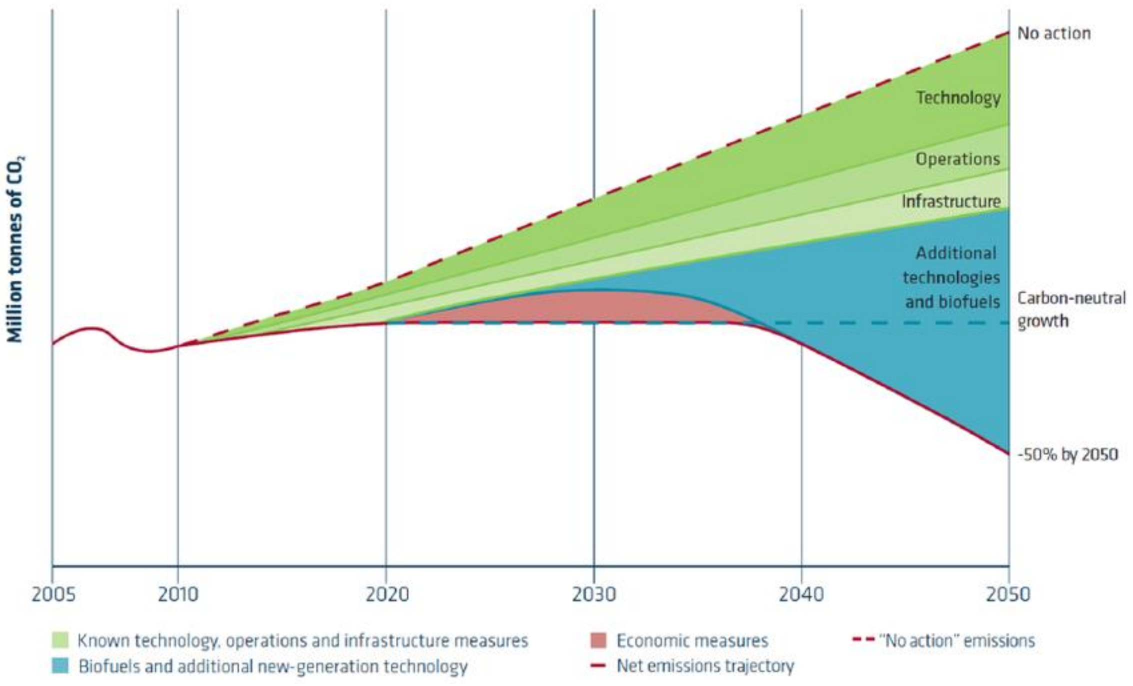
- Aviation is a key part in the complex web of global trade, political, cultural and personal exchanges and the broadening of horizons
- Travel & aviation industries were hard-hit by the pandemic, but well on the way to return to pre-2020 growth rates



: IATA Economics using data from Tourism Economic/IATA Air Passenger Forecast, April 2021.

- Increased environmental and societal pressures call for challenging reductions in carbon emission

Introduction & Motivation
The Challenge of Integrating Efficient Propulsion Systems Efficiently

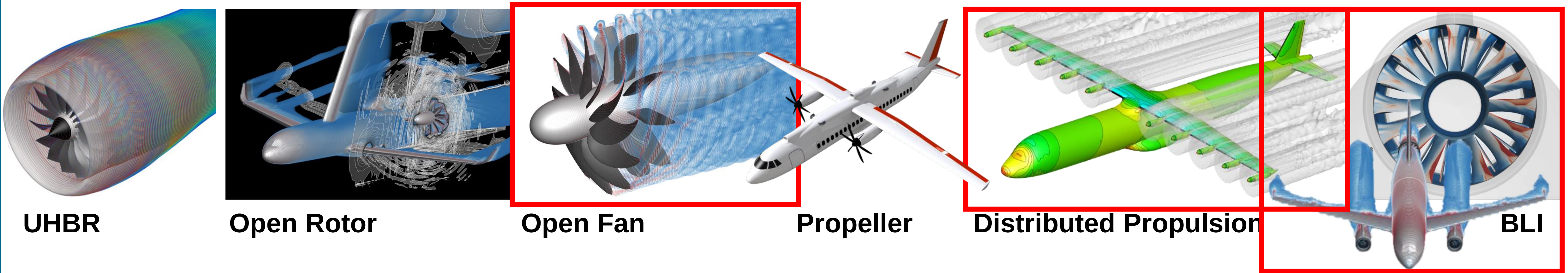


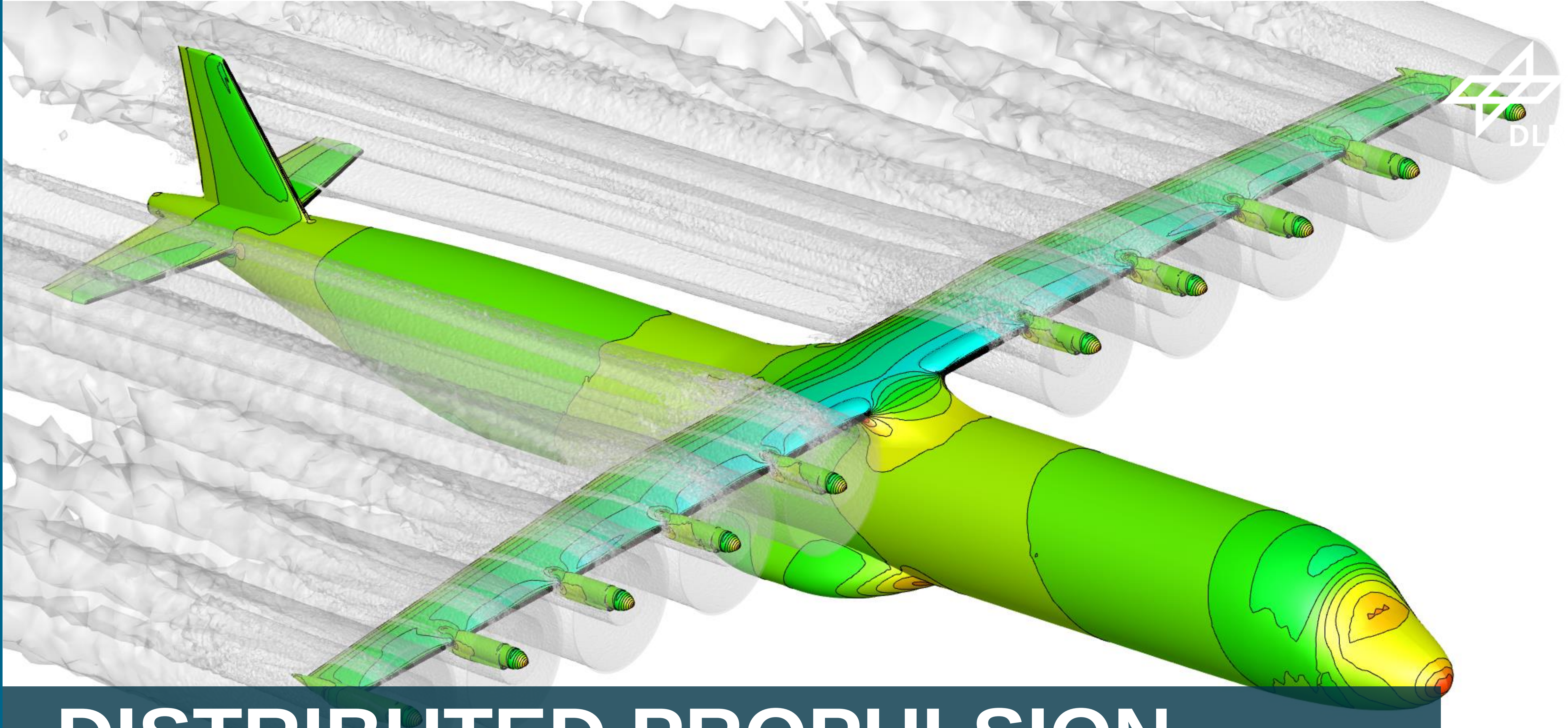
- Propulsion technology will be core part of technology answer
- Several promising engine technologies under study:
- UHBR turbofans (with geared fans), Open Rotor/Fan engines, Propellers, Distributed (propeller) propulsion, Boundary Layer Ingesting (BLI) engines
- Most target improvements in propulsive efficiency:

$$\text{Thrust: } F = \dot{m}\,(v_9 - v_0)$$

$$\text{Propulsive Efficiency: } \eta_P = 2/(1 + \mathrm{v}_9 / \mathrm{v}_0)$$

- Mostly clear propulsive efficiency advantages at engine level
  - Challenge (aerodynamics and beyond) is integration of these propulsion technologies with the airframe





DISTRIBUTED PROPULSION

DENNIS KELLER
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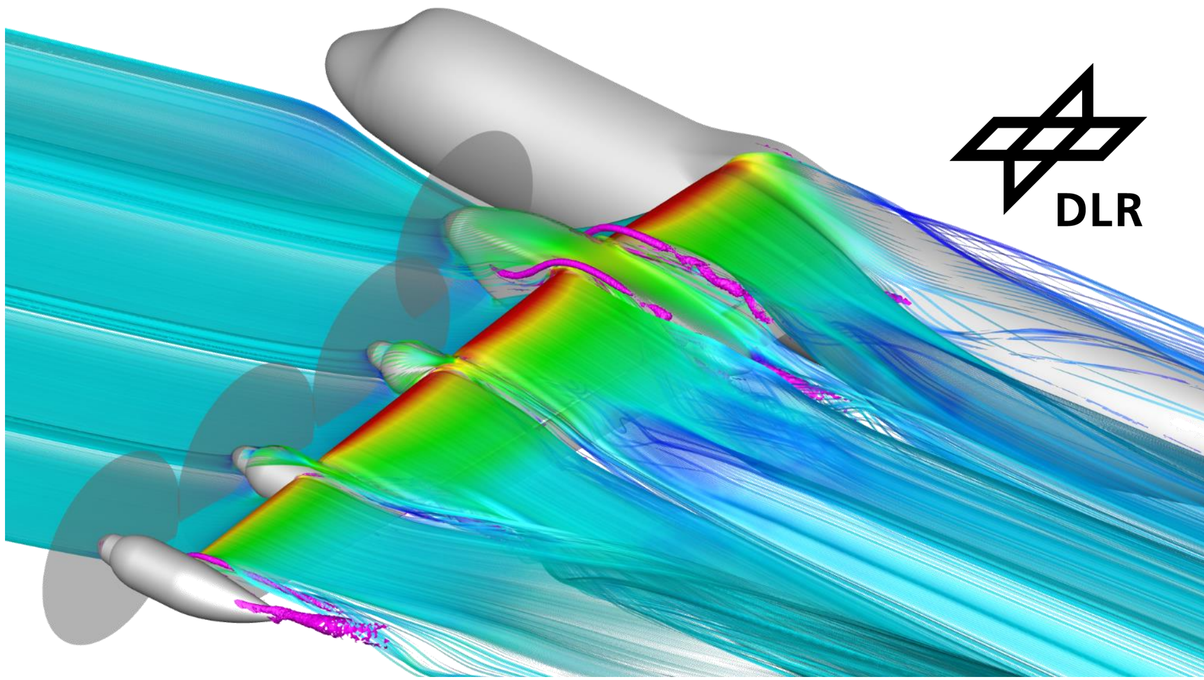
Distributed Propulsion
Motivation

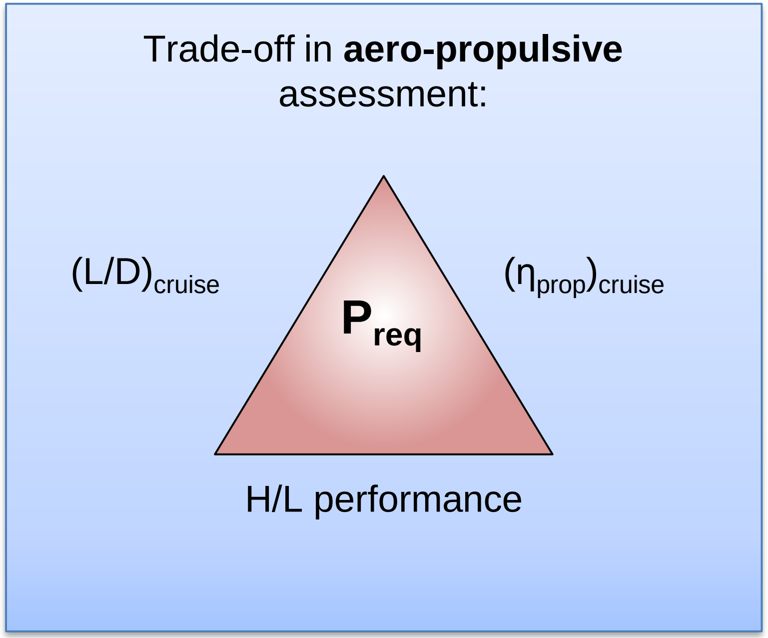


(Hybrid-)electric propulsion as a promising approach to significantly reduce CO_2 emissions

- Opens up design space due to scalability of electric motors

“Distributed propulsion“ one new design option

- Advantages are primarily based on flight mechanical / safety considerations (control surface size, installed thrust, …)
- Potential for improvements of aerodynamic efficiency at cruise:
  - “Direct” efficiency improvement (wing-tip propeller, thrust re-distribution, shape,…)
  - “Indirect” efficiency improvement (high-lift perfo)
- Optimal performance requires detailed trade-off studies



Distributed Propulsion
The LuFo SynergIE Project

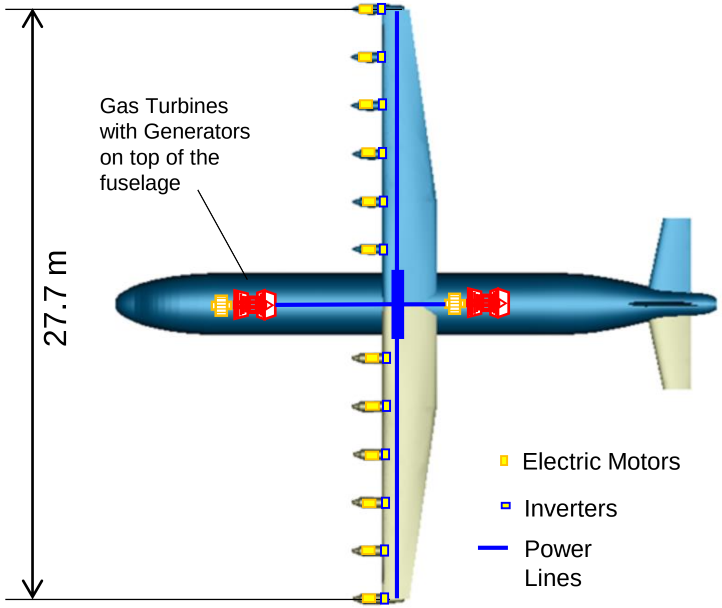
German nationally funded project **SynergIE** (2018-2021)

“SynergIE” hybrid-electric concept aircraft studied at conceptual level and using hi-fi CFD parameter studies

DLR TAU-Code RANS-based studies using actuator disc propeller modeling performed for:

- Basic integration effects
- Wing Tip Propeller
- Streamwise propeller position / propeller count
- High-lift performance evaluation
- Wing size
- Impact of lift distribution
- Thrust re-distribution
- Wing L.E. shape modification
- Variation of nacelle diameter
- …

TLARS	
Payload	70 PAX
Range	1000 nm
Cruise Mach	0.55
Cruise Altitude	27000 ft
TOFL @ SL,ISA	1400 m
Approach Speed	120 kts



2 Prop

6 Prop

12 Prop

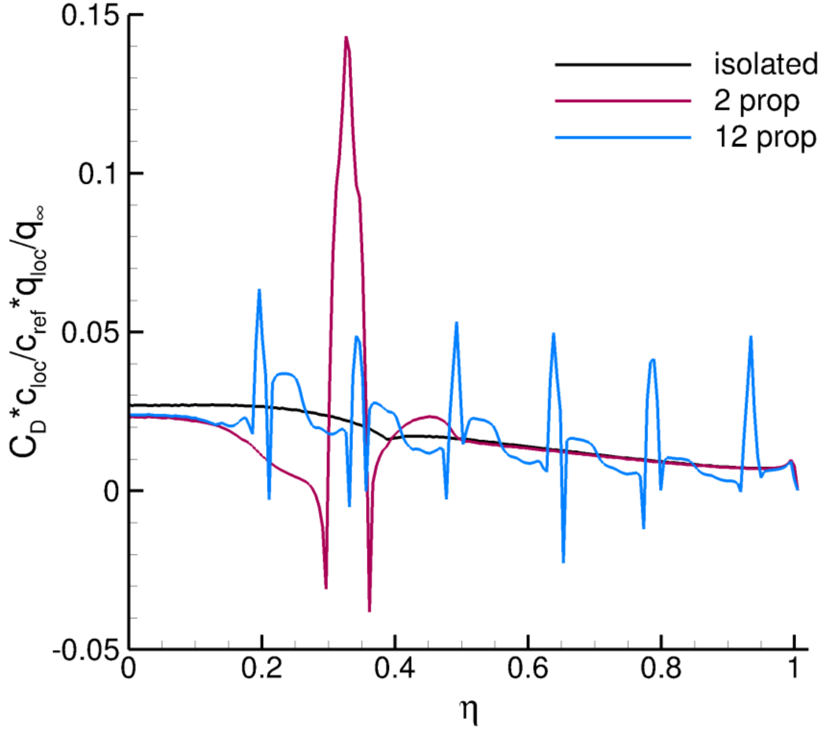
courtesy of Georgi Antanasov

Evaluation of aero-propulsive efficiency (aerodynamics + propeller) via analysis of required propulsive power:

$$P_{req} \sim \frac{C_T}{\eta_{prop}} \approx \frac{C_D}{\eta_{prop}} = \frac{C_L}{\frac{L}{D} * \eta_{prop}}$$

cruise flight!

Distributed Propulsion: Impact on Wing Aerodynamics
Basic Propeller Integration Effects – 2 vs 12 Propellers



	2 Prop (isolated)	2 Prop		12 Prop	
			vs. 2 Prop (iso)		vs. 2 Prop (iso)
$(C_L)_{AF}$	0.526	0.523	-0.4 %	0.522	-0.6 %
$(L/D)_W$	28.7	29.9	4.2 %	28.9	0.7 %
$(L/D)_{AF}$	17.3	17.7	**2.3 %**	17.4	**0.2 %**
$T_{req}{}^*$	11.75 kN	11.45 kN	**-2.6 %**	11.67 kN	**-0.7 %**
η_{Prop}	90.4 %	91.7 %	1.5 %	93.6 %	3.6 %
$\mathbf{P_{req}}{}^*$	2.196 MW	2.109 MW	**-3.9 %**	2.106 MW	**-4.1 %**

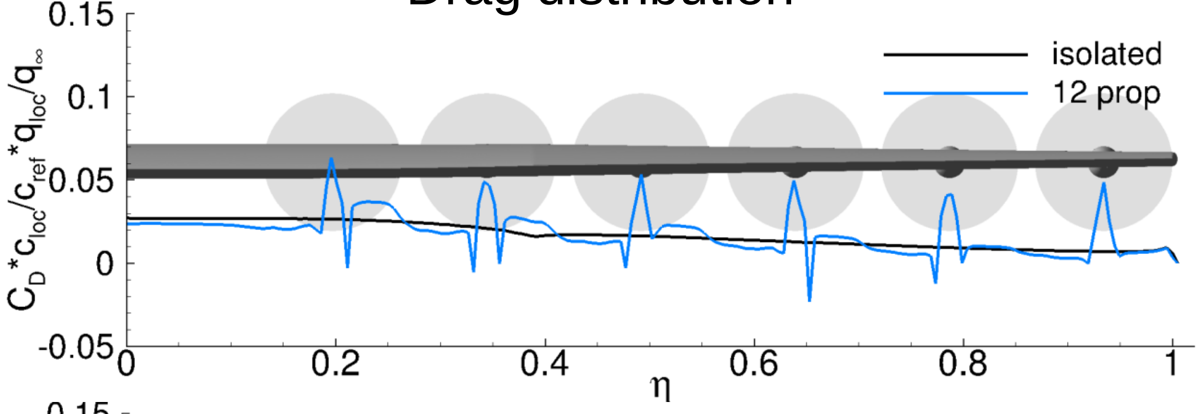
* for entire A/C

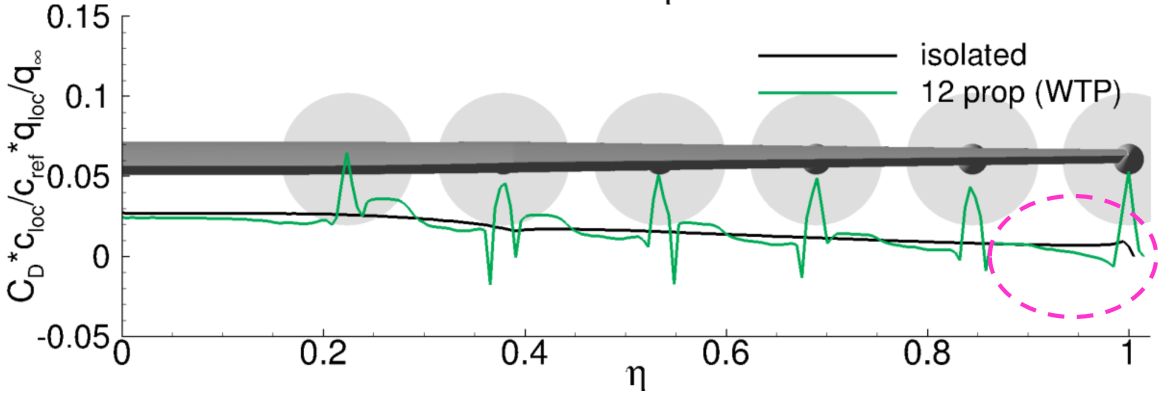
- Beneficial propeller slipstream effect possible
- Superior aerodynamic efficiency of 2 Prop vs. 12 Prop
- Drag increase in downwash area decreases towards wing tip
- Required propulsive power similar due to increase in propeller efficiency of 12 Prop (vs. 2 Prop)

Distributed Propulsion: Impact on Wing Aerodynamics
Basic Propeller Integration Effects – Wing-Tip Propeller

Impact on wing aerodynamics

Drag distribution





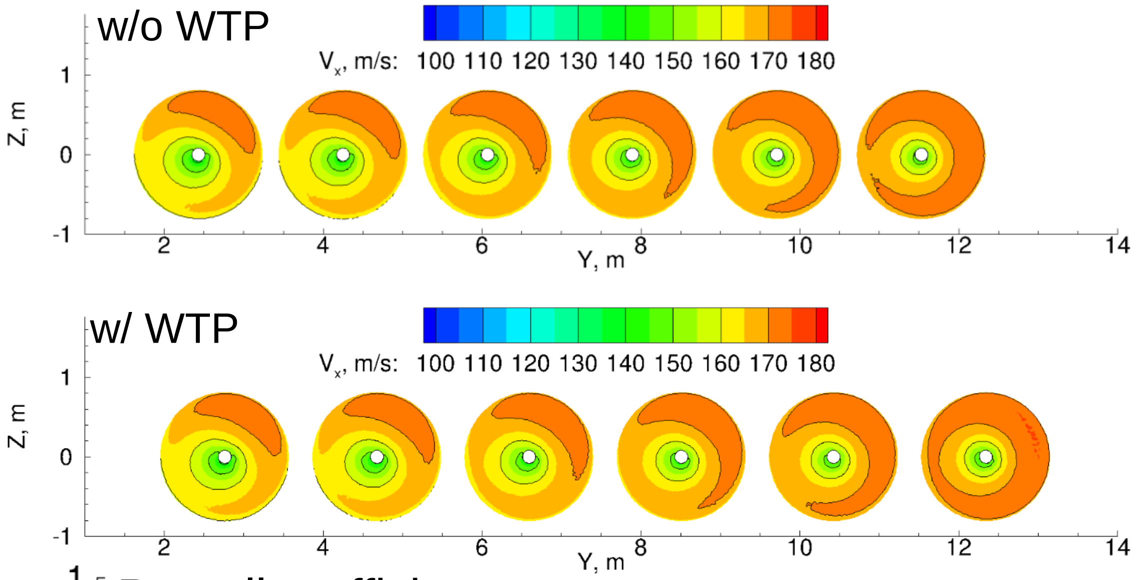
	12 eProp (w/o WTP)		12 eProp (w/ WTP)	
		vs. 2 Prop (iso)		vs. 2 Prop (iso)
$(C_L)_{AF}$	0.522	-0.7 %	0.522	-0.6 %
$(L/D)_W$	28.9	0.7 %	29.2	2.3 %
$(L/D)_{AF}$	17.4	**0.2 %**	17.5	**0.8 %**
T_{req}*	11.67 kN	**-0.7 %**	11.59 kN	**-1.4 %**

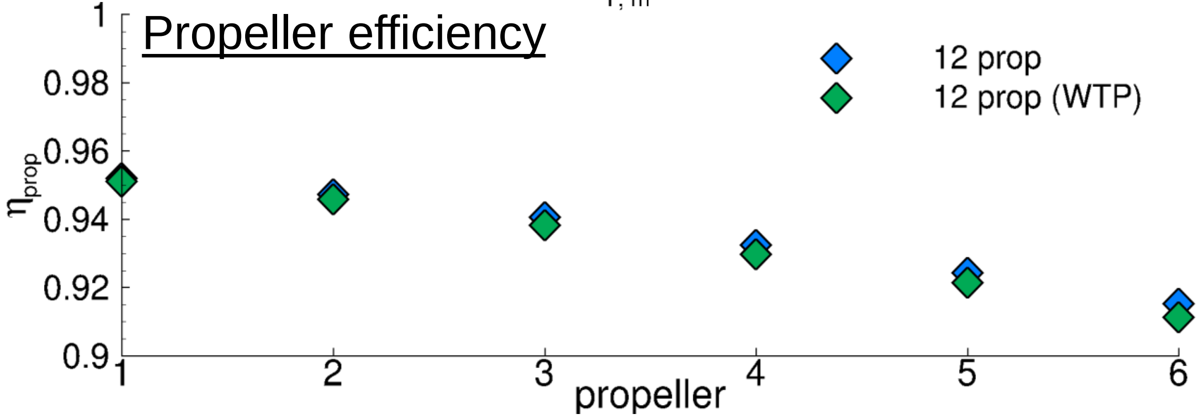
* for entire A/C

- WTP beneficial for L/D

Distributed Propulsion: Impact on Wing Aerodynamics
Basic Propeller Integration Effects – Wing-Tip Propeller

Impact on propeller efficiency and req. power



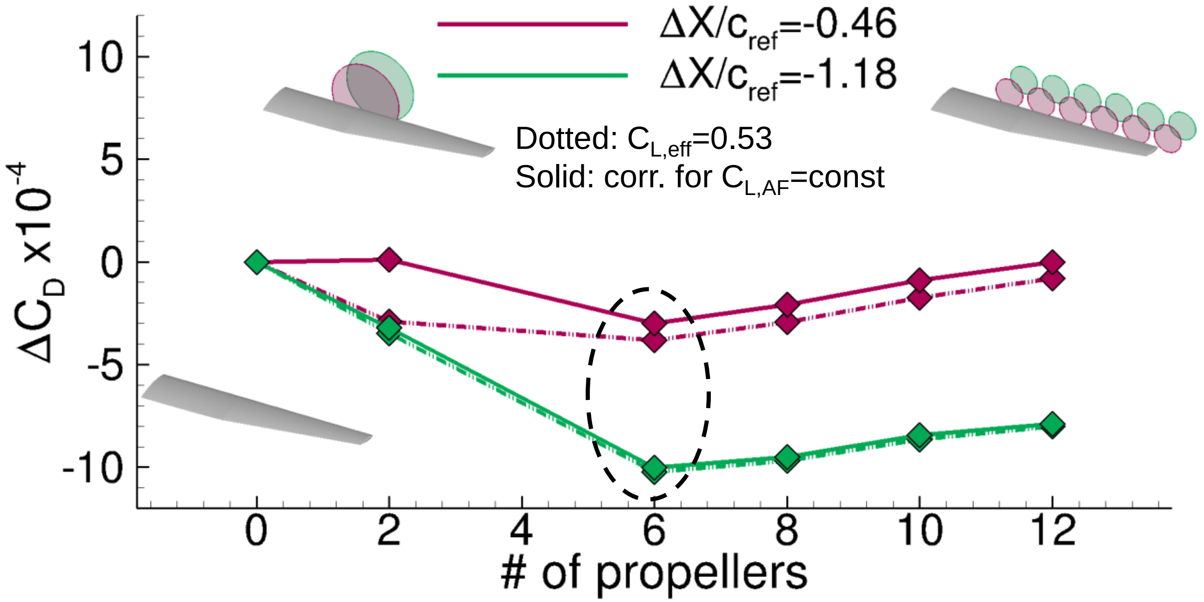


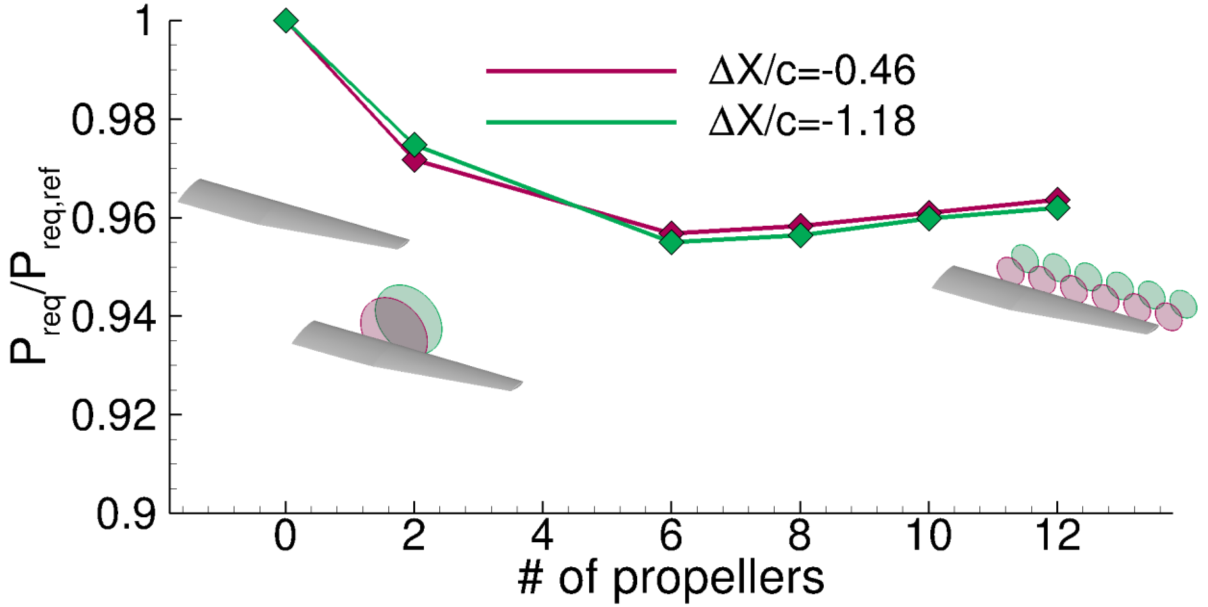
	12 eProp (w/o WTP)		12 eProp (w/ WTP)	
		vs. 2 Prop (iso)		vs. 2 Prop (iso)
$(C_L)_{AF}$	0.522	-0.7 %	0.522	-0.6 %
$(L/D)_W$	28.9	0.7 %	29.2	2.3 %
$(L/D)_{AF}$	17.4	**0.2 %**	17.5	**0.8 %**
T_{req}*	11.67 kN	**-0.7 %**	11.59 kN	**-1.4 %**
η_{Prop}	93.6 %	3.6 %	93.3 %	3.3 %
P_{req}*	2.106 MW	**-4.1 %**	2.096 MW	**-4.5 %**

* for entire A/C

- WTP beneficial for L/D
- Reduced propeller efficiency counteracts beneficial effect on aerodynamic efficiency

Distributed Propulsion:
Configuration Study: Number of Propellers

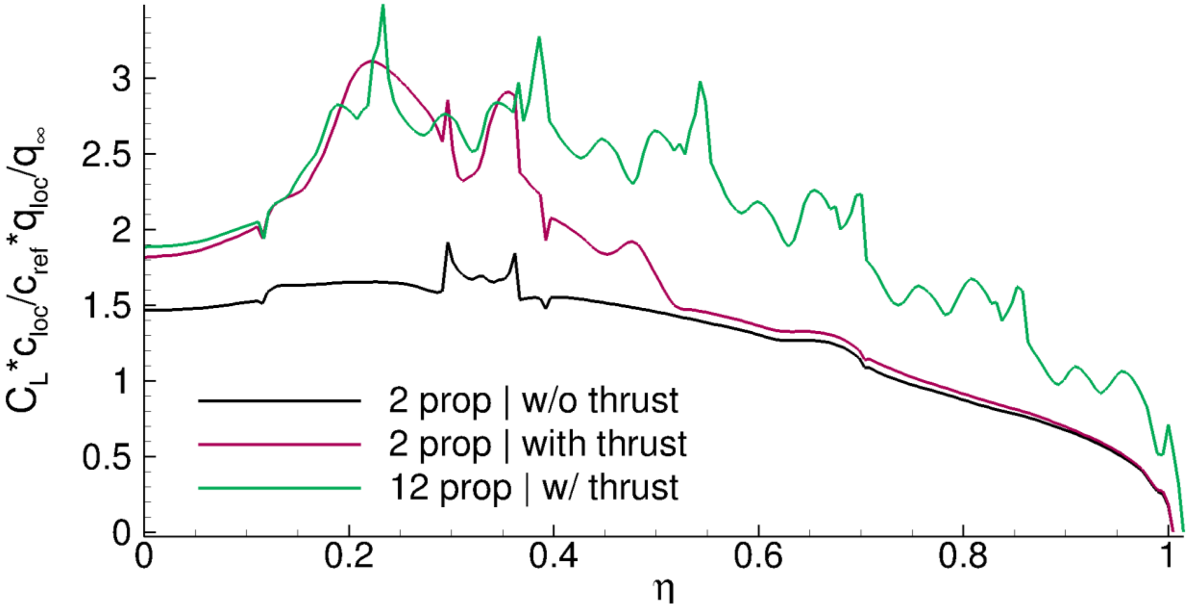




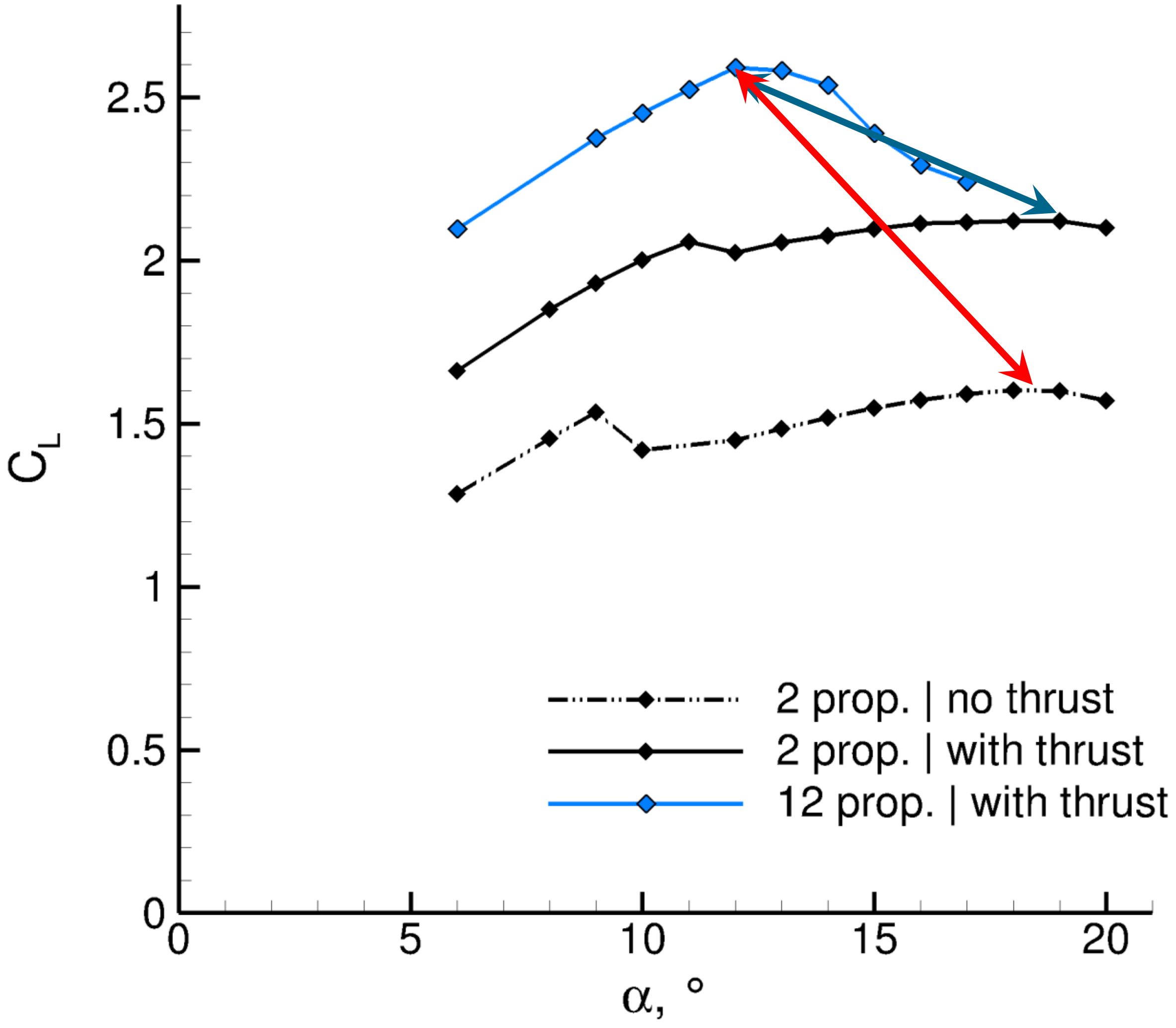
- Beneficial propeller slipstream effect in wing aero performance possible
- Strong dependence on prop-wing-distance
- Minimum C_D with 6 propellers
- Propeller efficiency benefits from installation due to reduced inflow velocity

Design study philosophy:
- S_{wing} = const.
- $\sum S_{prop}$ = const.
- X_{prop}/D_{prop} = const.

Distributed Propulsion:
Basic Propeller Integration Effects – High-Lift

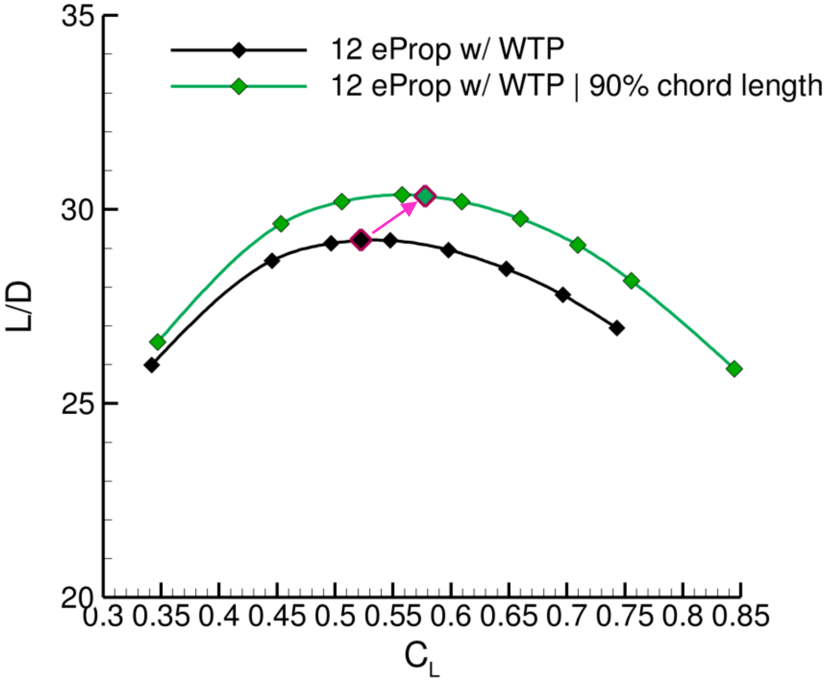


- No L.E. device, Plain flaps ($c_{F/A}/c$=0.2, δ_F=20° / δ_A=10°)
- Take-Off conditions: M=0.181, T=56 kN
- $C_{L,max}$=2.59 / $C_{L,eff,max}$=2.74
- **$\Delta C_{L,max}$=0.47** vs. 2eProp with thrust
- **$\Delta C_{L,max,eff}$=1.14 (≈+71%)** vs. 2eProp w/o thrust

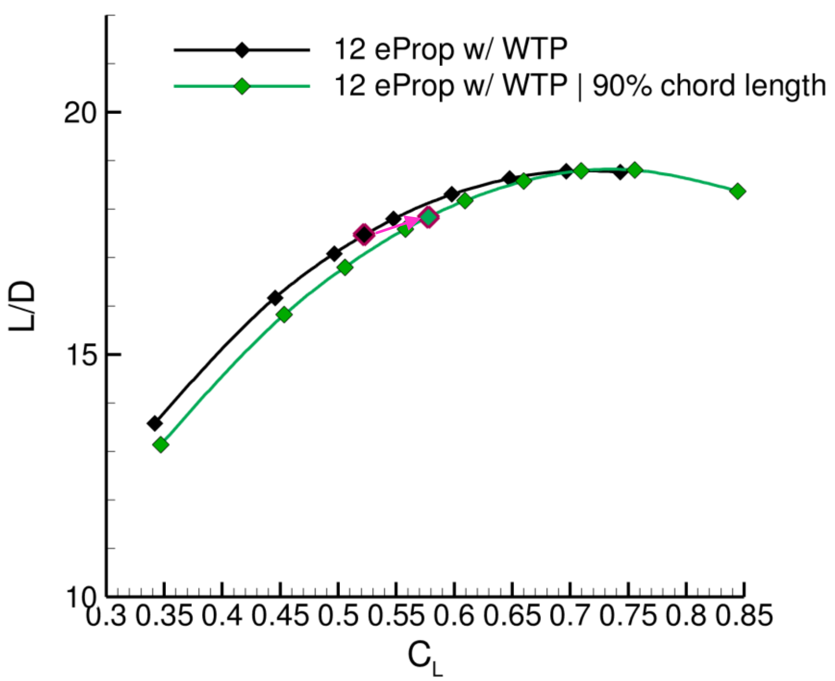


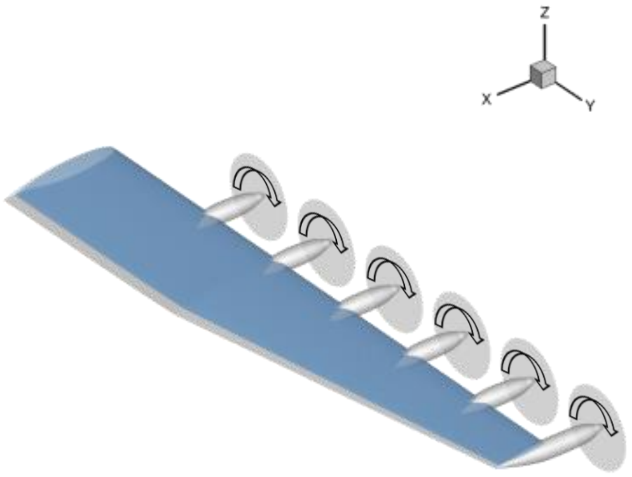
Distributed Propulsion:
Configuration Study: Wing Size Reduction

w/o fuselage/tail-C_D



w/ fuselage/tail-C_D





90 % wing size:

- **Assumption:** Wing size reduction via chord length decrease by 10 % possible due to improved H/L-performance

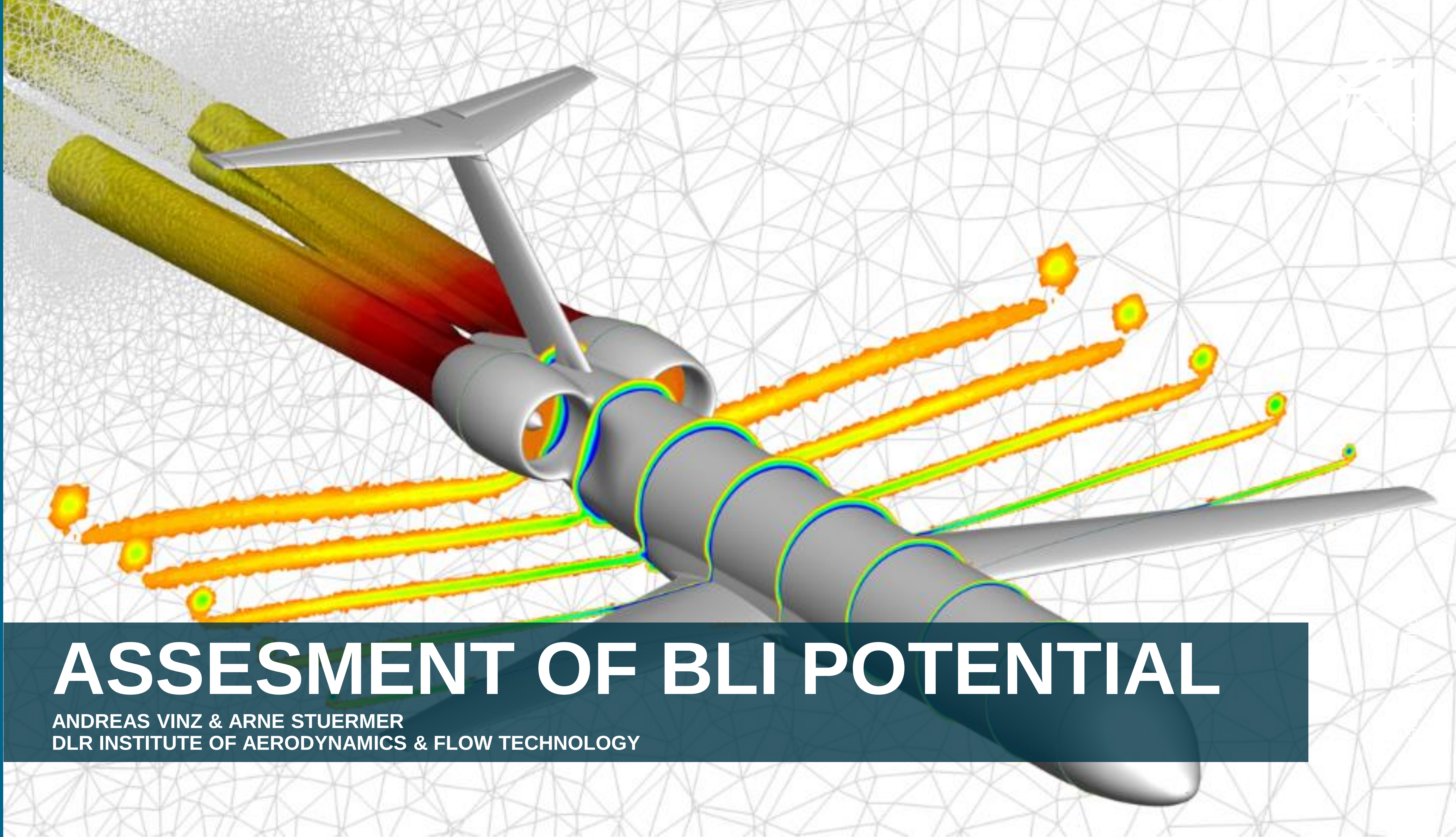
	vs. 12 Prop (BSL)	vs. 2 Prop
L/D	2.1 %	1.4 %
η_{Prop}	0.2 %	1.6 %
P_{req}	**-2.3 %**	**-3.3 %**

Distributed Propulsion: Summary & Conclusions

- Clear potential for improved (cruise) performance of distributed propeller propulsion seen in the SynergIE project

- Vast set of of design parameters require careful study – even just in terms of maximizing the aerodynamic efficiency
  - Balancing between best airframe and best propeller performance often critical
- High lift performance clealy benefits from distributed propellers at take-off – approach performance (little to no thrust) is challenging

- Certification criteria, off-design performance (1-x propeller inpoperative,…) are still unclear
- Continued work with refined design studies under way in the frame of the EU-fundend IMOTHEP project



ASSESMENT OF BLI POTENTIAL

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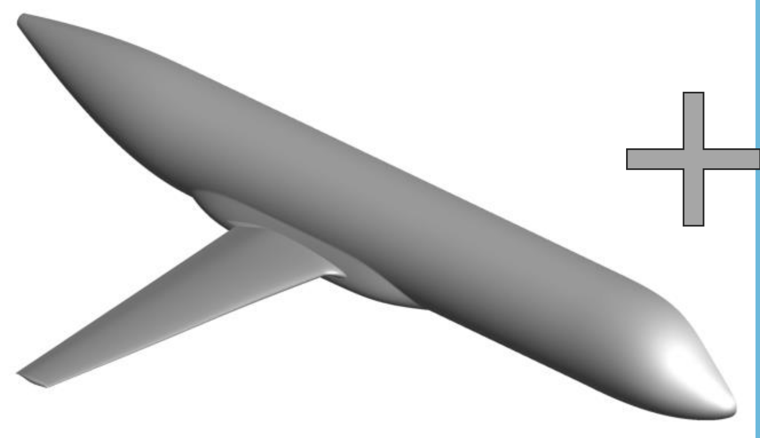
Assessment of BLI Performance Benefit
Introduction

DLR TuLam-Aircraft	CRISP-Multi-Fan Engine



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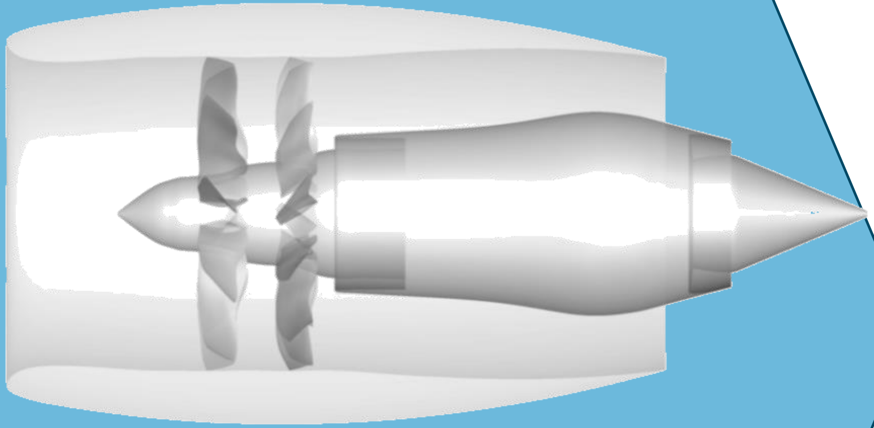


Aircraft	
Length	37.57 m
Wing area	122.0 m²
Wing span	34.0 m

Engine	
Fan diameter	2.343 m
Nr. of blades 1/2	10/12
Bypass ratio	17:1

DLR AGATA project (2016-2022):

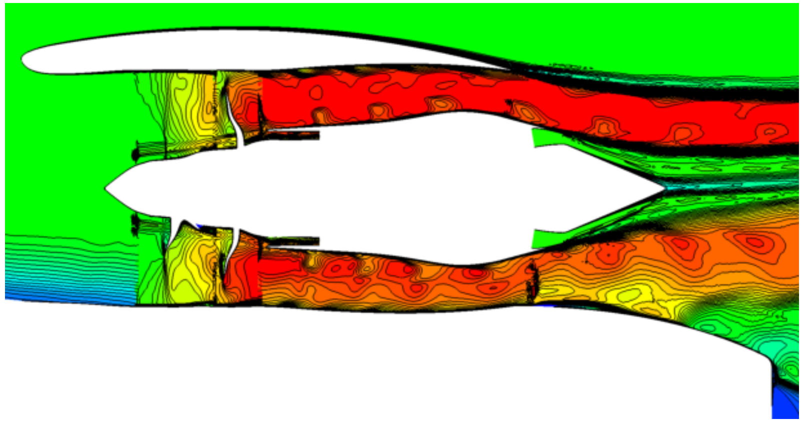
- Focus on BLI impact on fan performance and acoustics
- Large-scale model engine tests at DLR in Cologne
- Conta-rotating fan engine

Aircraft from DLR TuLam Project – Toughen-up Laminar Technology

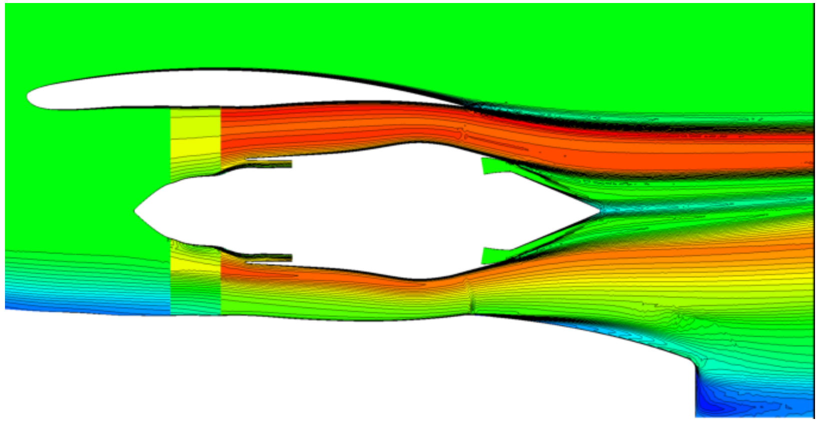
- SMR aircraft with Forward Swept Natural Laminar Flow Wing (FSW-NLF)
- Top Level Aircraft Requirements (TLARs) match with A320-200
- Cruise design point: Ma=0.78, $Re_{AMC}=24*10^6$, $C_L=0.52$

Assessment of BLI Performance Benefit
Numerical Analysis Approach

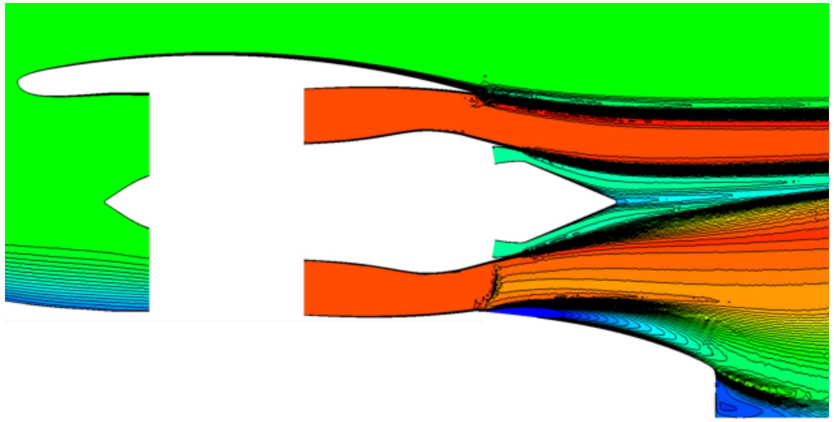
① 3D-Rotor



② 2D Actuator Disc



③ Engine BC



Studies of installed engine modeling fidelity in CFD driven by analysis goals

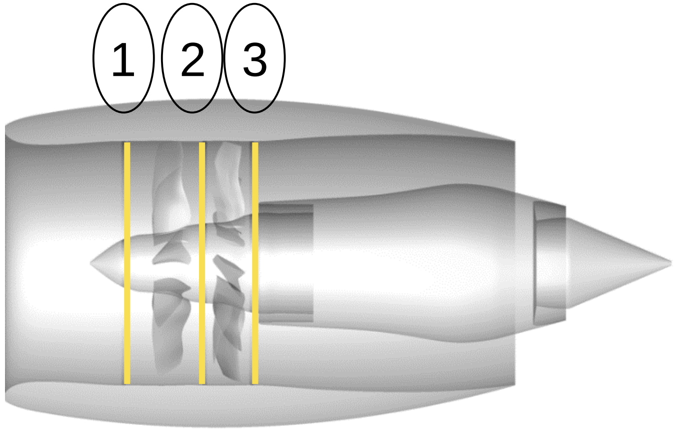
1. Fully modeled fan in uRANS simulations – current highest fidelity and accuracy, at high computational costs
2. Steady RANS approach with actuator disc modeling of the fan stages – shown as a good accuracy approach for studies of airframe-fan interactions at lower computational costs
3. Steady RANS simulations with the classical engine boundary condition for relevant results on the airframe side

Assessment of BLI Performance Benefit
Numerical Analysis Approach

Very good match between AD and uRANS engine peroformance predicitions (~1%)

	p_{t2} / p_{t1} [-]	p_{t3} / p_{t2} [-]	p_{t3} / p_{t1} [-]	m [kg/s]
uRANS Isolated Engine	1.148	1.116	1.281	319.6
AD Isolated Engine	1.131 **(-1.4%)**	1.122 **(+0.5%)**	1.269 **(-0.9%)**	315.6 **(-1.3%)**
uRANS BLI	1.147	1.113	1.276	310.2
AD BLI	1.125 **(-1.9%)**	1.123 **(+0.9%)**	1.263 **(-1.0%)**	308.9 **(-0.4%)**

	uRANS		**AD**	
	Isolated Engine	**BLI**	**Isolated Engine**	**BLI**
Runtime [h]	168	336	8 **21x faster**	12 **28x faster**
CPU hours	215 040	668 128	1024 **210x better**	1536 **434x better**

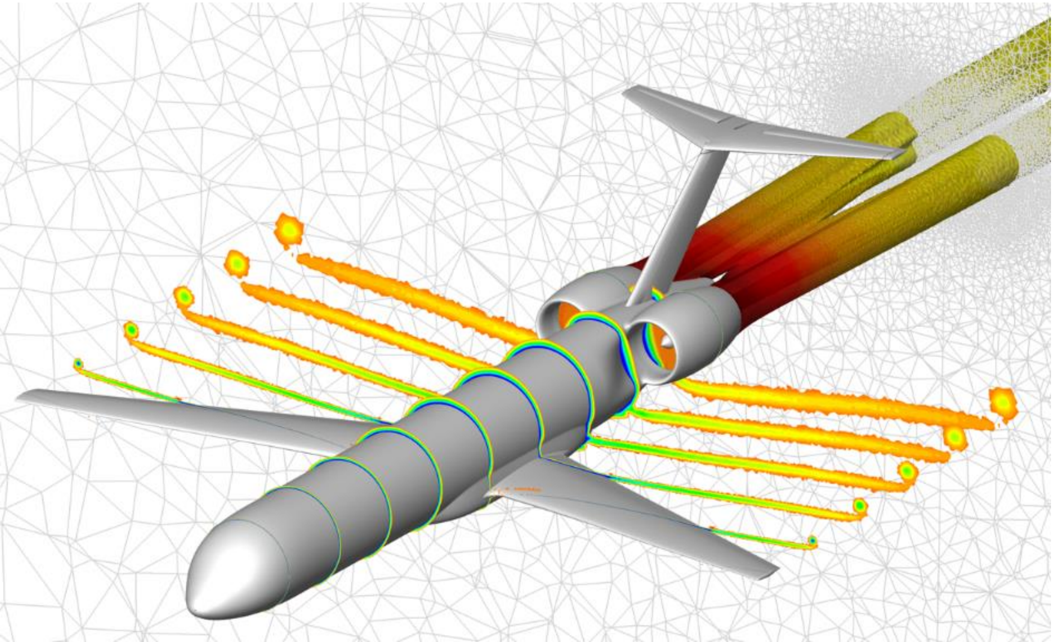


Assessment of BLI Performance Benefit
Numerical Analysis Approach

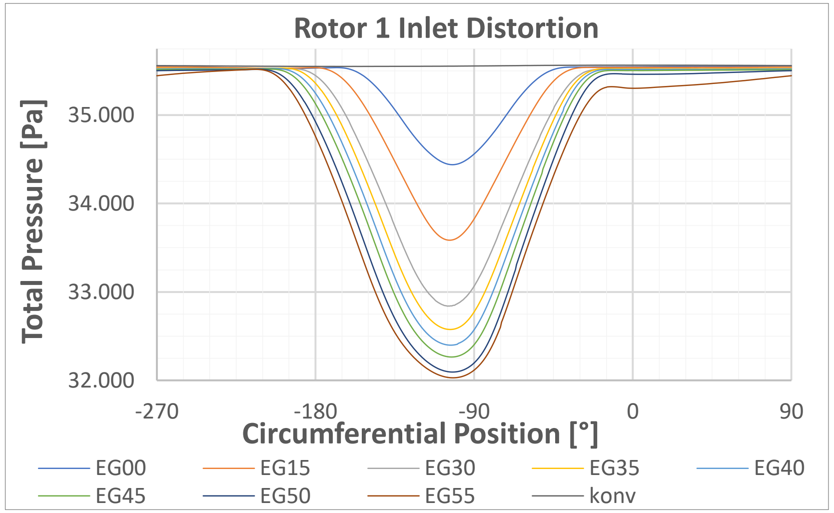
- Study of BLI performance benefits at aircraft level using an actuator disc approach for a thrust-trimmed aircraft at cruise conditions:
  - $C_L = 0.52$
  - $C_t = C_D$ (Thrust = Drag)

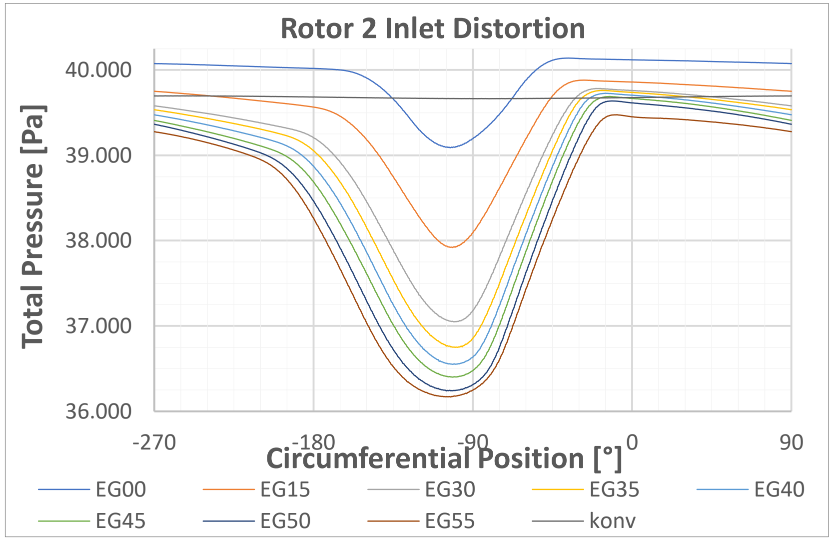
- Fixed core engine operating point:
- P_{tot}/P_{inf} (= 1.393)
- T_{tot}/T_{inf} (= 2.269)

Cruise flight	
Mach number	0.78
Altitude	35 000 ft
Static temperature	228.8 K
Static pressure	23842 Pa
Density	0.363 kg/m³



Assessment of BLI Potential
Inflow Distortions for Rotor 1 and Rotor 2



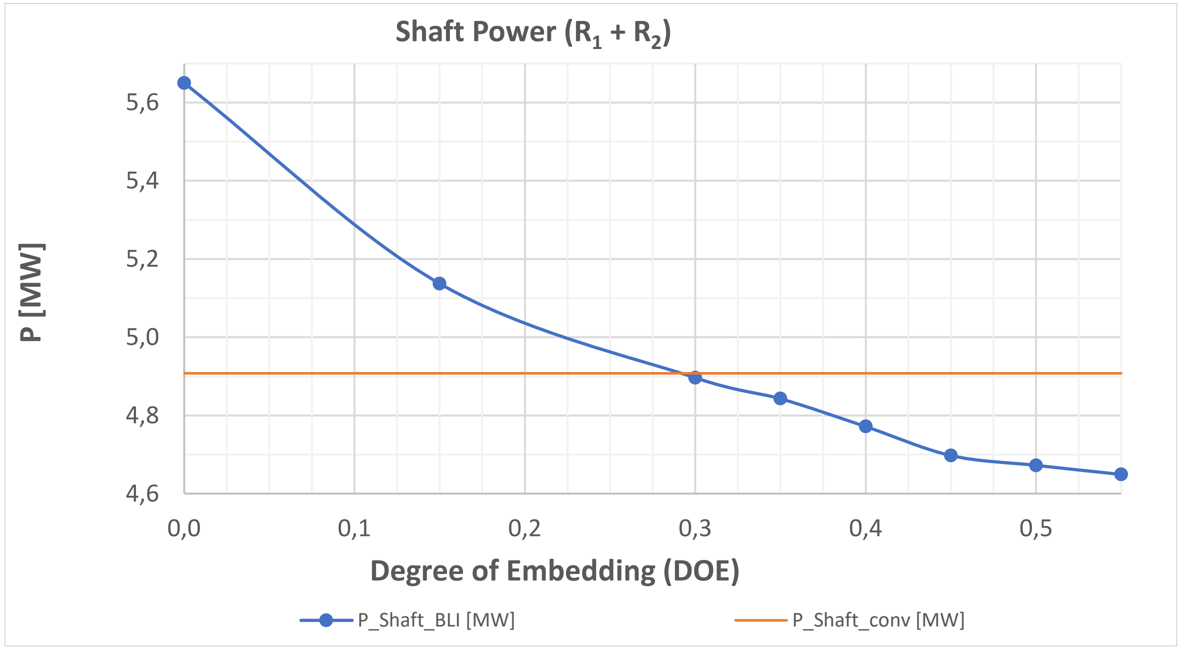


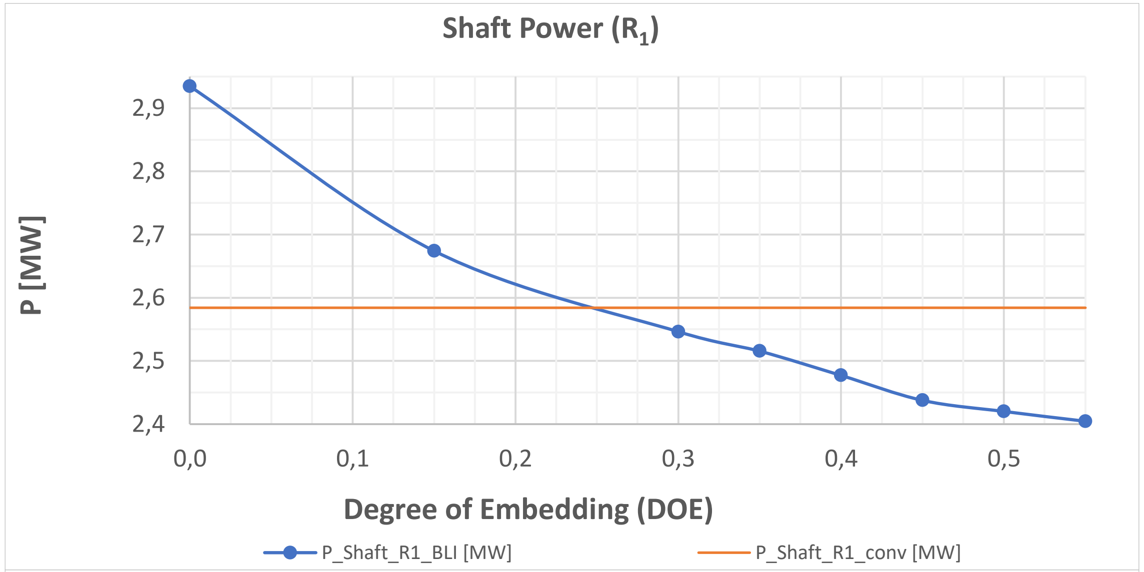
DOE	DC60	Θ [°]
Conv	0.001	--
0	0.124	-102.5
0.15	0.220	-104.0
0.30	0.293	-105.0
0.35	0.318	-103.5
0.40	0.332	-103.5
0.45	0.341	-103.0
0.50	0.349	-102.0
0.55	0.342	-102.0

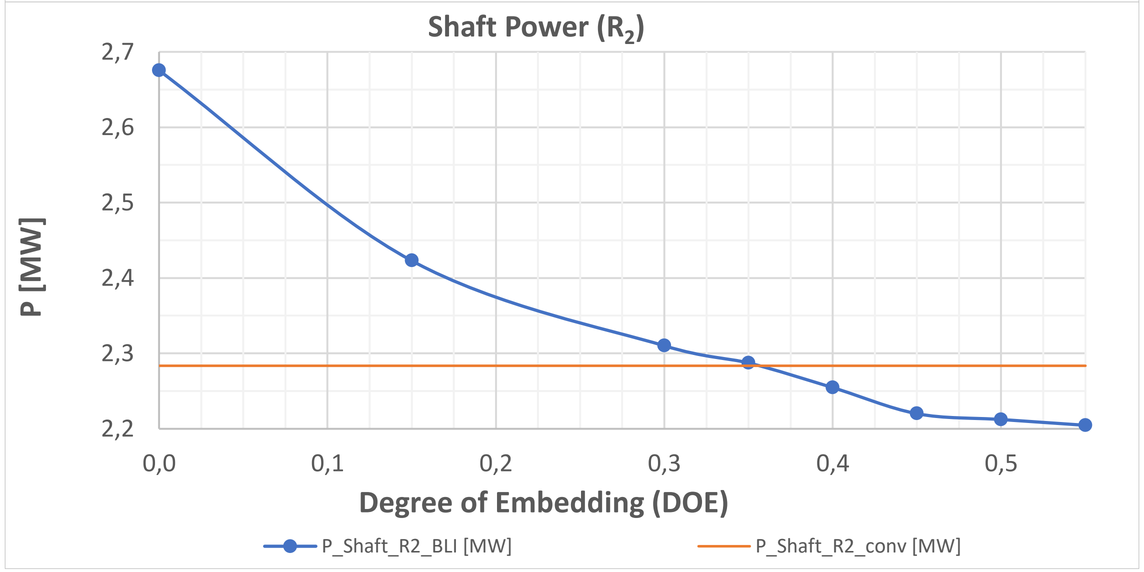
DOE	DC60	Θ [°]
Conv	0.003	--
0	0.110	-103.0
0.15	0.205	101.5
0.30	0.275	-100.5
0.35	0.298	-100.0
0.40	0.308	-101.5
0.45	0.313	-101.5
0.50	0.316	-101.5
0.55	0.306	-102.5

1. Magnitude of inflow distortion diminishes only slightly for the second rotor (~10%)
2. Circumferential broadening of inflow distortion for second rotor due to swirl effect and interaction of front blades with fuselage boundary layer

Assessment of BLI Potential
BLI Impact on Required Rotor Shaft Power

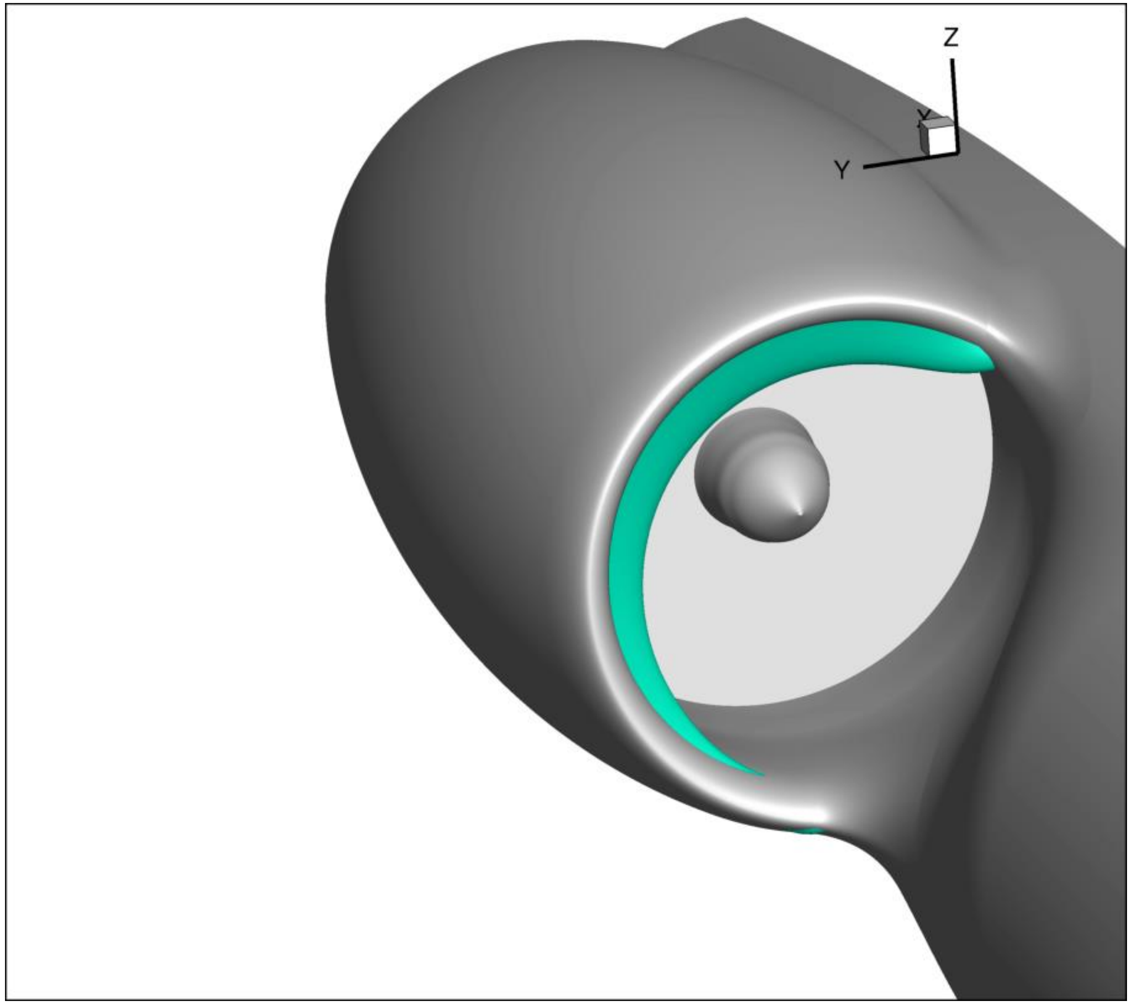


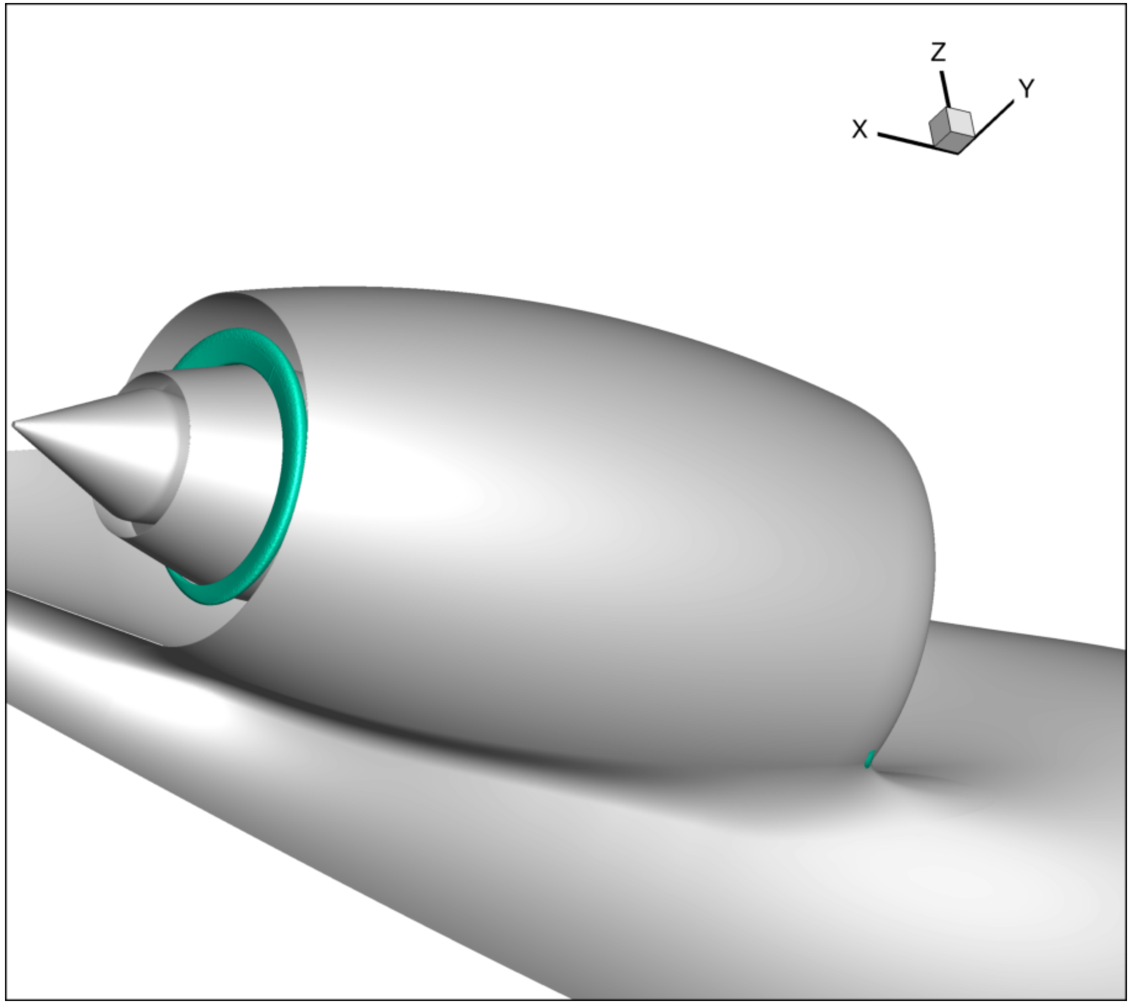




- Shaft power reduction potential due to BLI:
  - P_{DOE55} reduced by 5.3% versus P_{conv}
- „Break-even“ at DOE = 30%
- Altered loading balance between rotors 1 & 2

Assessment of BLI Potential
Aerodynamic Analysis





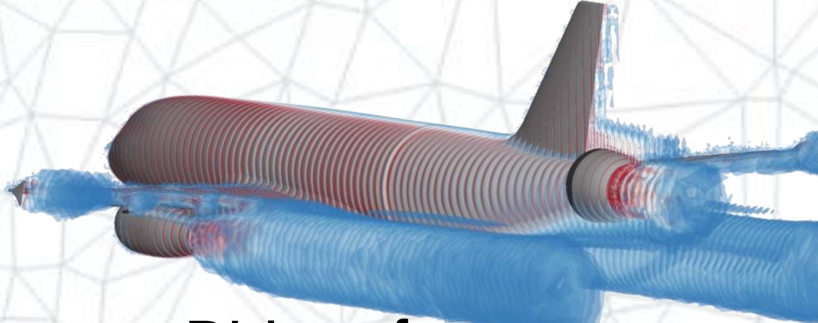
EG55

Trend: EG ↑

Shocks on upper & lower nacelle↓

Shock on inner lip ↑

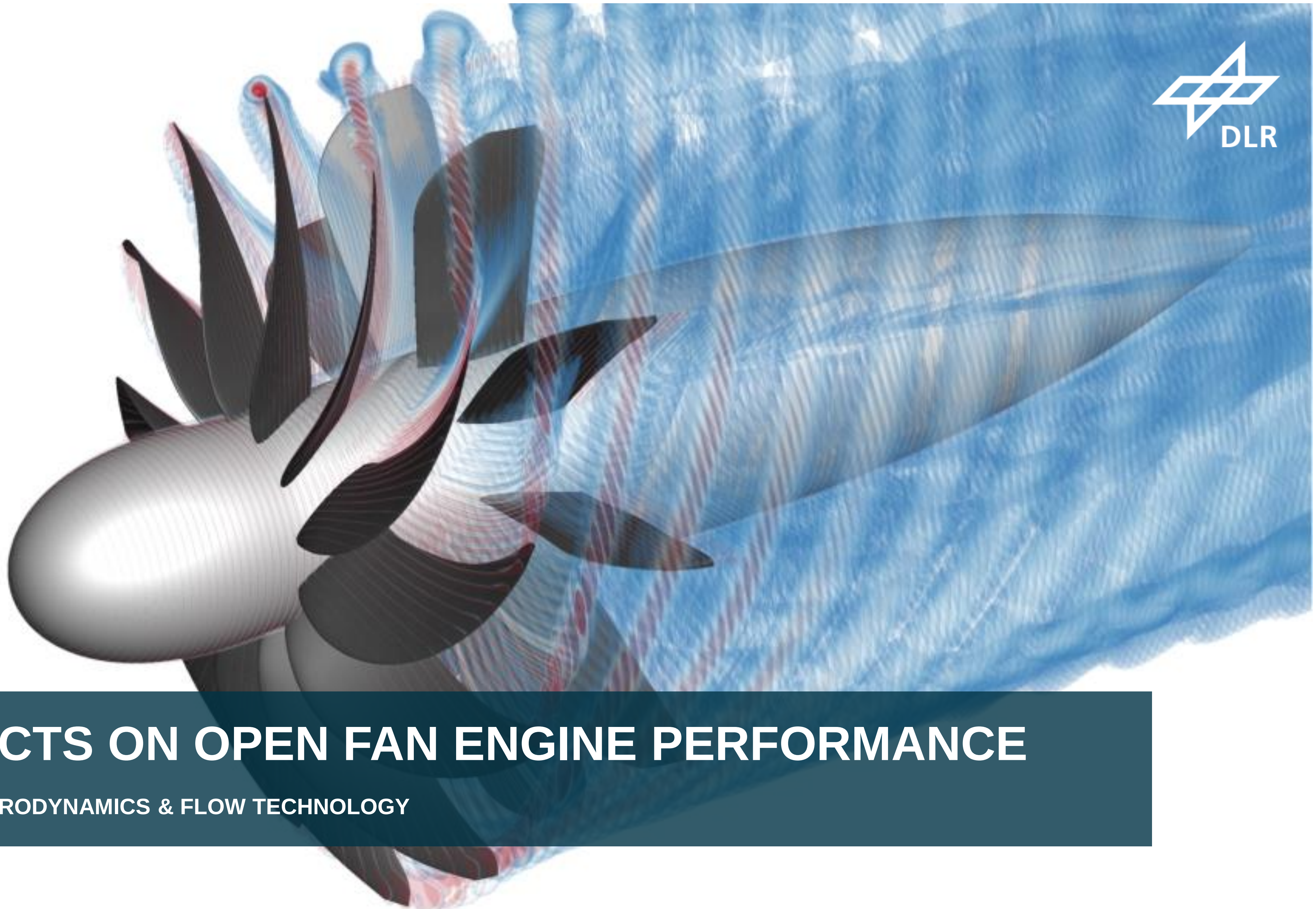
Assessment of BLI Performance Benefit
Summary & Outlook



- Studies of rear-engined aircraft concept in AGATA indicate a BLI performance benefit versus classic under-wing mounted engine aircraft on the order of ~5%

- Project scope did not allow for a refinement of the engine-airframe integartion design, to address identified aerodynamic losses of the nacelle integration
  - Actual benefit may be somewhat larger
  - But: Known aircraft structural weight increases due to rear-mounted engine installation may reduce efficiency improvement potential at aircraft level
  - But: Electrically driven propulsors may recover some of that disadvantage

- Outlook: BLI may truly come into ist own for more radical departures from tube-and-wing configurations, i.e. BWB-type configurations



AOA EFFECTS ON OPEN FAN ENGINE PERFORMANCE

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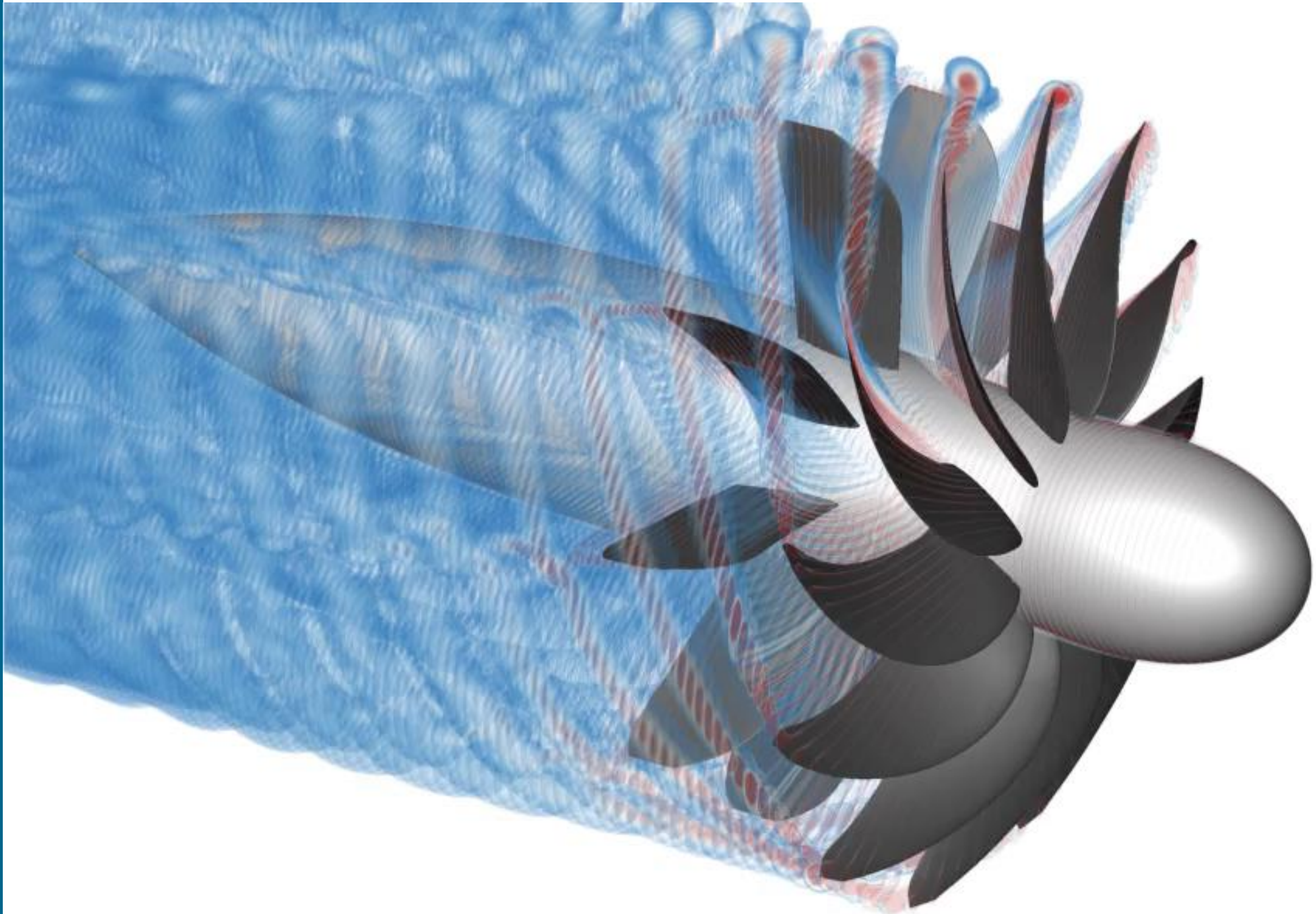
AoA Effects on Open Fan Engine Performance
Introduction



Open Rotor and Stator (ORAS) or Unducted Single Fan (USF) or Open Fan

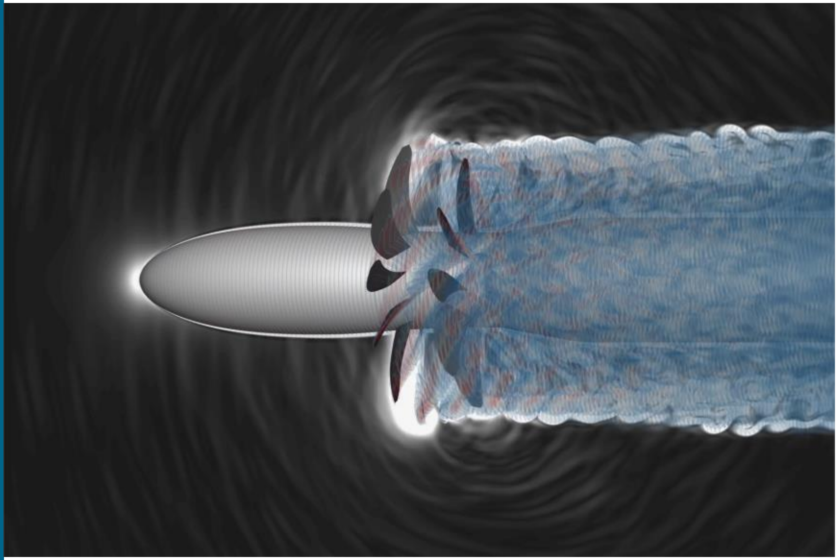
- High bypass ratio → high propulsive efficiency

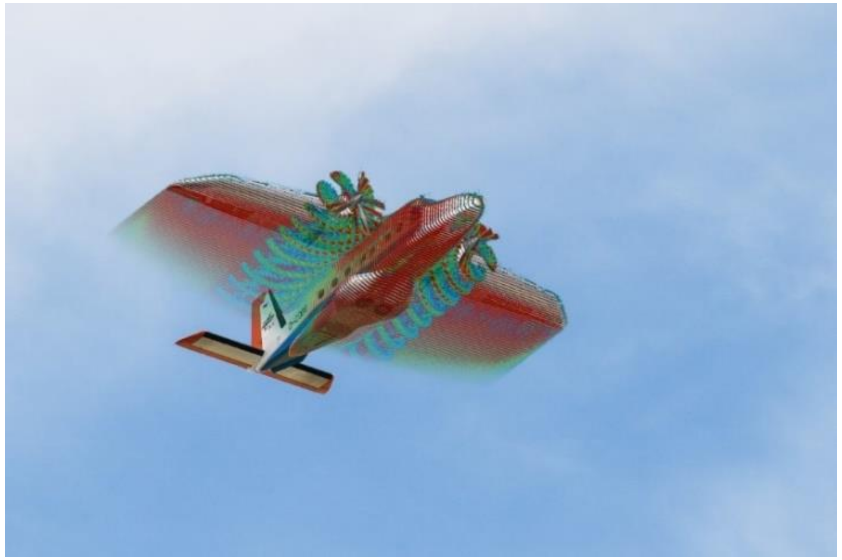
Clean Sky 2 funded studies of installation effects since 2022

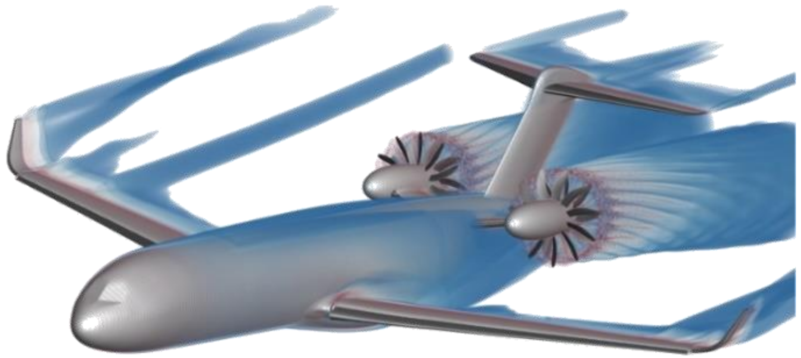
- Here: Impact of AoA on ORAS performance

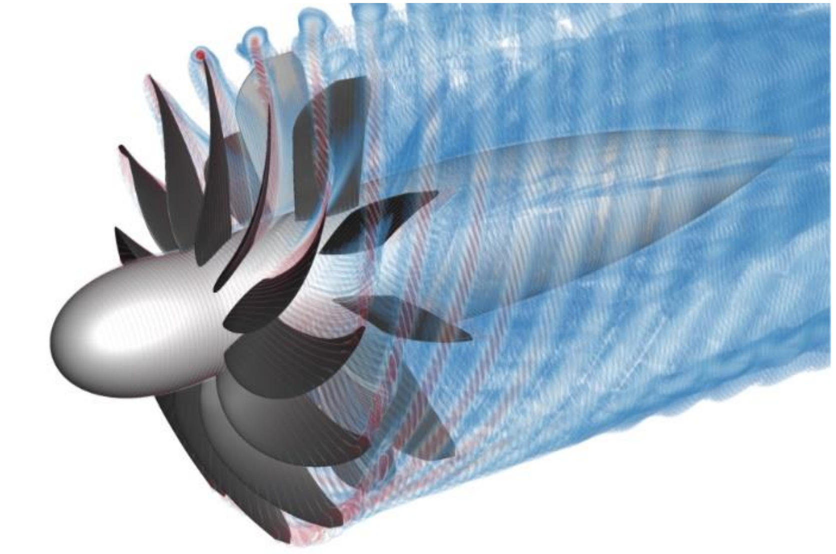
Generic Open Fan design with 12 rotor blades and 9 SRVs (Swirl Recovery Vanes)

AoA Effects on Open Fan Engine Performance Numerical Analysis Approach





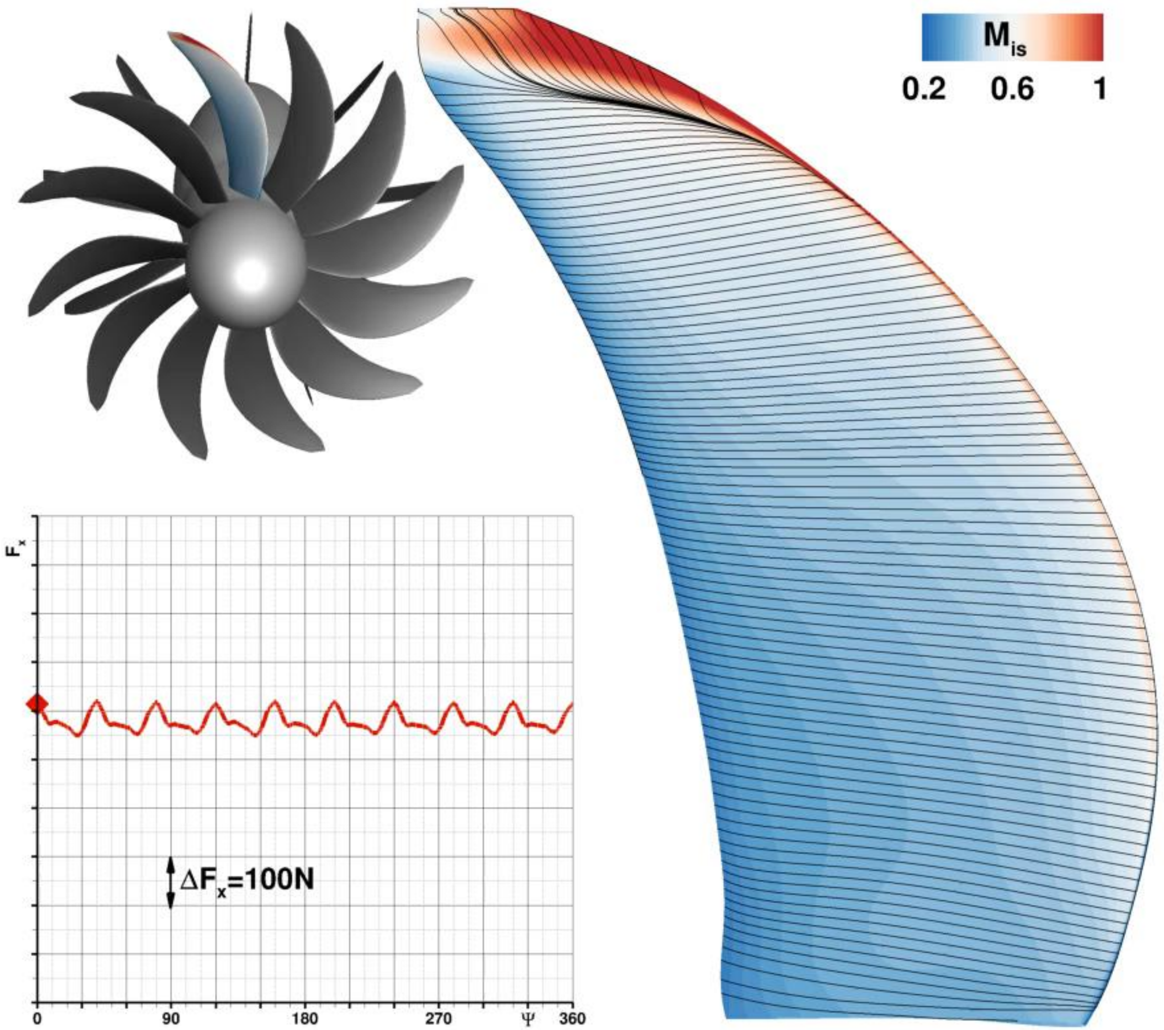


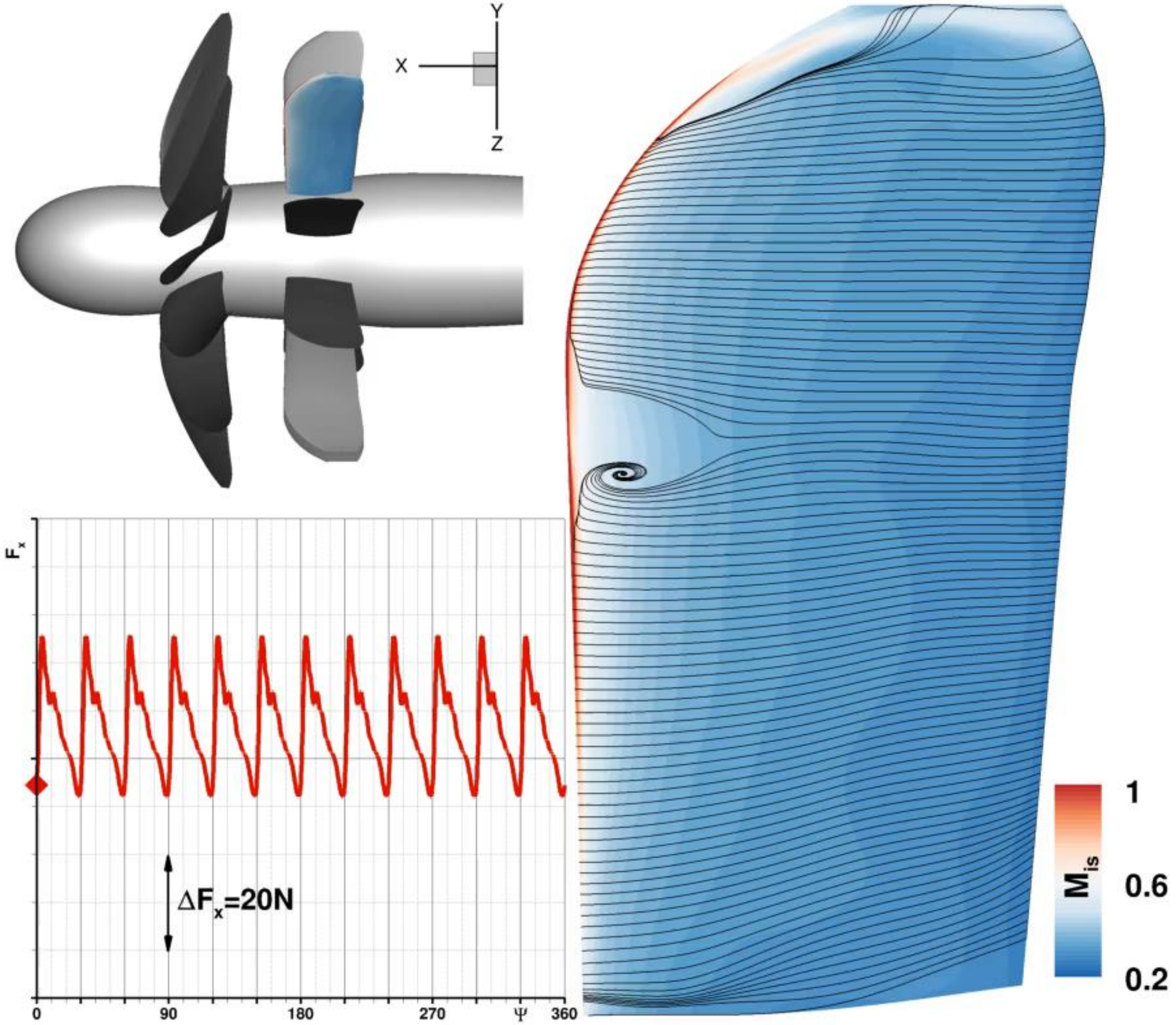


- DLR TAU Code CFD analysis, building on previous related expertise
- uRANS investigations of geometrically fully represented rotor & stator
- Studies done for noise-emissions ciritcal take-off condition:

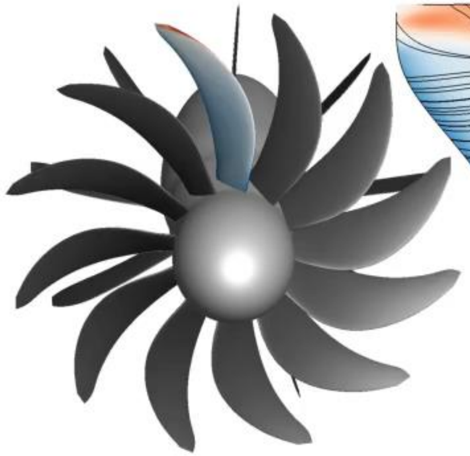
Case	M	h [ft]
Take-Off @ α=0°	0.273	2132.55 @ ISA+10
Take-Off @ α=10°	0.273	2132.55 @ ISA+10

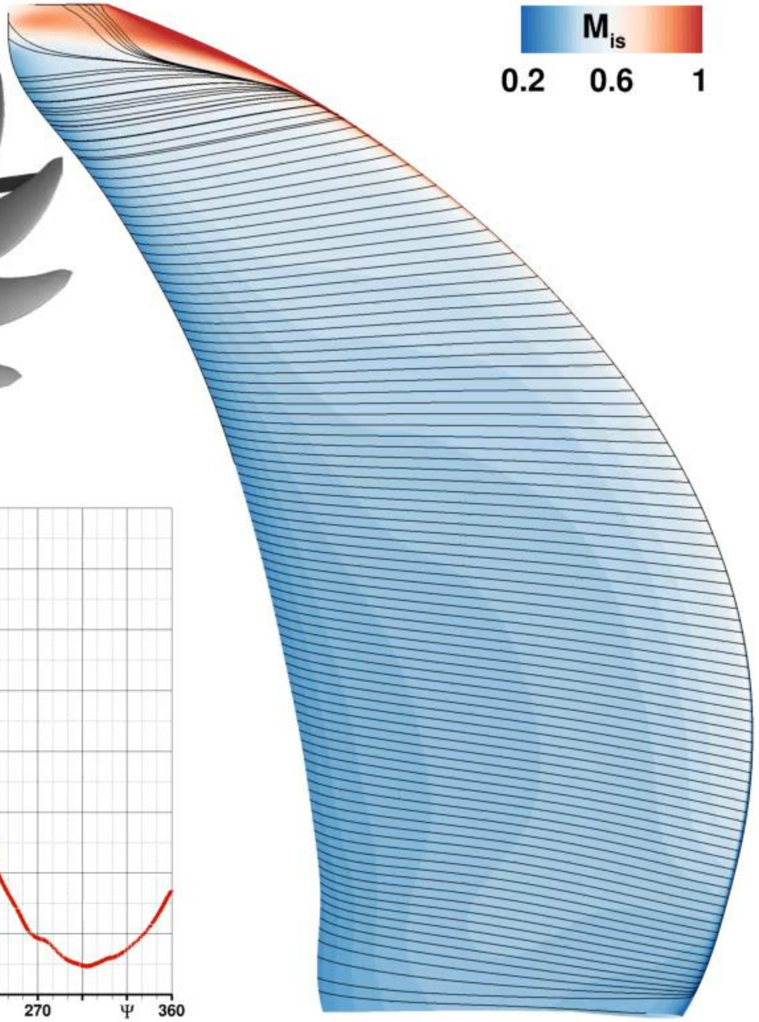
AoA Effects on Open Fan Engine Performance Aerodynamic Analysis @ α=0°

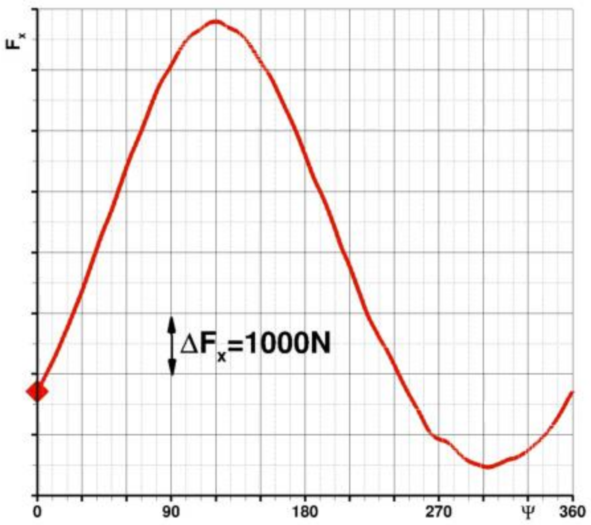


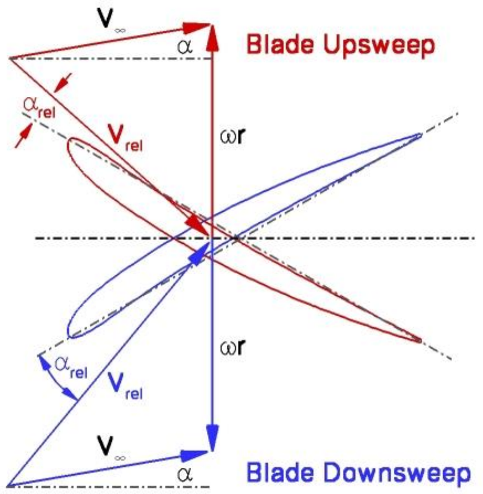


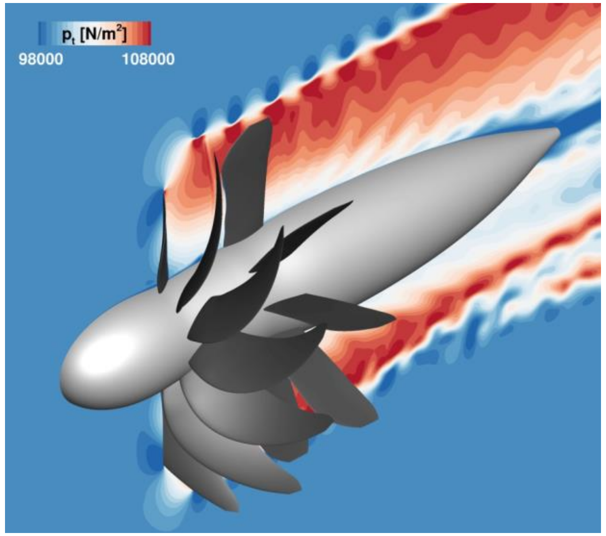
AoA Effects on Open Fan Engine Performance
Aerodynamic Analysis @ α=10°

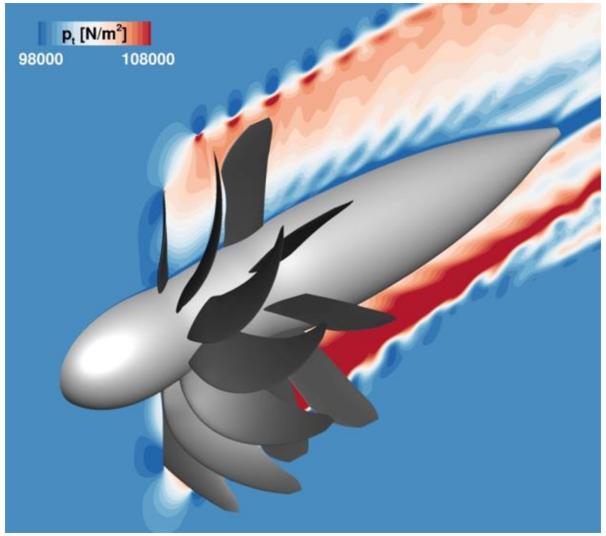




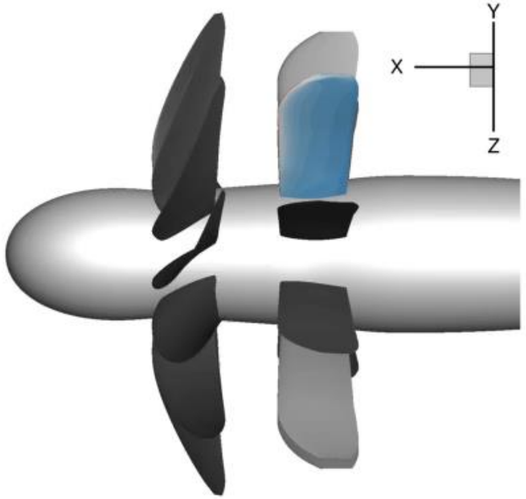


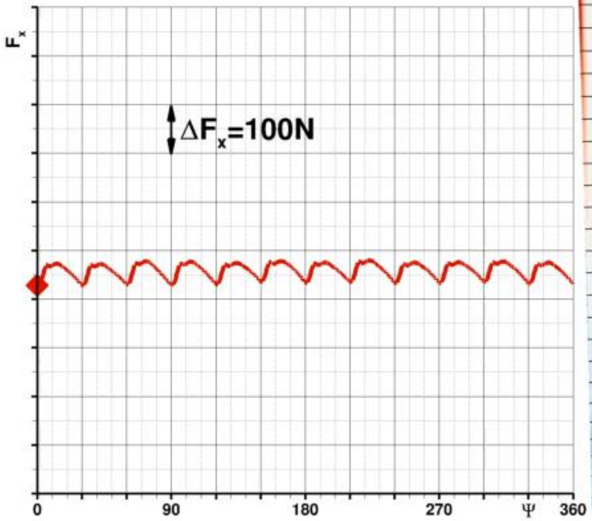


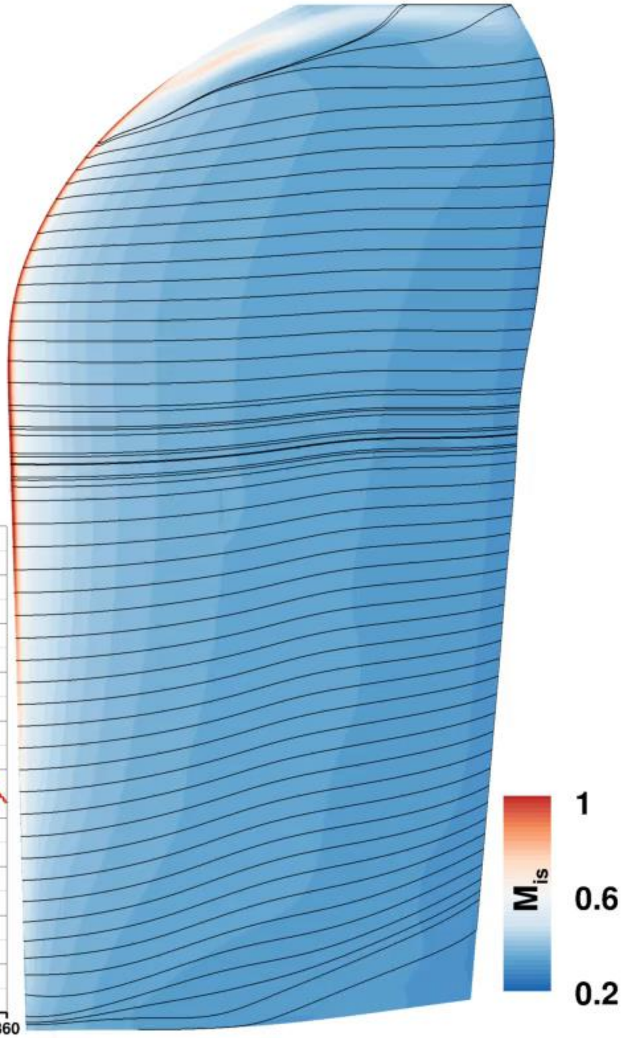


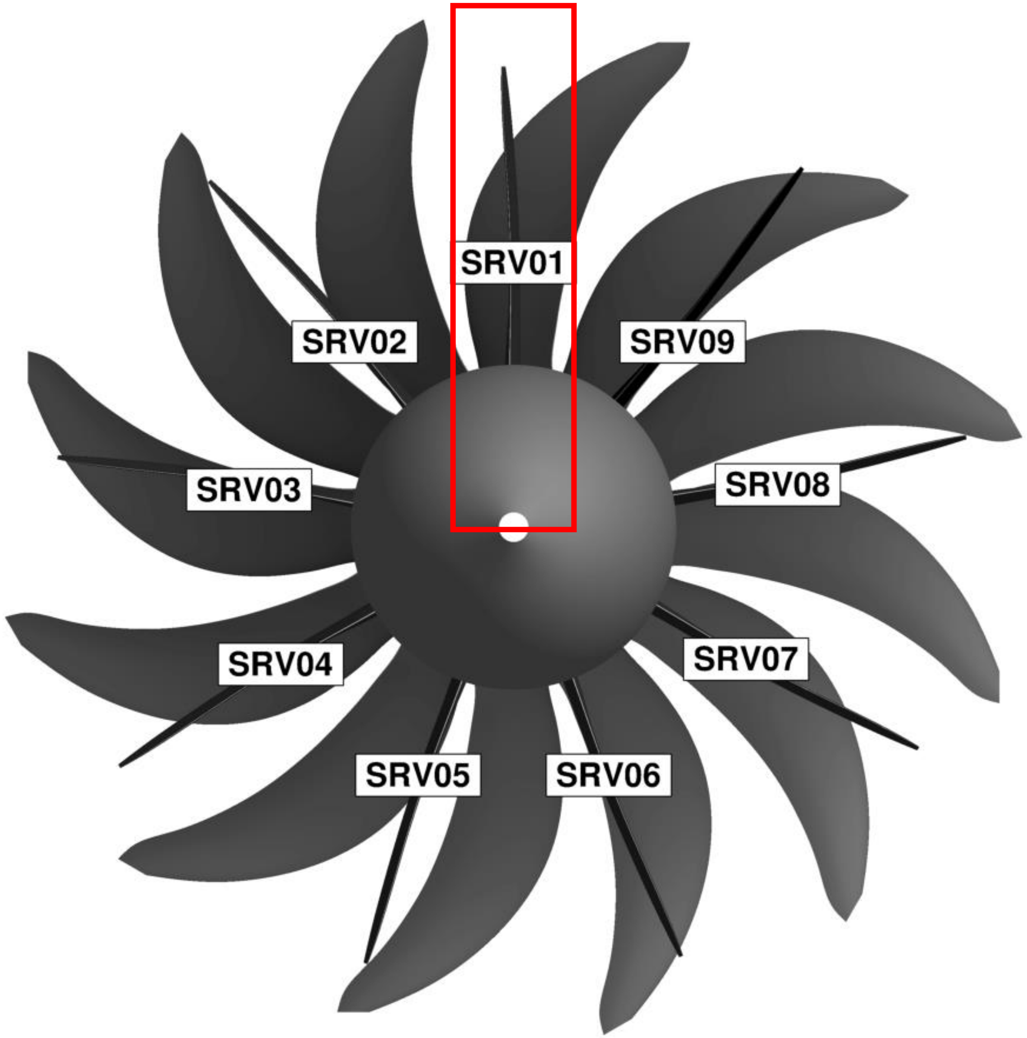


AoA Effects on Open Fan Engine Performance
Aerodynamic Analysis @ α=10°

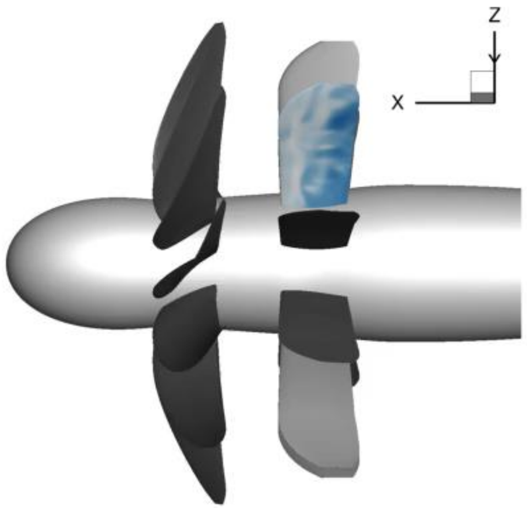


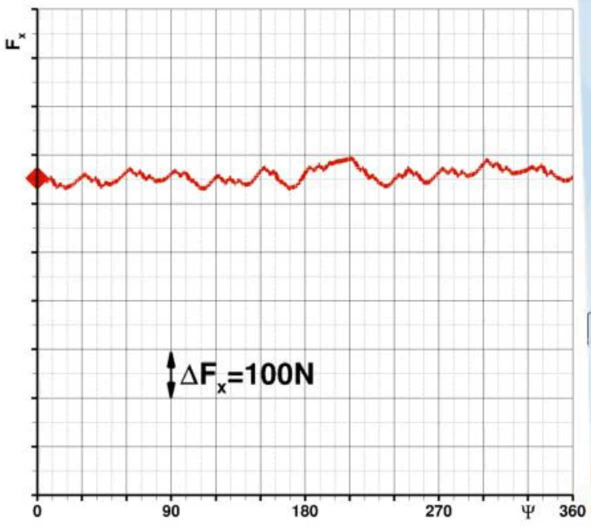


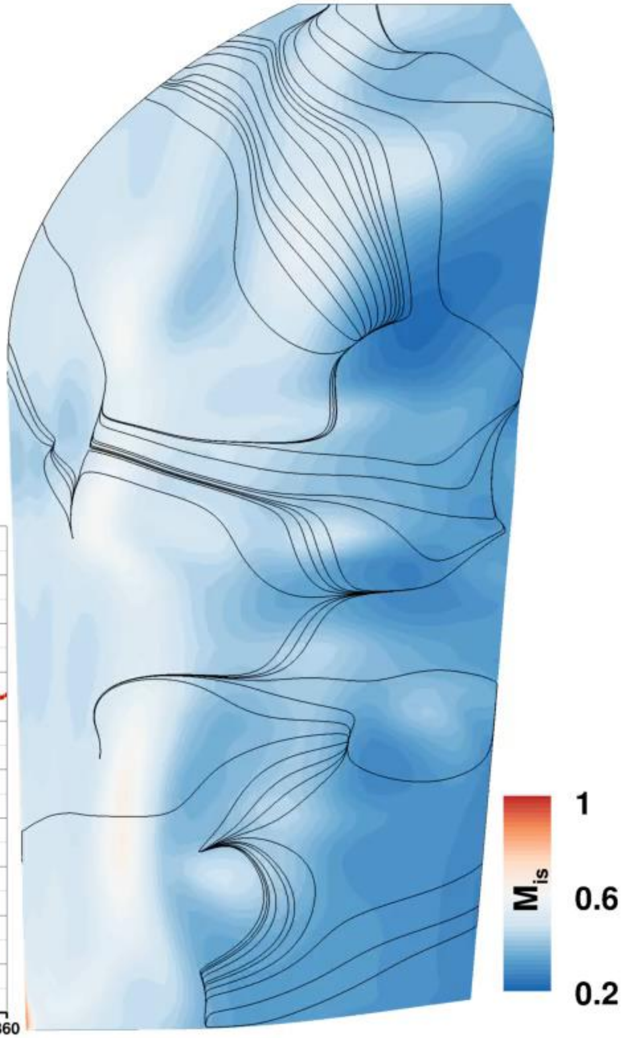


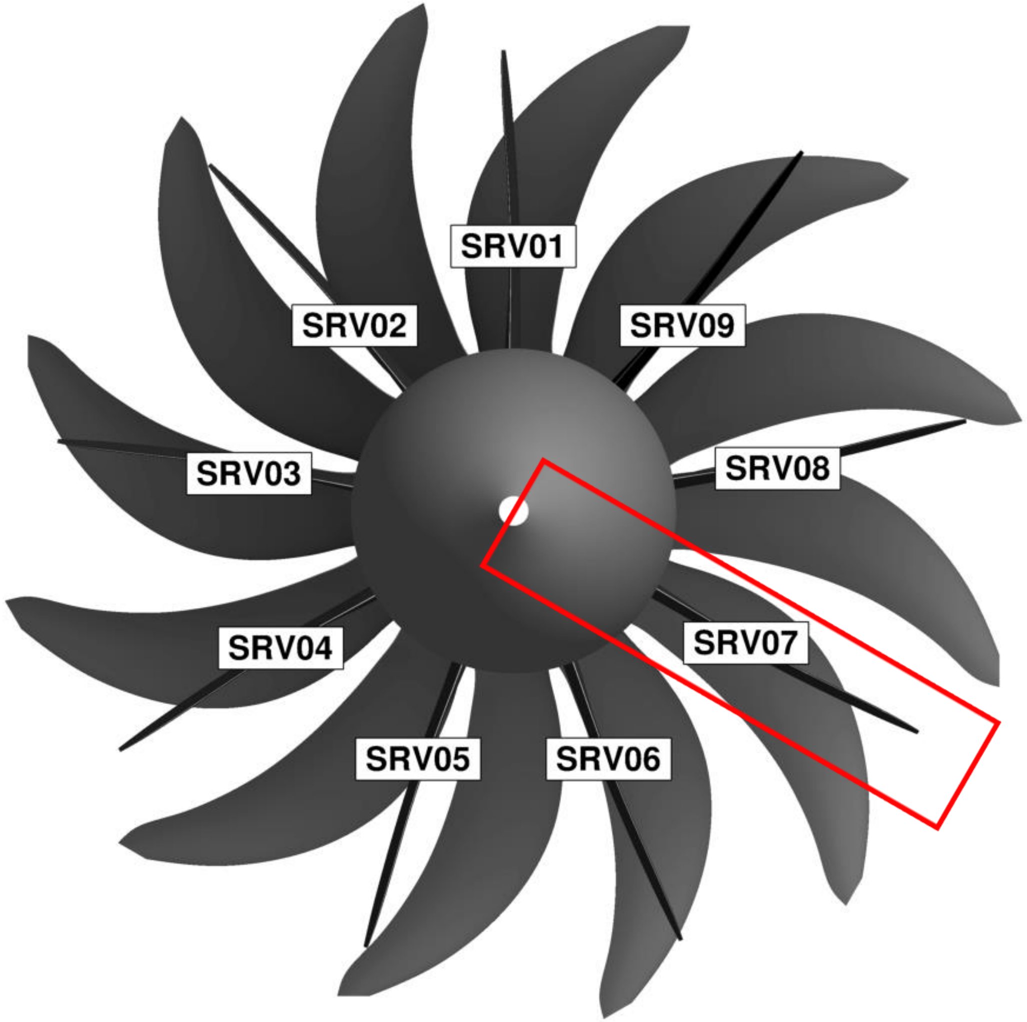


AoA Effects on Open Fan Engine Performance
Aerodynamic Analysis @ α=10°

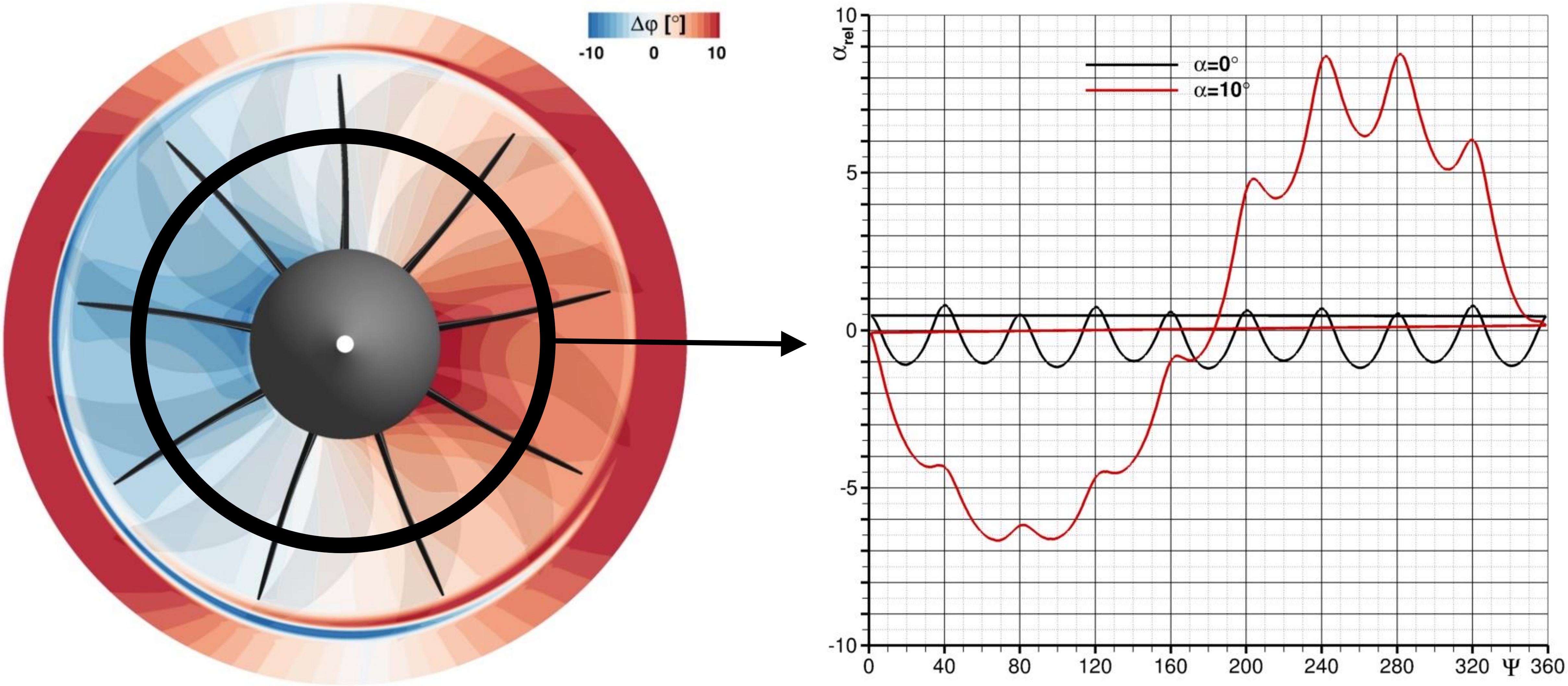




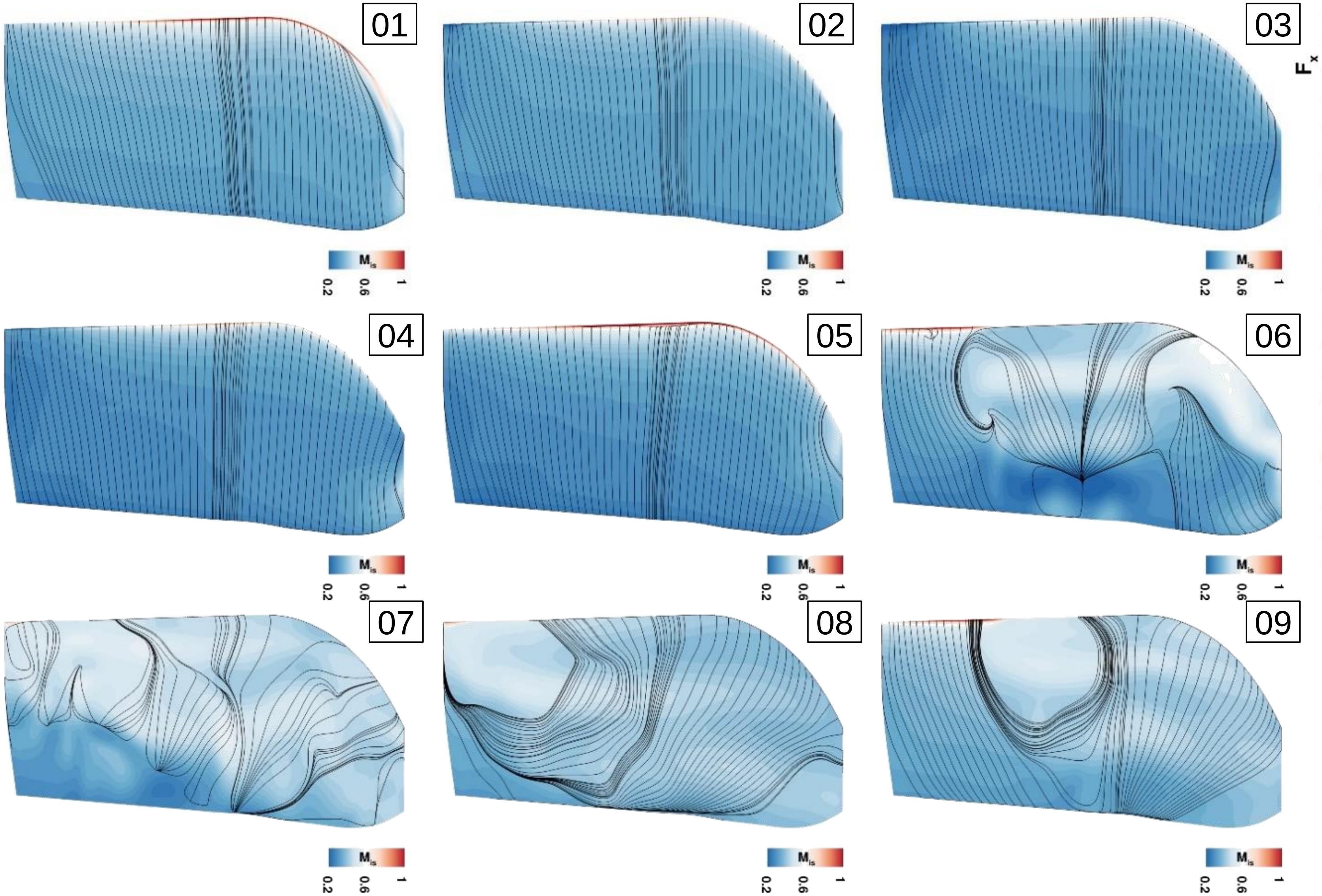


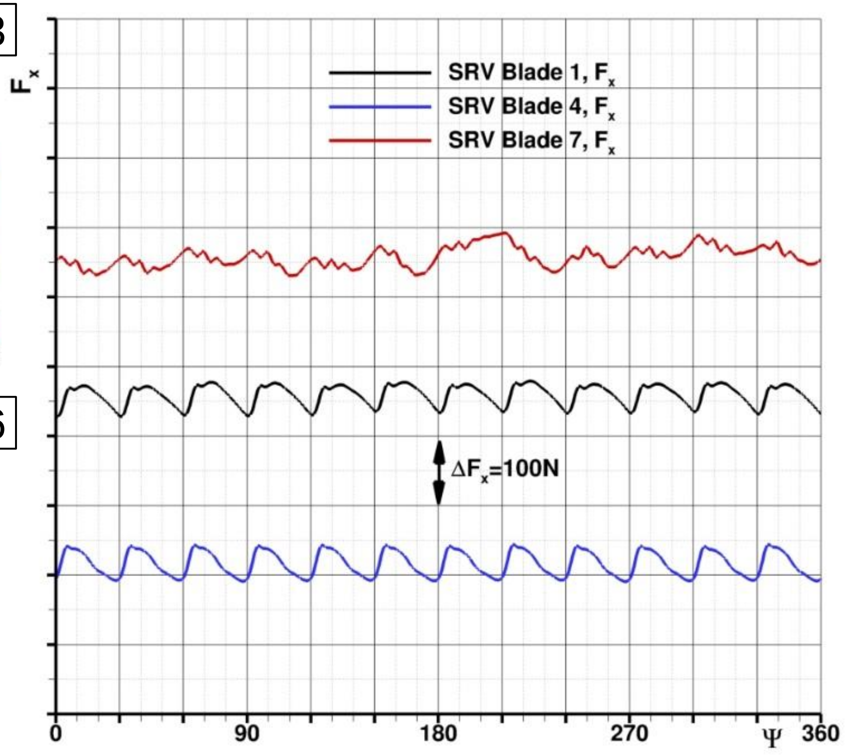


AoA Effects on Open Fan Engine Performance
Aerodynamic Analysis @ α=10°

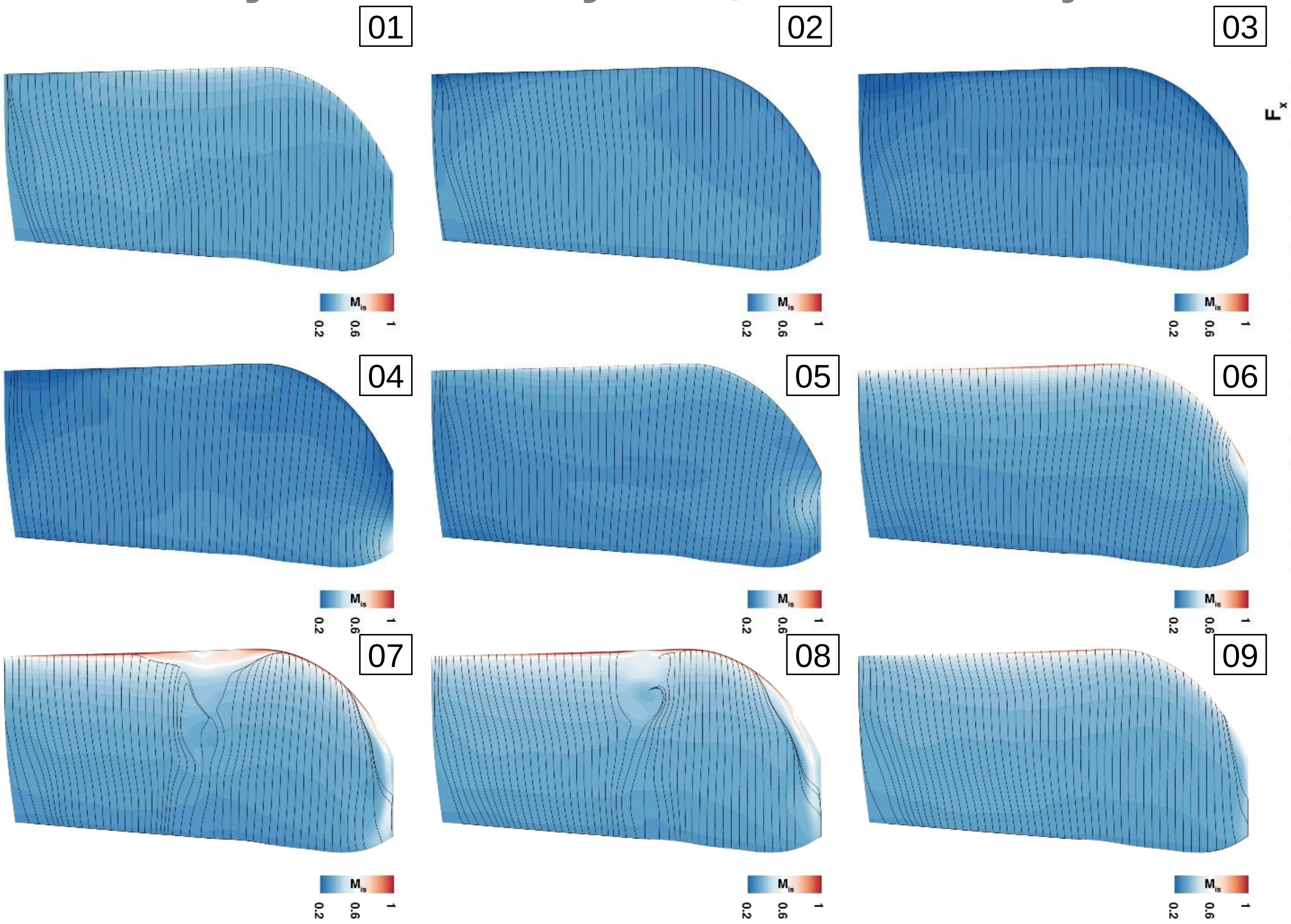


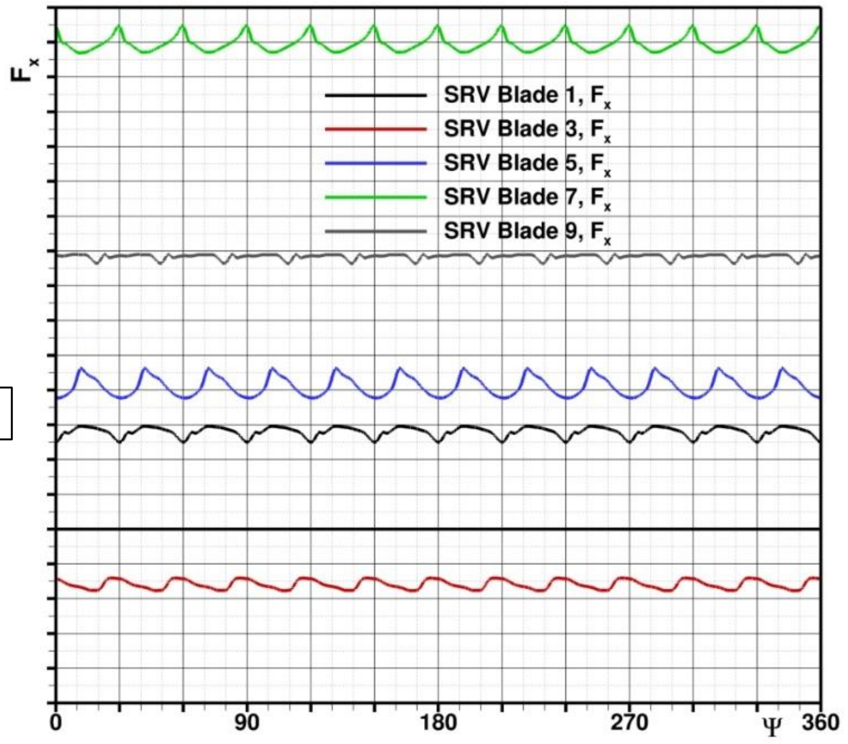
AoA Effects on Open Fan Engine Performance
Aerodynamic Analysis @ α=10° - Baseline SRV Pitch





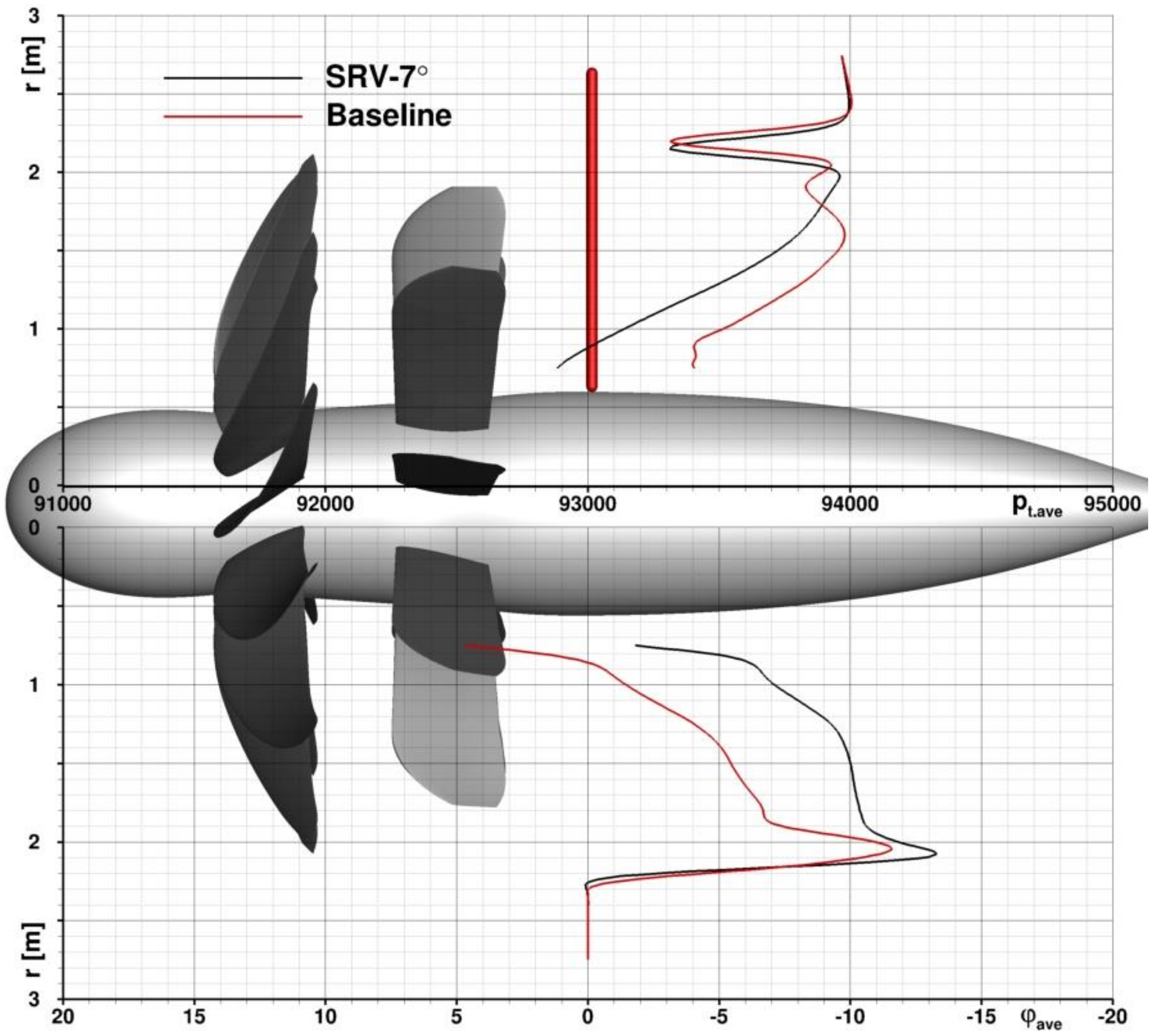
AoA Effects on Open Fan Engine Performance
Aerodynamic Analysis @ α=10° - Adjusted SRV Pitch





AoA Effects on Open Fan Engine Performance
Aerodynamic Performance Impact - Adjusted SRV Pitch

	C_T	C_P	η	$C_{T,R}:C_{T,S}$
α=0°, Baseline	0.792	1.428	0.670	94:6
α=0°, SRV-7°	0.779	1.428	0.659	96:4
α=10°, SRV-7°	0.811	1.462	0.670	95:5



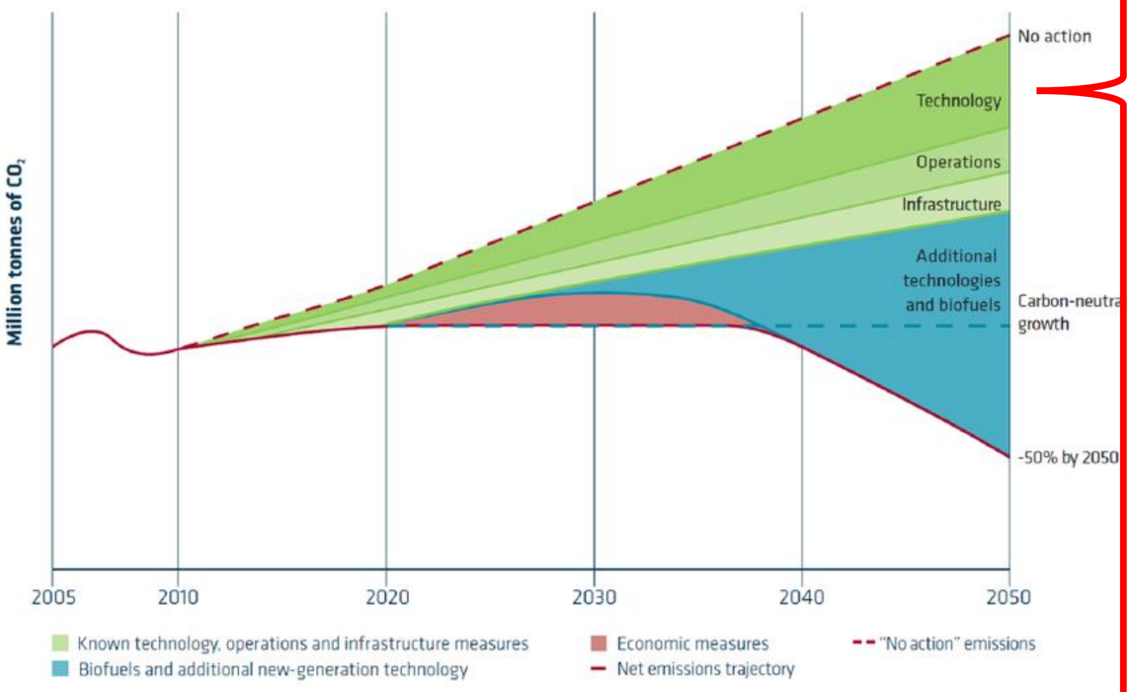
Angle of attack requires SRV pitch adjustments to avoid separated flow

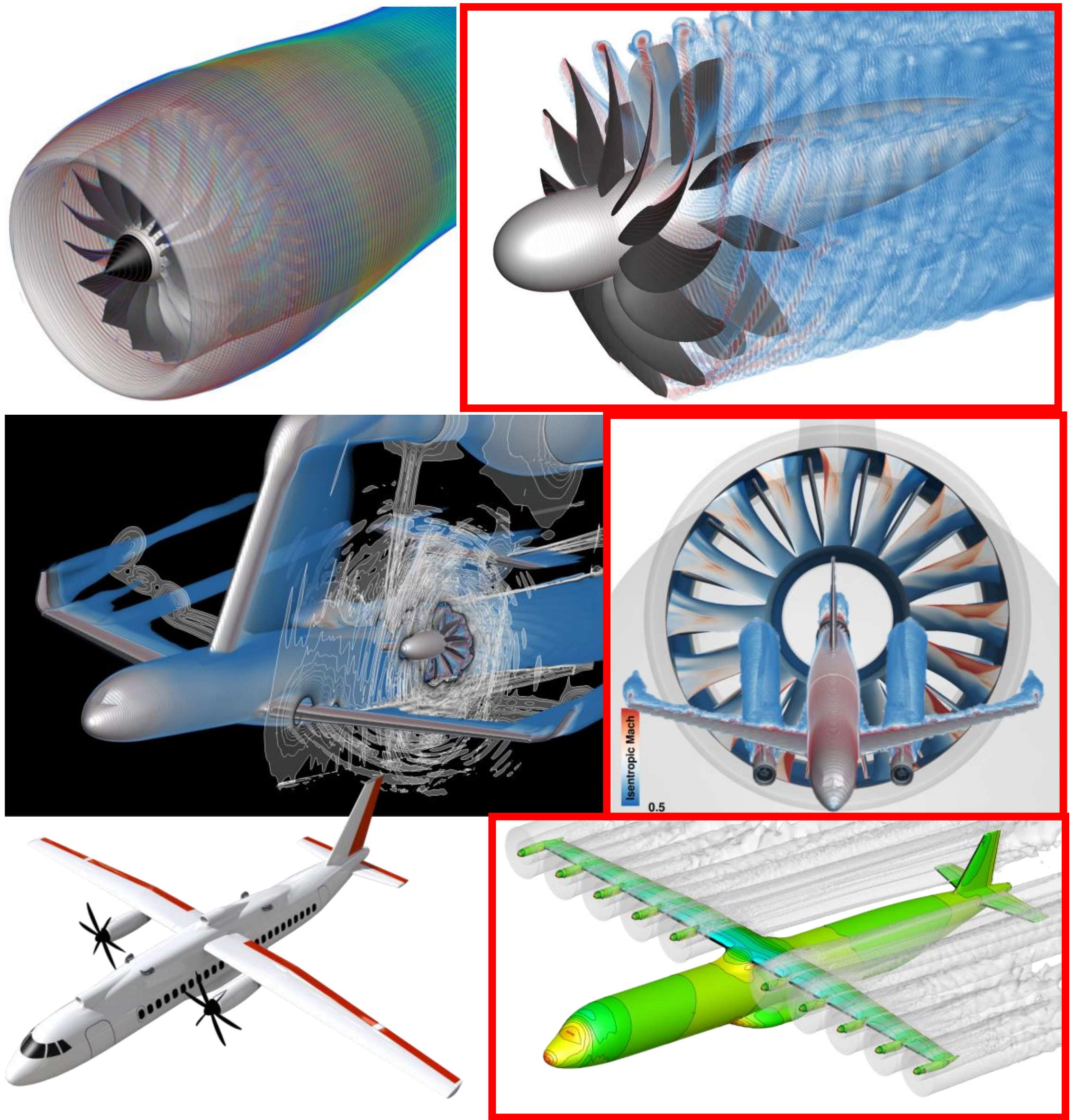
- Efficiency penalty due to installation effects

AoA Effects on Open Fan Engine Performance
Summary & Conclusions

- Installation effects have an important impact on an Open Fan engine operating point
- Angle of attack requires SRV pitch adjustments to avoid separated flow, at the cost of reduced efficiency
- Results point to azimuthal variation of the SRV pitch as a possible solution to mitigate the performance penalty
- Additional studies on the simulation approach as well as further aerodynamic analysis discussed in AIAA AVIATION paper
- Continued research collaborations with industry now addressing wing integration of Open Fan engines in nationally and EU funded projects

Introduction & Motivation
The Challenge of Integrating Efficient Propulsion Systems Efficiently





Promising technologies
Devil in the details

Thanks for your interest!

ENGINE-AIRFRAME INTEGRATION STUDIES FOR FUTURE EFFICIENT PROPULSION SYSTEMS

Arne Stuermer

DLR Institute of Aerodynamics & Flow Technology, Team Leader Engine-Airframe Integration

IWACC 8 @ UTIAS, Toronto, ON, CA, May 31-June 2, 2023

DLR