What drives noise from UAM vehicles, how about noise reduction ?

Adaptiert von Vortrag Bauhaus Luftfahrt expert workshop 16/17. Sept. 2019, Taufkirchen

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Outline

- Introduction
- Some remarks about sources to be expected
- Reduction concepts
- Summary & Conclusions


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City airbus
Augsburg TV

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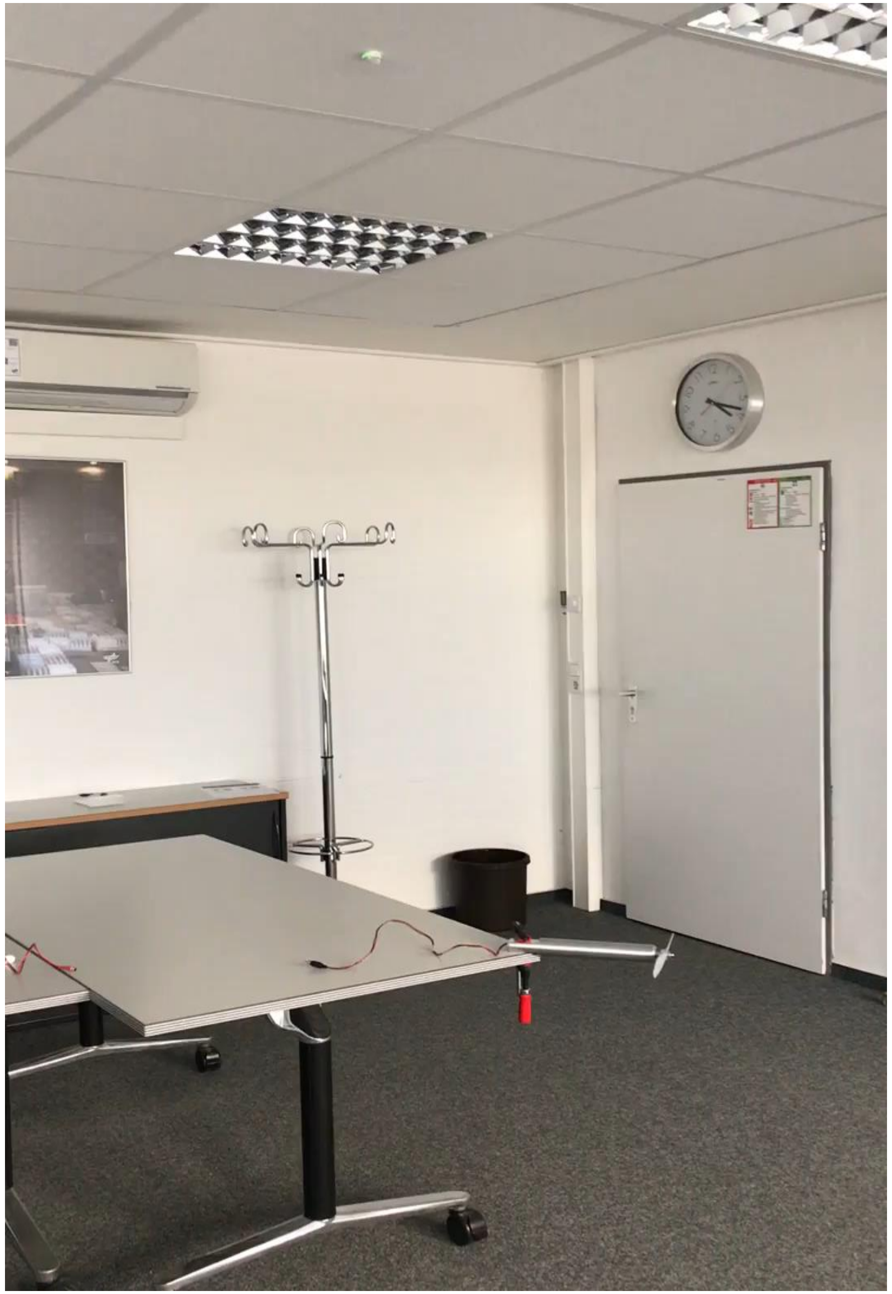
Observations on UAVs and UAMVs

- Small UAVs and 1-5 passenger UAMVs feature VTOL capability enabled by (open) rotors
- Open rotors are significant sources of noise in UA(M)Vs (either tilted propellers or multicopter)
- Rotors are rel. small compared to typical aircraft propellers or helicopter rotors -> rel. importance of broadband components higher
- Blade tip Mach no. for UA(M)Vs rel. small: $M_{tip} \simeq 0.2 - 0.5$ tonal self noise of rotors relevant only for BPF or first (very) few harmonics
- Depending on actual design of UA(M)V rotor installation tone sources may be dominant.
- Multi-propeller / multi-rotor arrangements typical for UA(M)Vs: specific effects
  - Multiple tone sources interference
  - Distributed (deconcentrated) thrust
- Very many vastly different vehicle designs proposed: concrete generally valid prediction difficult

Observations on UAVs and UAMVs



Rotors and the importance of installation

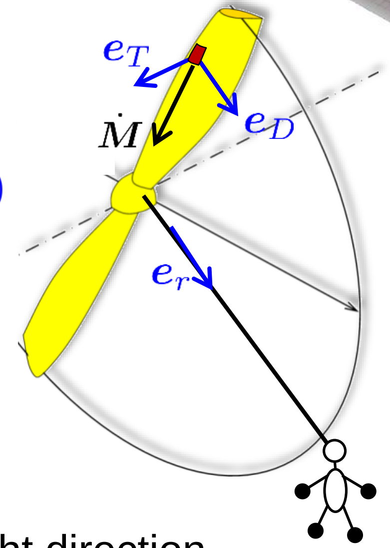
Installed pusher propeller (Piaggio), Take-off

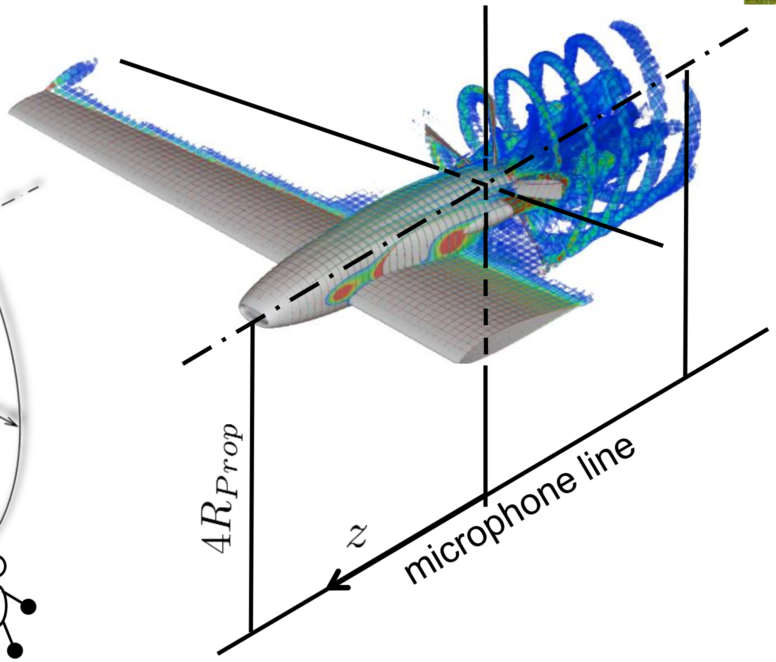
$$p'(\boldsymbol{x},t) \simeq \frac{1}{4\pi a_\infty}\int_{\partial V_B} \frac{\dot{f}_r}{r|1-M_r|^2} + \frac{(f_r + a_\infty\rho_\infty v_n)\boldsymbol{e}_r\cdot\dot{\boldsymbol{M}}}{r|1-M_r|^3}\, dS(\eta)$$

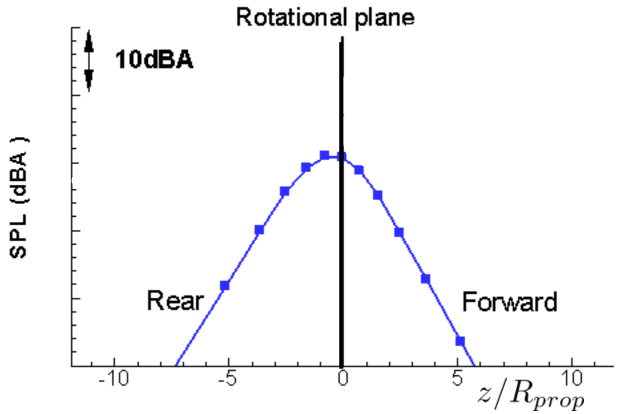
$$+\frac{1}{4\pi}\int_{\partial V_B} \frac{-f_M - \rho_\infty v_n}{r^2(1-M_r)^2} + \frac{f_r + \rho_\infty v_n(1-M^2)}{r^2(1-M_r)^3}\, dS(\eta)$$

$$f_r = [T\boldsymbol{e}_T + D\boldsymbol{e}_D(\tau)]\cdot\boldsymbol{e}_r$$

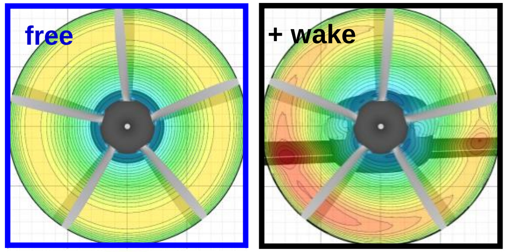
$$\dot{f}_r = \underset{0}{\cancel{\dot{T}}}\boldsymbol{e}_r\cdot\boldsymbol{e}_T + \underset{0}{\cancel{\dot{D}}}\boldsymbol{e}_r\cdot\boldsymbol{e}_D(\tau) + D\boldsymbol{e}_r\cdot\dot{\boldsymbol{e}}_D(\tau)$$







- isolated no radiation in/against flight direction since $\dot{T} = \dot{D} = 0$ & $\dot{\boldsymbol{M}}, \dot{\boldsymbol{e}}_D \perp \boldsymbol{e}_r$ on prop-axis
- installation effects increase loading noise by load fluctuations on blade from wing wake



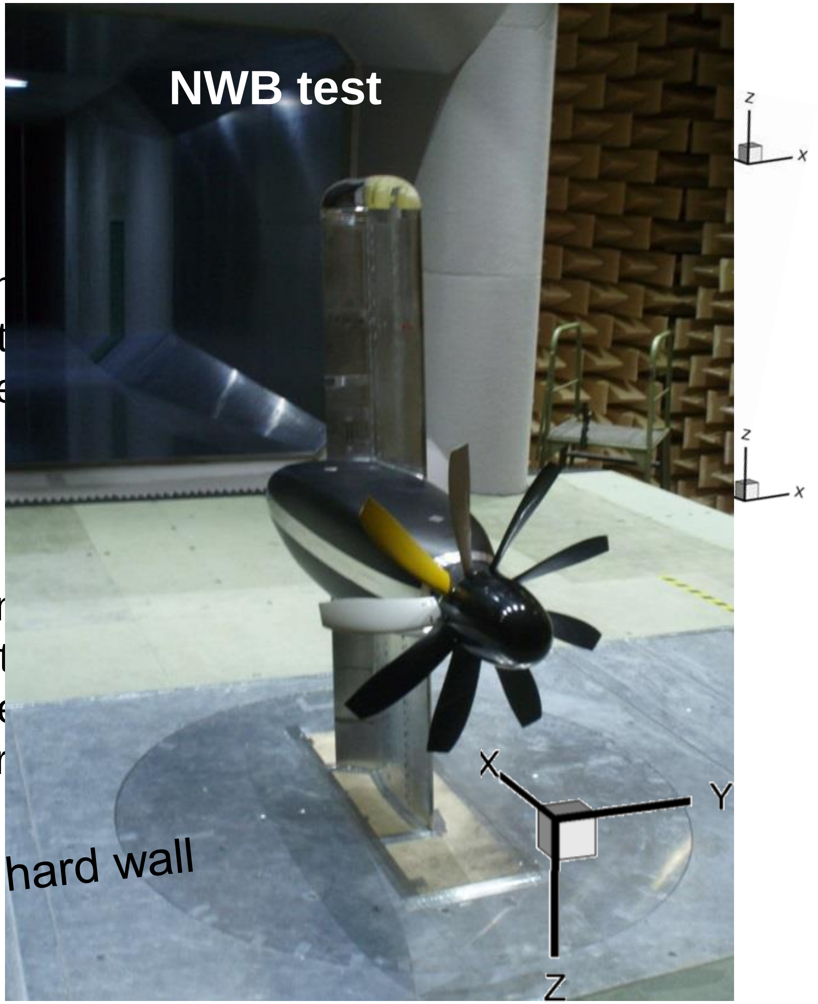
Aero-load distribution $\boldsymbol{f} = T\boldsymbol{e}_T + D\boldsymbol{e}_D(\tau)$

CFD, CAA: Yin, Stürmer, Aversano 2009, AIAA 2009-3332

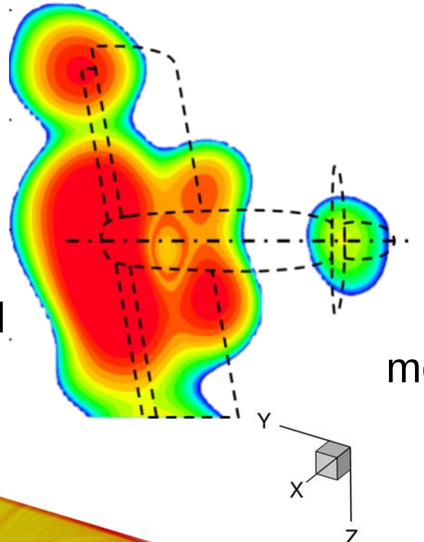
Installed Propeller Noise

sour
3 rot
force

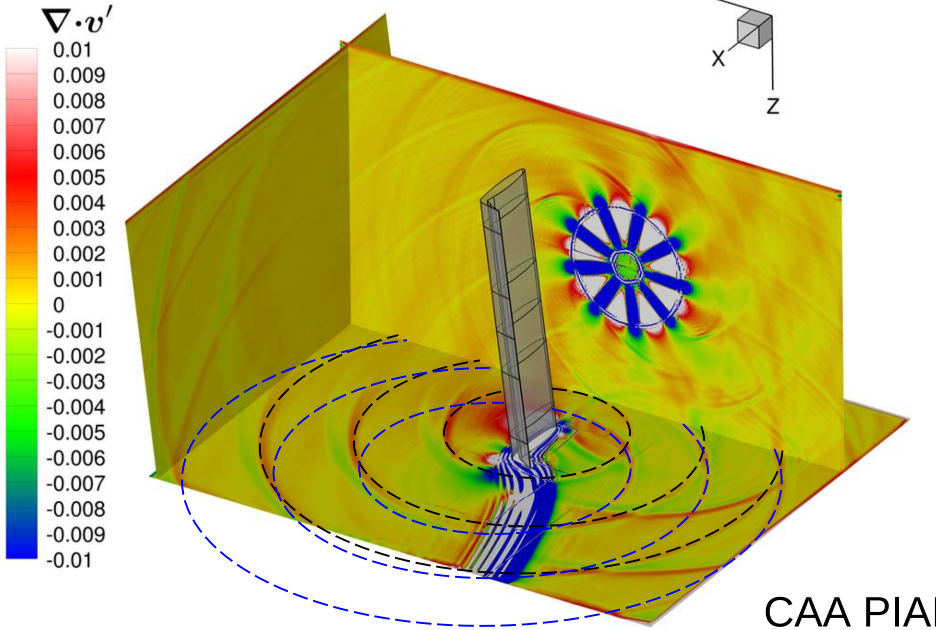
sour
3 rot
force
inter



propeller induced
- leading edge sound
- flap sound



measurement

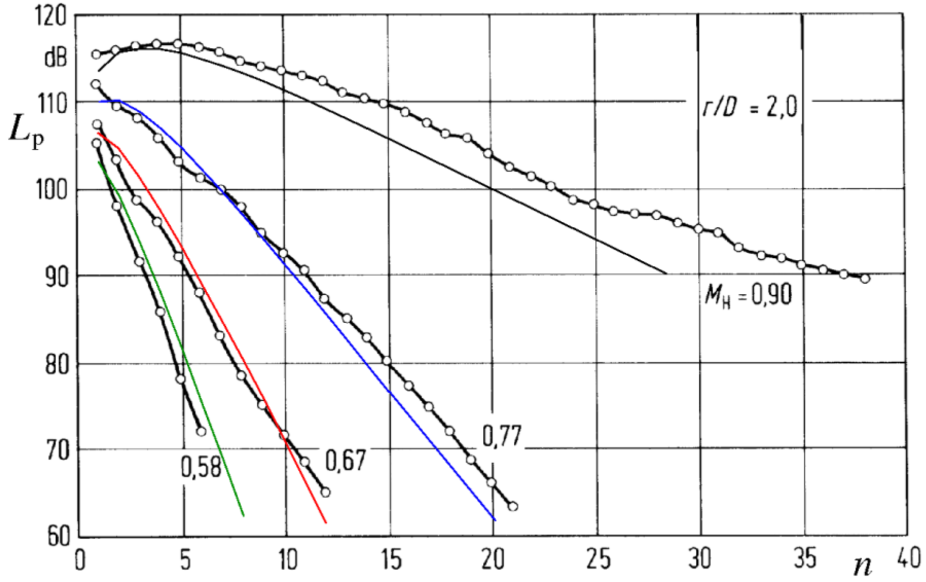


CAA PIANO

→ **Prop-noise reduction by reduced rpm + higher blade loading → increased installation noise**

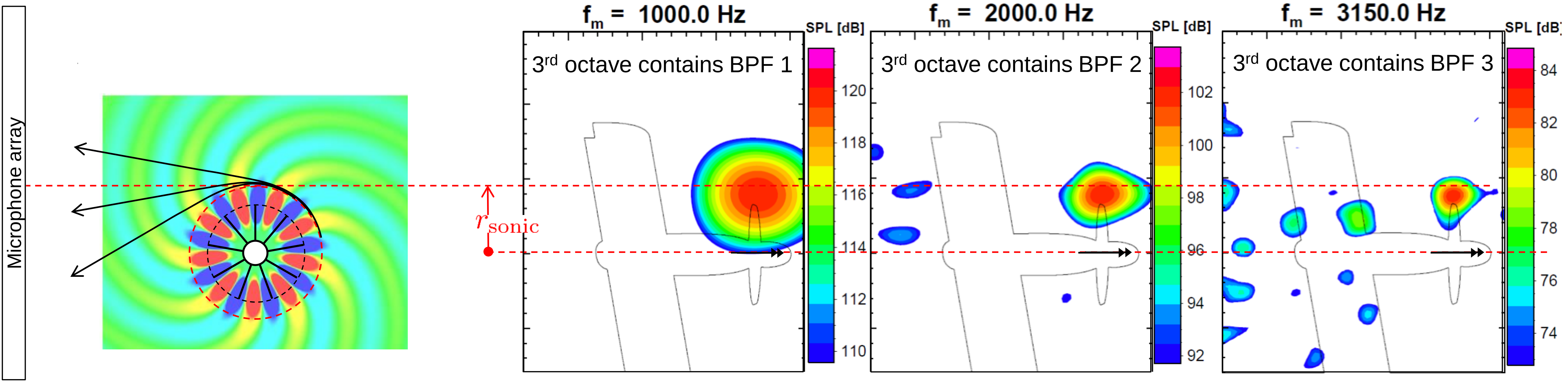
AIAA 2014, Dierke, Delfs, Lenfers, Buchholz,Almoneit (Bürgernahes Flugzeug)

Results: array source localisation



$$V_\infty = 51 \text{ m/s},\ N_P = 7144 \text{ rpm},\ \beta = 28^o$$

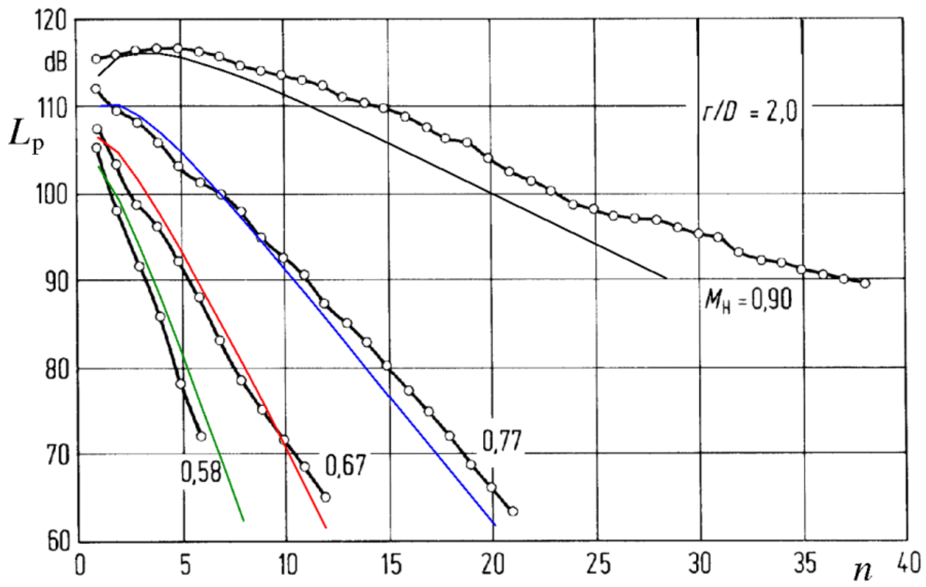
$$M_{tip} = 0.73$$

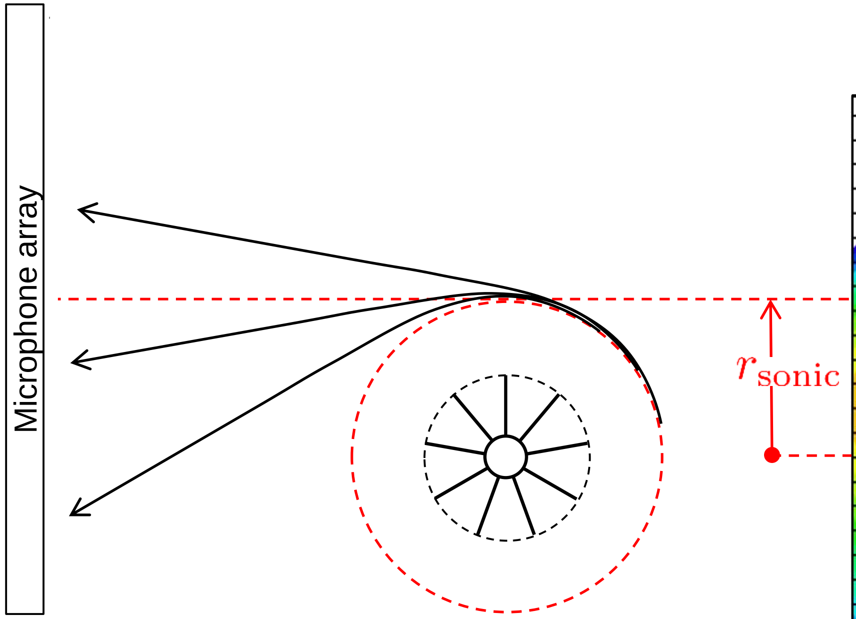


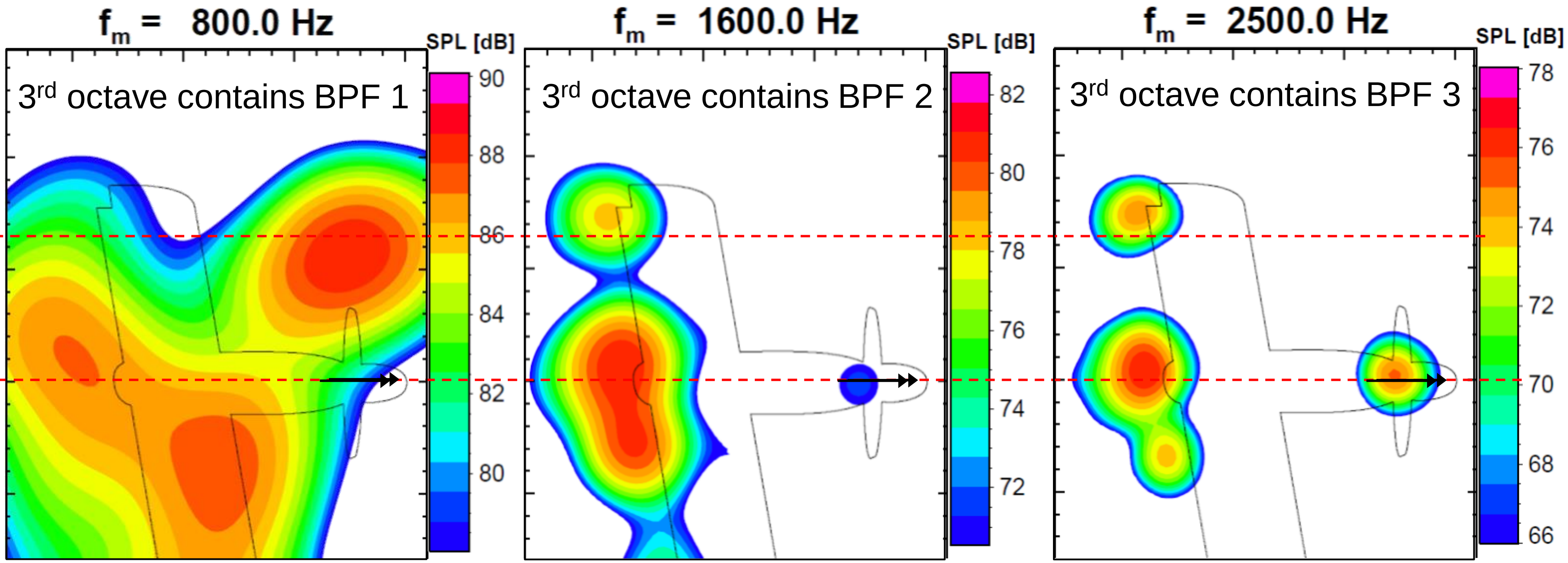
Results: array source localisation

$$V_\infty = 51 \text{ m/s}, \; N_P = 5105 \text{ rpm}, \; \beta = 28^o$$

$$M_{tip} = 0.52$$



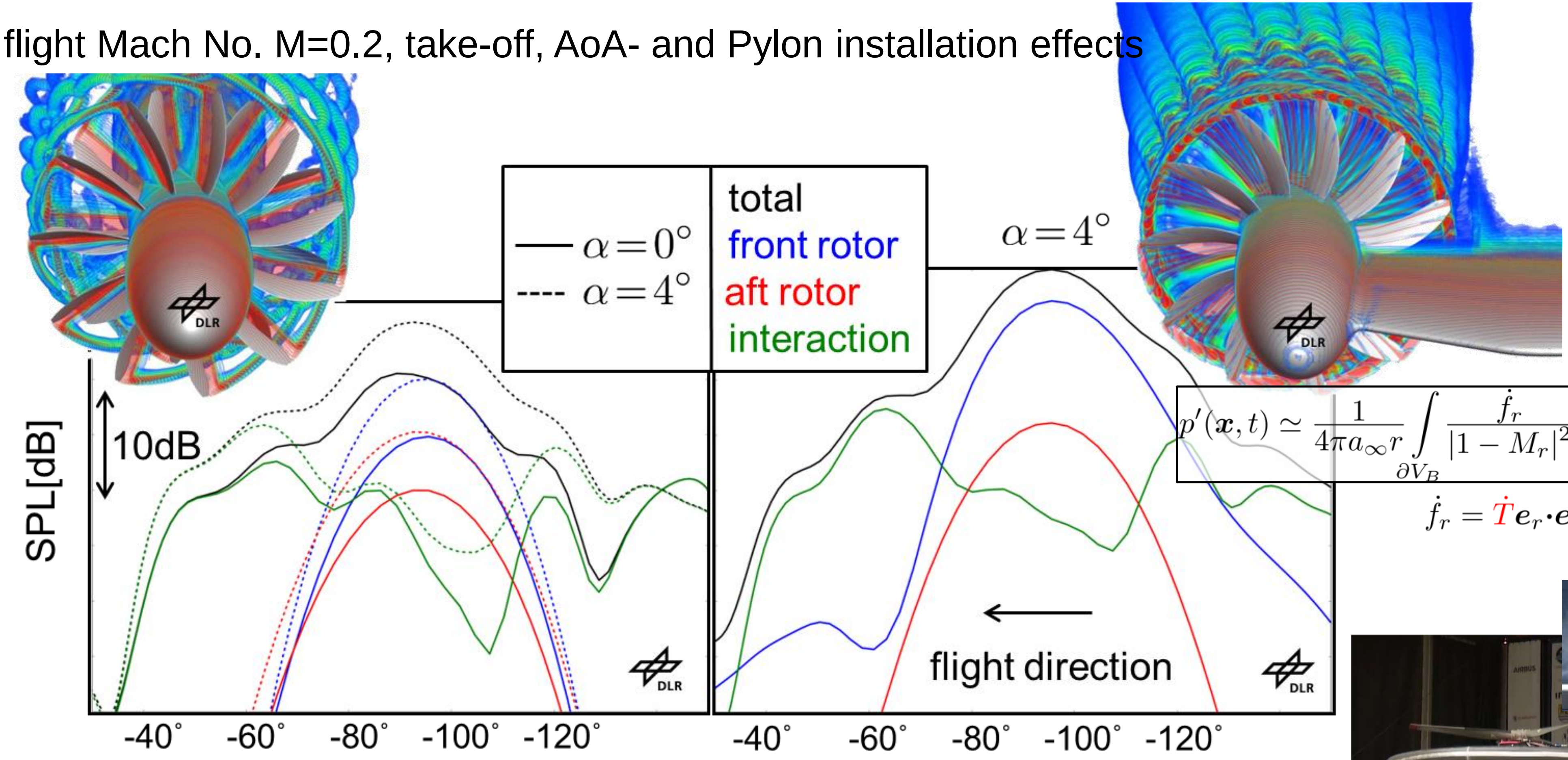




→ **Prop-noise reduction by reduced rpm → propeller noise induced airframe noise (installation)**

Source installation effects on Contra Rotating Open Rotor

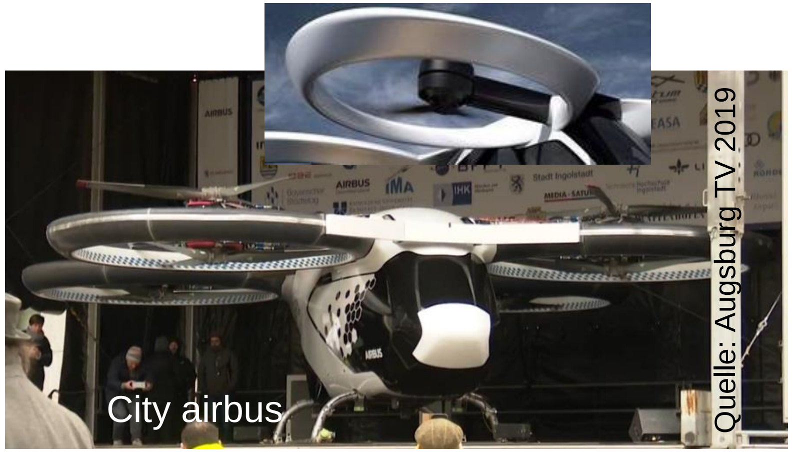
flight Mach No. M=0.2, take-off, AoA- and Pylon installation effects



Farfield (10D) prediction along flyover line

$$p'(\boldsymbol{x},t) \simeq \frac{1}{4\pi a_\infty r} \int_{\partial V_B} \frac{\dot{f}_r}{|1-M_r|^2} + \frac{(f_r + a_\infty \rho_\infty v_n)\boldsymbol{e}_r \cdot \dot{\boldsymbol{M}}}{|1-M_r|^3} \, dS(\eta)$$

$$\dot{f}_r = \dot{T}\boldsymbol{e}_r \cdot \boldsymbol{e}_T + \dot{D}\boldsymbol{e}_r \cdot \boldsymbol{e}_D(\tau) + D\boldsymbol{e}_r \cdot \dot{\boldsymbol{e}}_D(\tau)$$



uRANS+FW-H (TAU+APSIM+)

R. Akkermans, A. Stürmer, EU JTI 2012

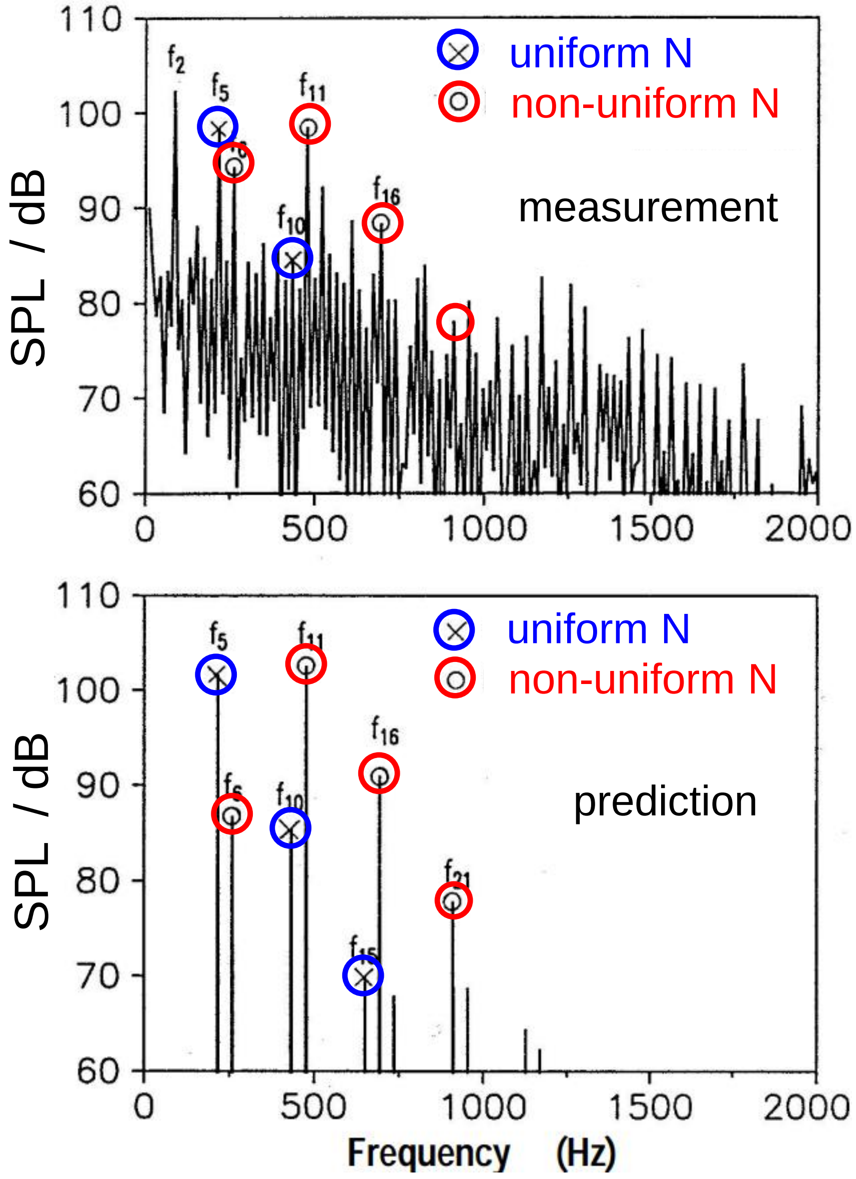
Propeller noise and non-uniform rotation speed

$$N = 2600\mathrm{rpm}$$

$$\frac{N'}{N} = 1.8\% \text{ at } n = 6$$

$$M_{\mathrm{tip}} = 0.68$$

„Re-discovered“ 2019* found also for brushless small electro motors



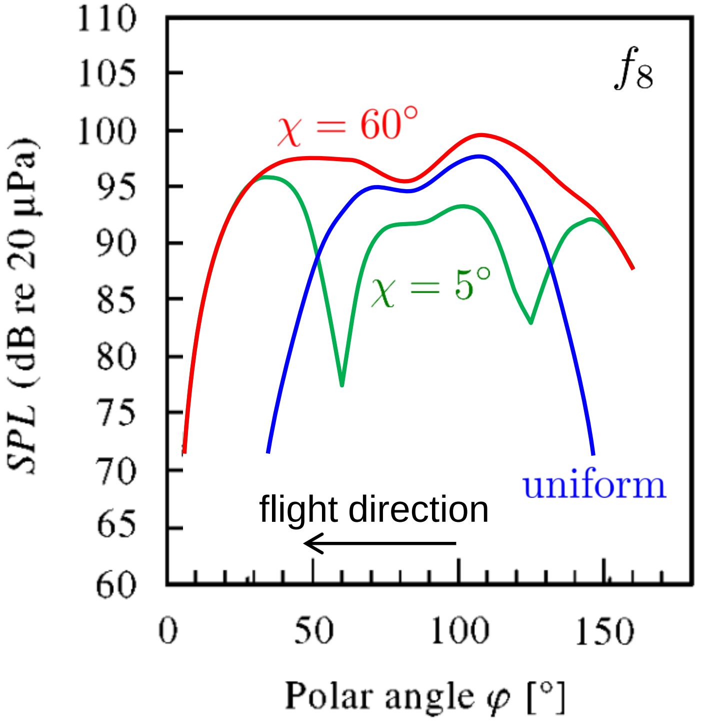
- piston engine induced 1.8% **non-uniformity of rotation** speed increases propeller noise massively
- particularly bad at low M_{tip} and in forward/rearward direction

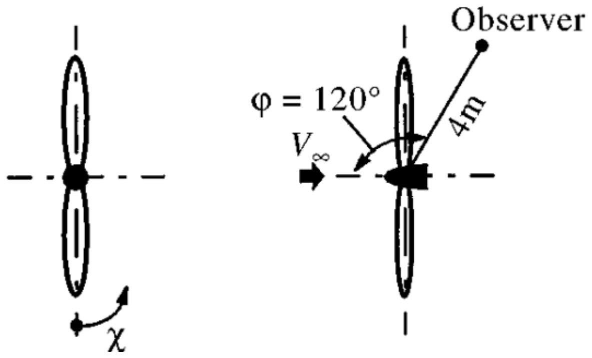
*) AIAA 2019-2499, McKay, Kingan

AIAA 97-1708, Dobrzynski, Gehlhar

Non-uniform rotation speed on prop noise – azimuthal dependence

$N = 2700/\mathrm{min} \quad A_n = 2\% \quad n = 6$



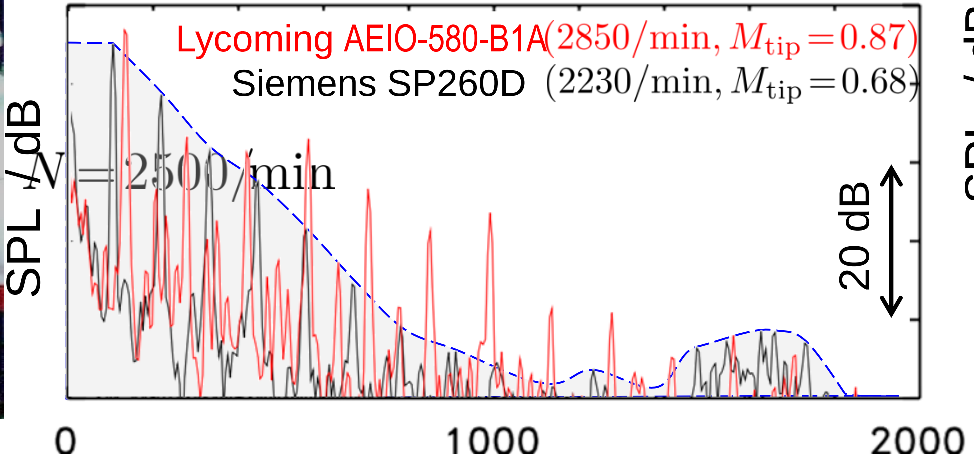


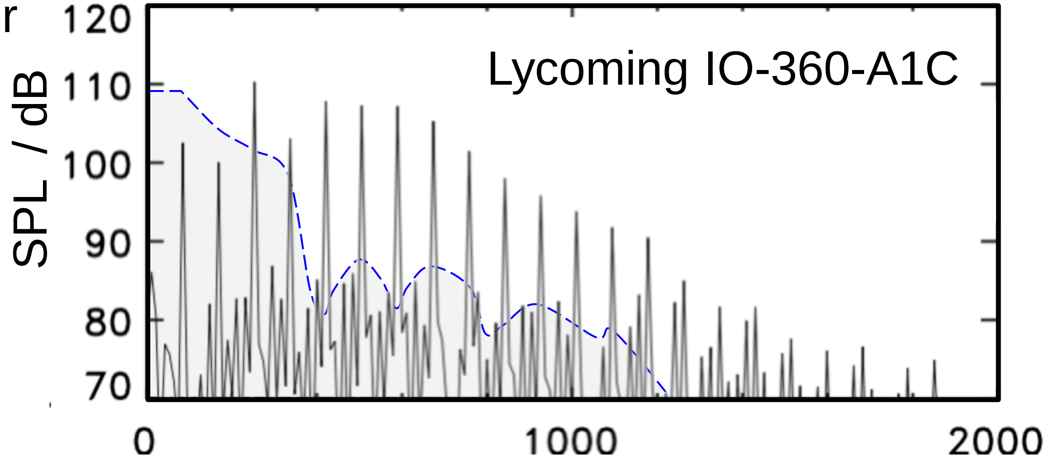
Why would an E-driven propeller be more silent ?

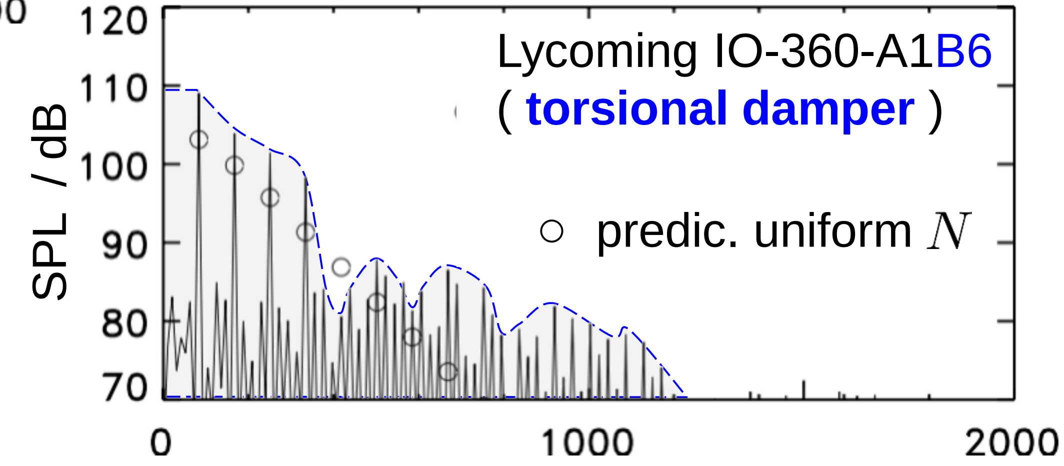
(e.g. test on Extra 330LT a/c with Siemens E-motor*)

4 stroke 4 cyl. piston engine drive

roughly evaluated from video*,1000ft flyover







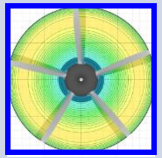
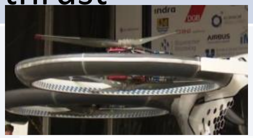
- Massive noise reduction by **homogenisation of rotational speed**
- (Elimination of piston engine exhaust noise)

→ Electric drive ☺
→ Gas turbine (turboprop) ☺

*) https://www.youtube.com/watch?v=WylLWeDtPy0&index=7&t=0s&list=PLw7lLwXw4H53YUddJ99vzOVFgn-o4f17U

AIAA 97-1708, Dobrzynski, Gehlhar

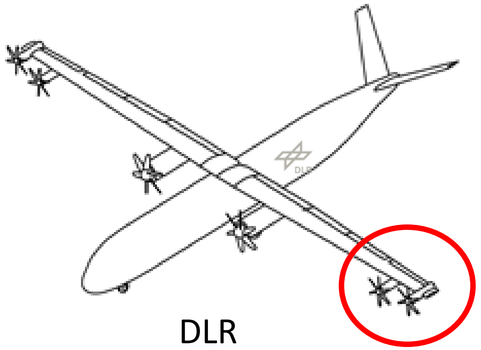
Theoretical expectations – sources of sound

component	Source/character	Directivity polar/azimuthal	Occurence/e.g.
Single Propeller / rotor isolated	steady blade load and blade thickness / tone unst. bl.load from AoA/tone↑ unst. bl.load from turb./broad spectr. 1/rev. non-uniform rot./tone ↑ ↓(?) copter mode: bl.-tip-vortex interact./ tone↑	Rotor plane/uniform Rotor plane/non-uniform↑ omnidirectional/uniform omnidirectional/ nonuniform directed forward/backward	any rotor Prop+copter any rotor from drive Landing copters 
Single Propeller installed	(un)steady inflow nonuniformity/tone+bbn	omnidirectional/nonuniform	Pusher prop upstream struts, pylon,... 
Multiple „stacked“ props Co-axial, co-rotating	Classical single prop mechanism/tone	Rotor plane/ uniform	Uber CRM 01 Multiple element airfoil principle for high lift/thrust 
Multiple contra rot. props Co-axial	Unsteady blade loads/tone+bbn↑↑	Omnidirectional/(non)uniform	City Airbus (perf. benef.) 
Multiple props/rotors non-coaxial	Superposition of single propeller (rotor) sources/tone, bbn.	Complex, props: rotor plane dominated/ nonuniform	GL-10 (NASA), VAHANA,.... 
Multiple props installed	See „Single Propeller installed“	Complex, totally nonuniform	City Airbus, Volocopter 
shrouded props./rotors	Tip Gap noise/ tone + bbn.	Omnidirectional/uniform	(City Airbus)
shrouded rotors installed	Unsteady blade loads, BLI/tone, bbn↑	Obliquely directed/uniform	Lilium 

and… (apart from noise LEVELs):

How about psycho acoustic effects?

- highly dynamic rpm thrust controlled yaw control (psycho acoustics!)



- Use design dof to deconcentrate acoustic power from tones to broadband

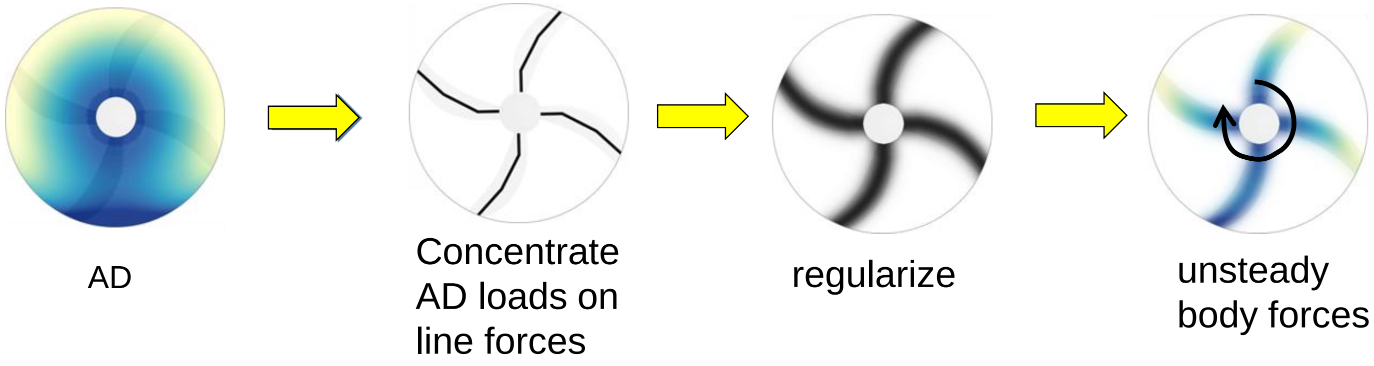
DLR 2019: M. Iwanizki, M. Strack, M. Plohr, M. Arzberger, T. Hecken

component	Noise reduction technology	benefit	drawback
Single propeller / rotor isolated	d→, rpm→, c_T↓, B↑ d↓, rpm→, c_T→, B↑ d↓, rpm→, B→ , c_T↑ (stacked co-rot.props) d→, rpm↓, c_T→, B↑ copter mode: avoid BVI by flight ops, rot. phas., shrd.	noise ↓ because Δf↑ noise↓↓ because M_{tip}↓,Δf↑ noise↓↓ because M_{tip}↓, bbn↓(?) noise↓↓ because M_{tip}↓,Δf ↑ noise↓: no vortex/bl. encounter	little effect 2/3/4 blades same thrust drag increase 2/3/4 blades same thrust drag + wake! increase drag increase oper. restrictions
Single Propeller installed	large distance of wing T.E. to pusher prop sweep (serration) of wing or prop. blade porous wing L.E. at tip vortex impingement location wing L.E. serration at tip vortex impingem. Location	less excess noise, wake dissipation less excess noise, from $\dot{T}, \dot{D}$↓ l.e. noise reduction l.e. noise reduction	weight increase weight and drag incr. lift decrease weight increase?
Multiple „stacked“ props Co-axial, co-rotating	as for single props	as for single props	as for single props
Multiple contra rot. props Co-axial	crop of rear rotor diameter shroud around rotor(s)	noise ↓↓ : no tip vortex rear prop impingement noise ↓: weaker tip vortex, benefit from cut off effects	thrust decrease weight increase
Multiple props/rotors non-coaxial	phasing among props (strict control over rotor rotational position), rotation direction	noise ↓↓ sectorially on ground	No(?) global noise reduction
Multiple props installed	as for single props installed	as for single props installed	as for single props
shrouded props/rotors	very small tip gap in shroud	noise ↓: weaker tip vortex	expensive to make
shrouded rotors installed	benefical arrangement at vehicle	noise ↓: shielding/diffraction losses	drag increase?

c_T - specific thrust d - diameter B - no. of blades T, D - thrust, drag

Ongoing research

- **SE²A, B1-3**: non-empirical fast prediction of installed propulsors



- use AD in RANS to represent (installed) rotor
- replace blades by rotating r.h.s. forces and sources in CAA perturbation
- no rotating grids in neither CFD nor CAA

- **EU-ENODISE**: validate SE²A method on generic cases + extension to broadband modeling
- **LUFO-evolve**: use method for acoustic characterization of drone noise
- **DLR-AACID**: experimental characterization of real drones

Summary & Conclusions

- Propeller noise reduction for E-drives
  - uniform rotation speed beneficial over piston engines induced rpm oscillations
  - potential from reduced rpm at increased pitch
- Noise reduction potential of E-driven propulsors are indirect:
  - new concepts of distributing thrust (more tight integration with a/c)
  - better use of noise shielding -> combined with new a/c concepts
  - more flexible use of thrust control (low noise engine operation along flight procedures)?
  - enabling of (adaptive) phase control among props (huge optimisation problems)
- Risks
  - new sources of highly integrated distributed propulsors (installation source noise)
  - highly dynamic rpm control for a/c control potentially extremely annoying (psycho acoustics)
- Many open questions: **more research on noise of UAMVs needed/addressed to explore potentials!**

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Thank you

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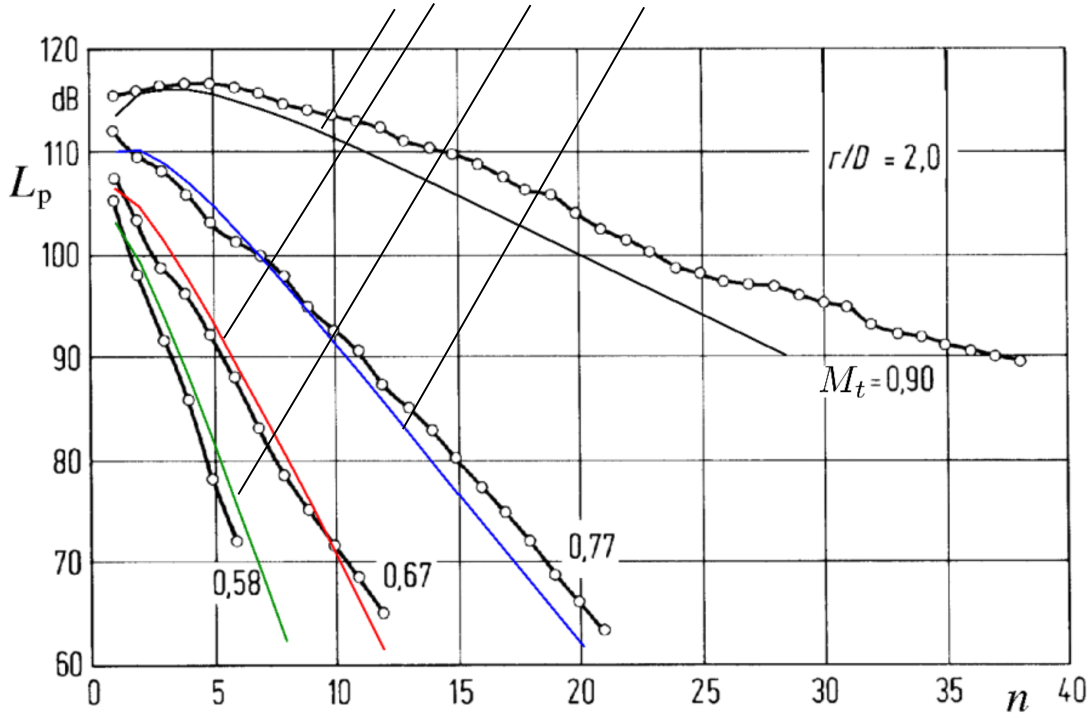
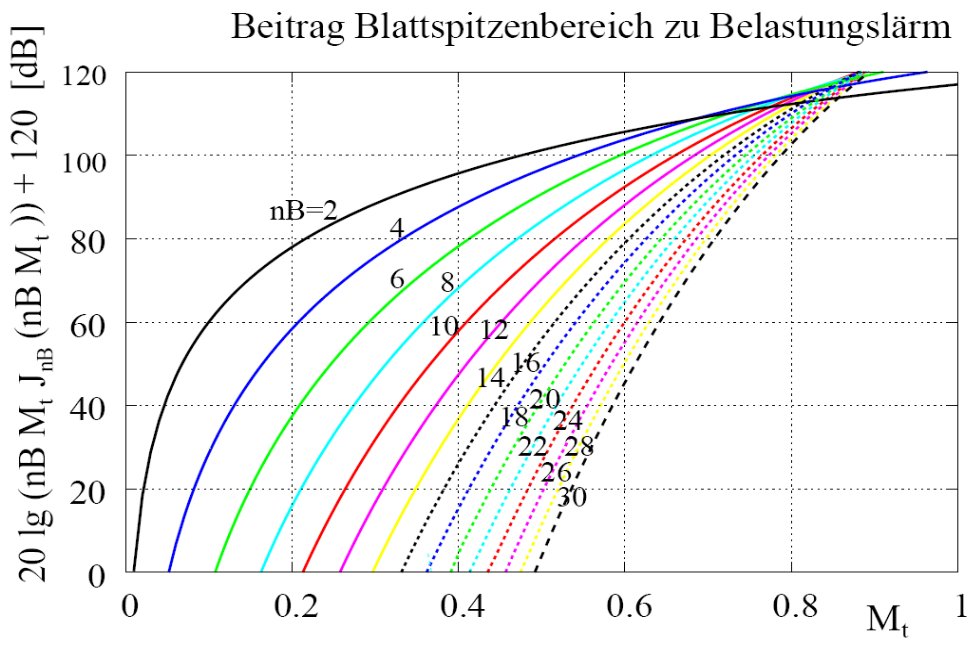
Propeller noise scaling (isolated)

Example of 2-bladed propeller

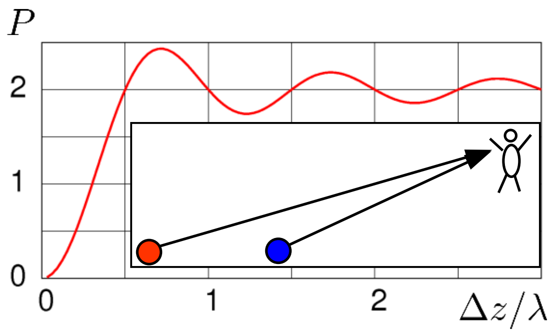
$$20\,\lg\left(nBM_t\,J_{nB}(0.9\,nBM_t)\right)+120$$

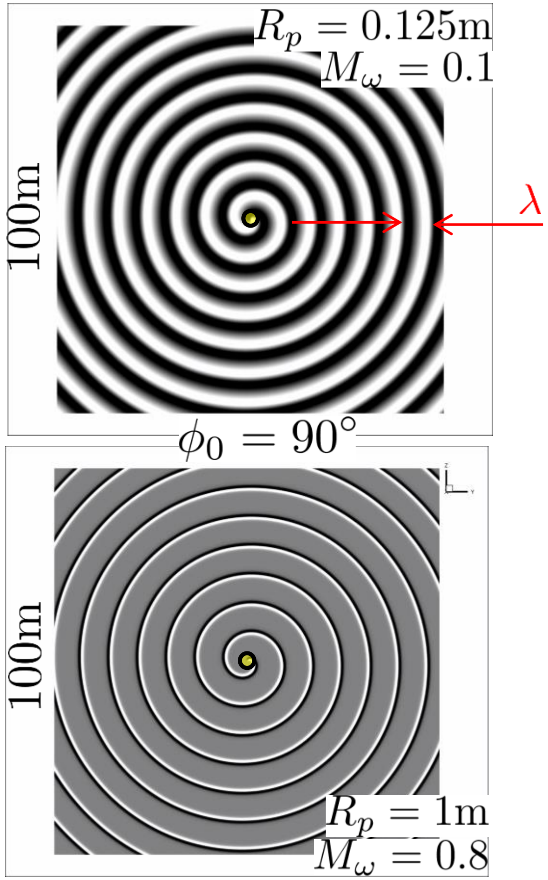


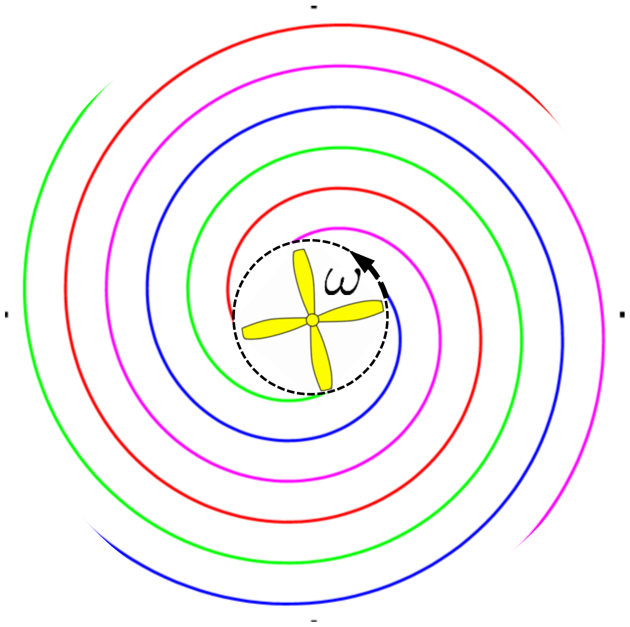


$$|\hat{p}_{nB}| \sim nBM_tJ_{nB}(nBM_t)\,\frac{T}{R_t} \simeq \frac{1}{2^{nB}(nB)!}(nBM_t)^{nB+1}\,\frac{T}{R_t}$$

On propeller anti-phasing



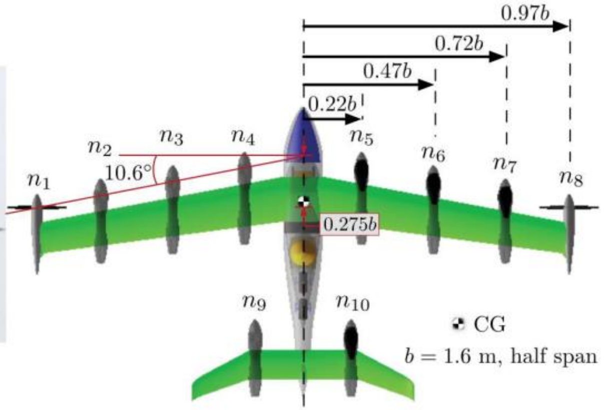




Phase lines of 4-bladed propeller

Compactness ratio $He = k_{nB}\Delta z = 2\pi \frac{\Delta z}{\lambda_{nB}} = 2nBM_{\text{tip}} \frac{\Delta z}{d} \overset{!}{<} 3$

$\boxed{n \overset{!}{<} \frac{3}{2} \frac{d}{\Delta z} \frac{1}{BM_{\text{tip}}}}$ $\Rightarrow$ global reduction hardly possible



$$\frac{\Delta z}{D} = \frac{0.4}{0.4064} < 1$$

https://ntrs.nasa.gov