Theoretical prediction of unsteady wall pressure during turbulence-airfoil-interaction

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Urban Air Mobilty (UAM)



Artist's sketch of UAM environment



Airbus CityAirbus eVTOL demonstrator

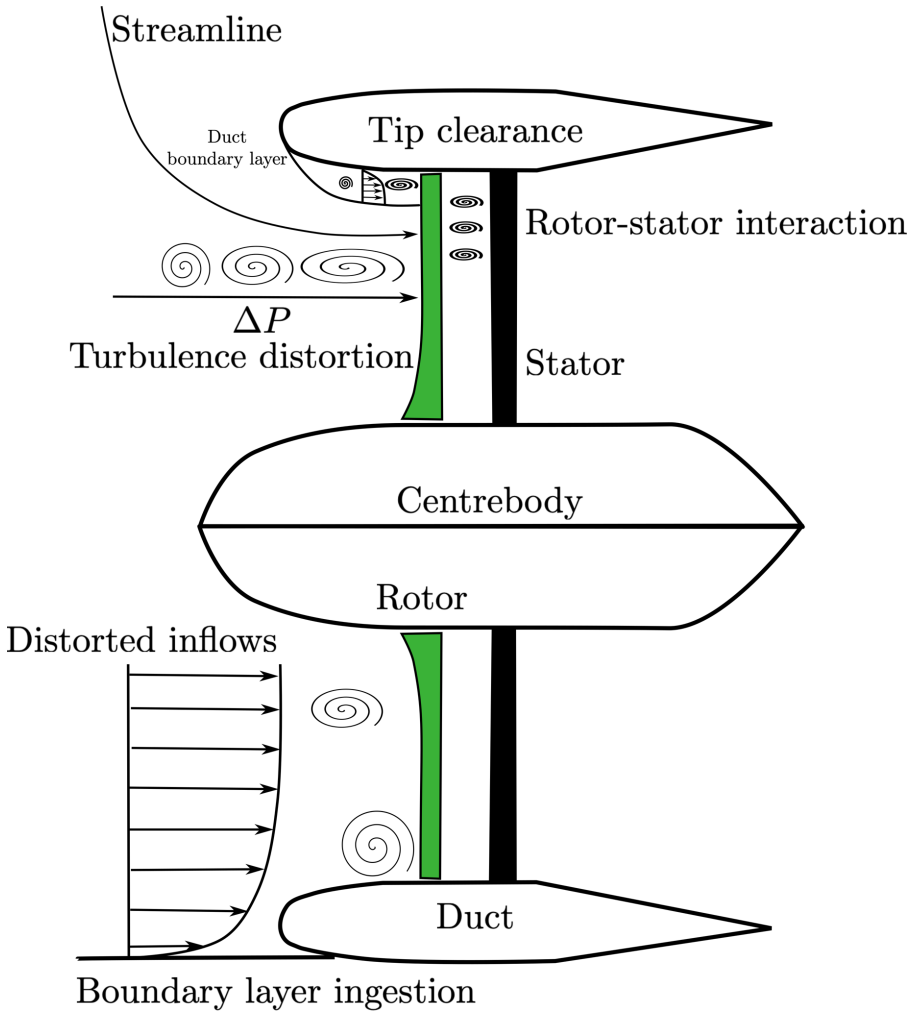
AIAA Aviation Forum 2019, Dallas, Texas.

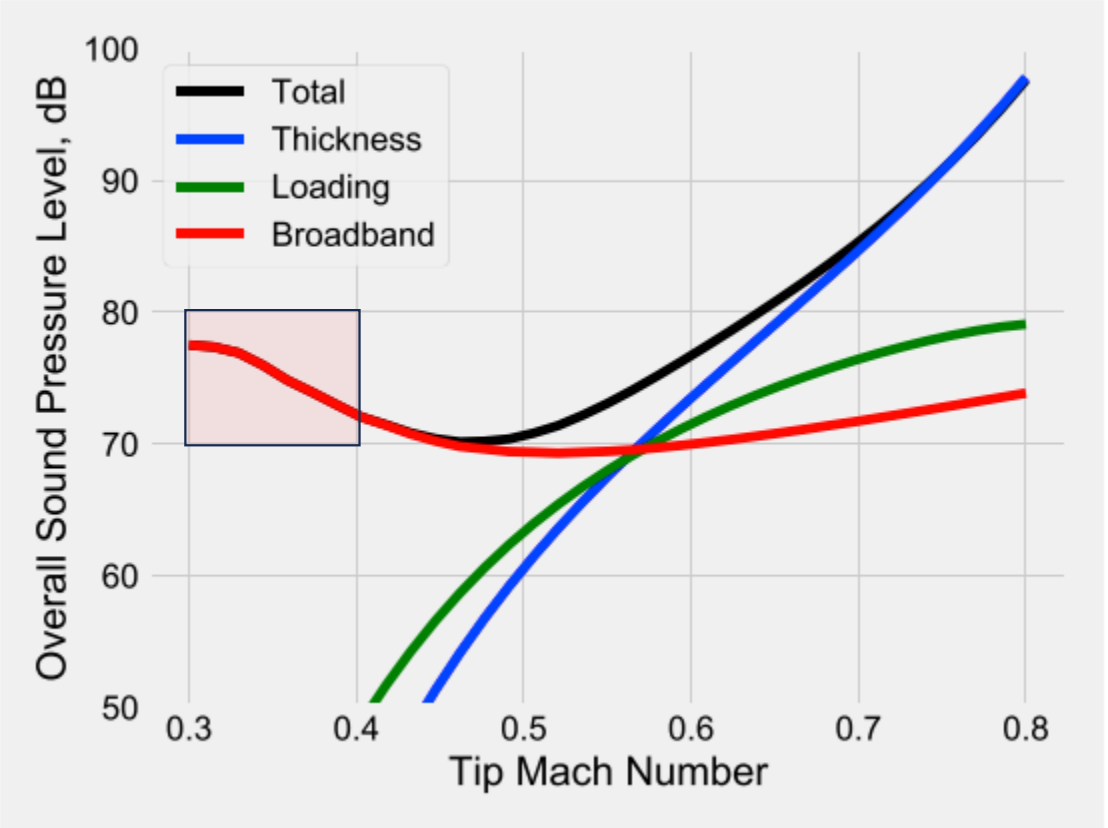
Simulations of Ducted and Coaxial Rotors for Air Taxi Operations

Patricia Ventura Diaz,* Rafael Caracuel Rubio,† and Seokkwan Yoon‡
NASA Ames Research Center, Moffett Field, California

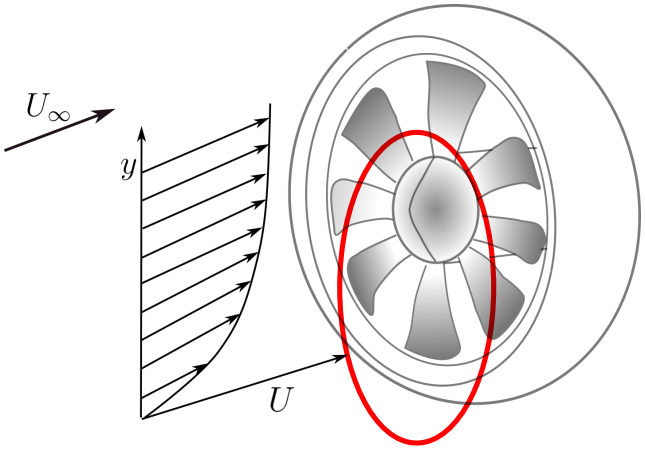
Ducted propellers feature prominently

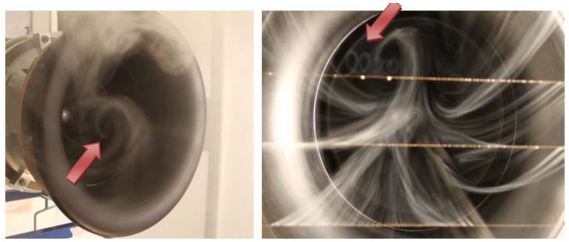
Unsteady Loading Noise Sources



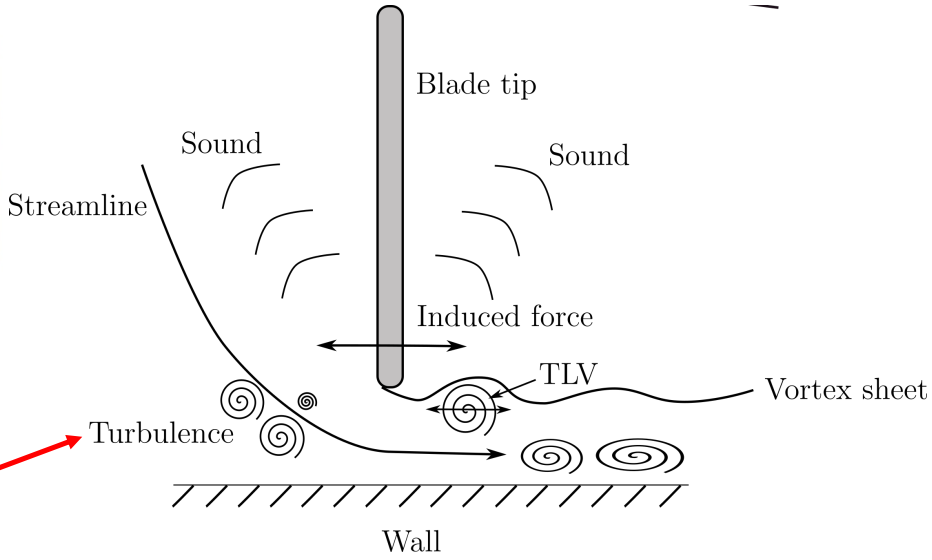


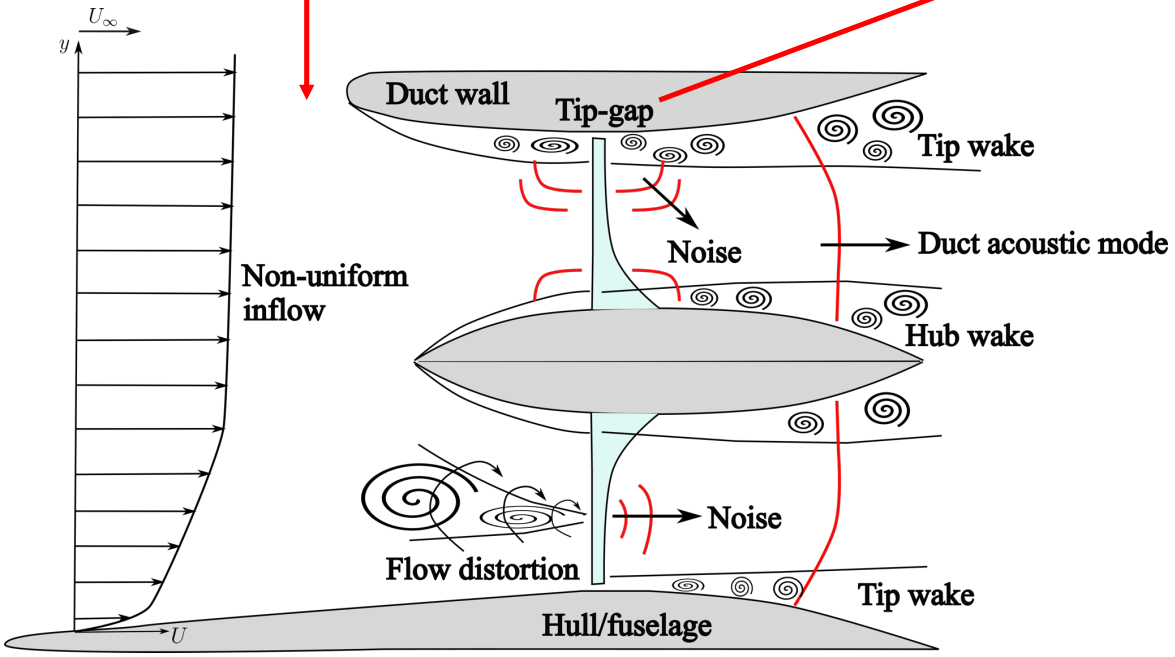
Greenwood, E., Brentner, K. S., Rau, R. F., & Ted Gan, Z. F. (2022). Challenges and opportunities for low noise electric aircraft. In *International Journal of Aeroacoustics* (Vol. 21, Issues 5–7, pp. 315–381). SAGE Publications Inc. https://doi.org/10.1177/1475472X221107377

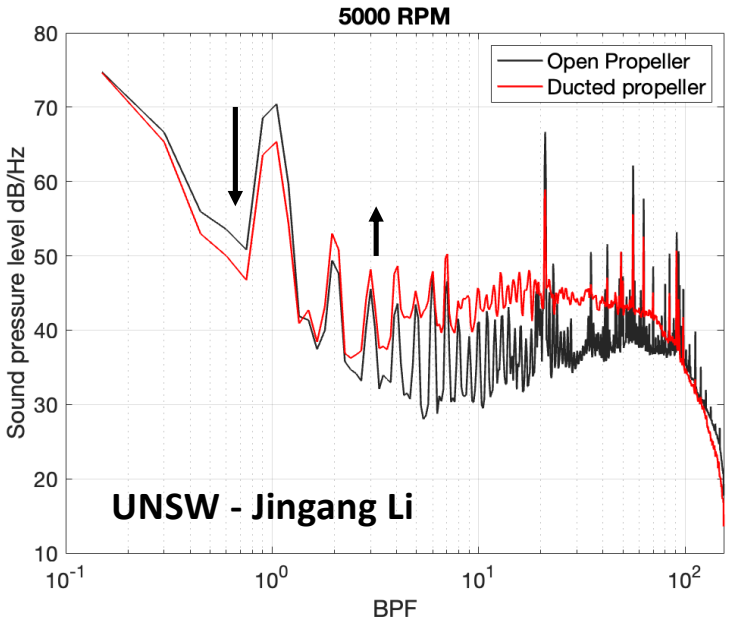




Sturm & Carolus







Turbulence-Airfoil Interaction Noise

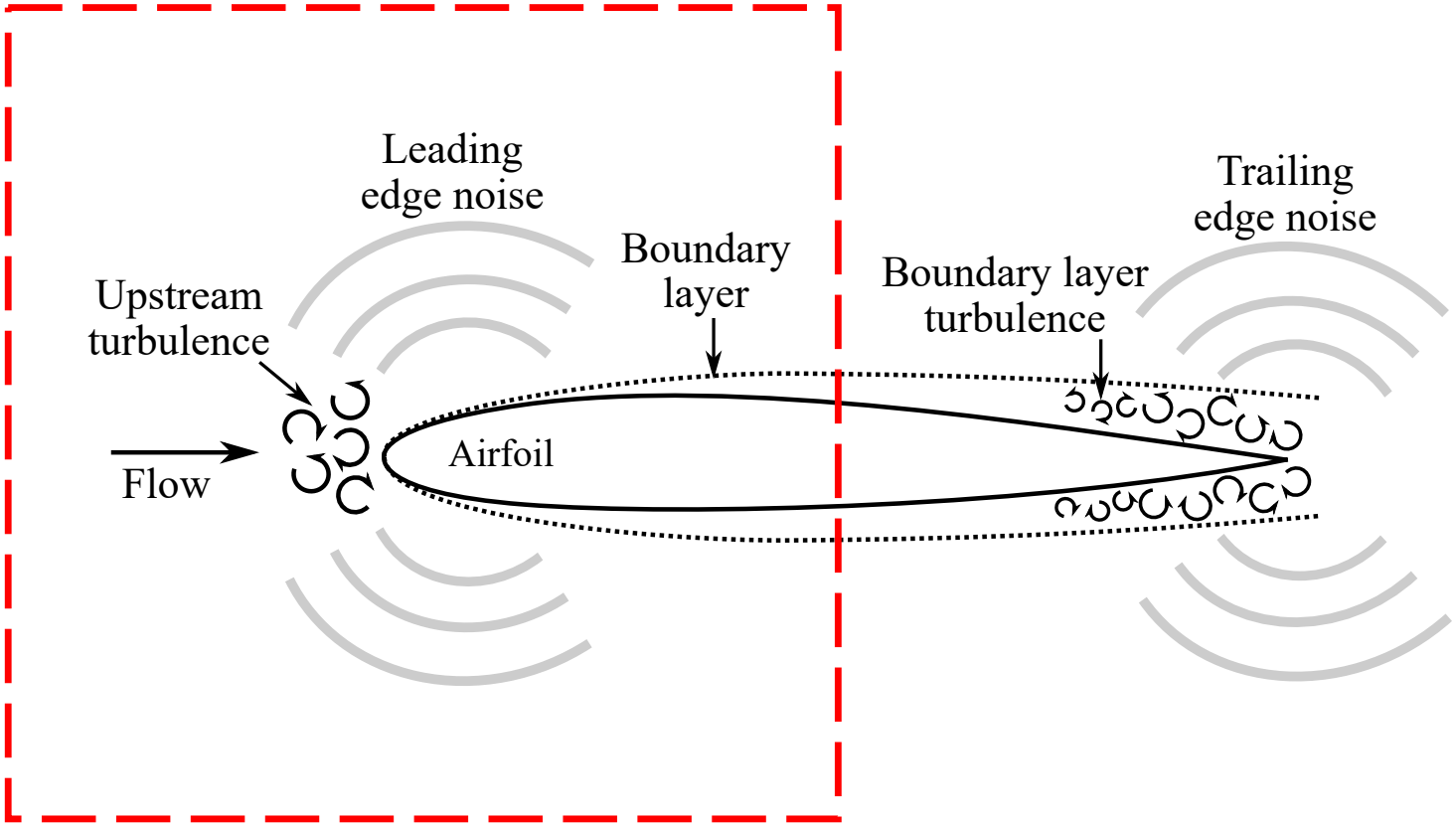
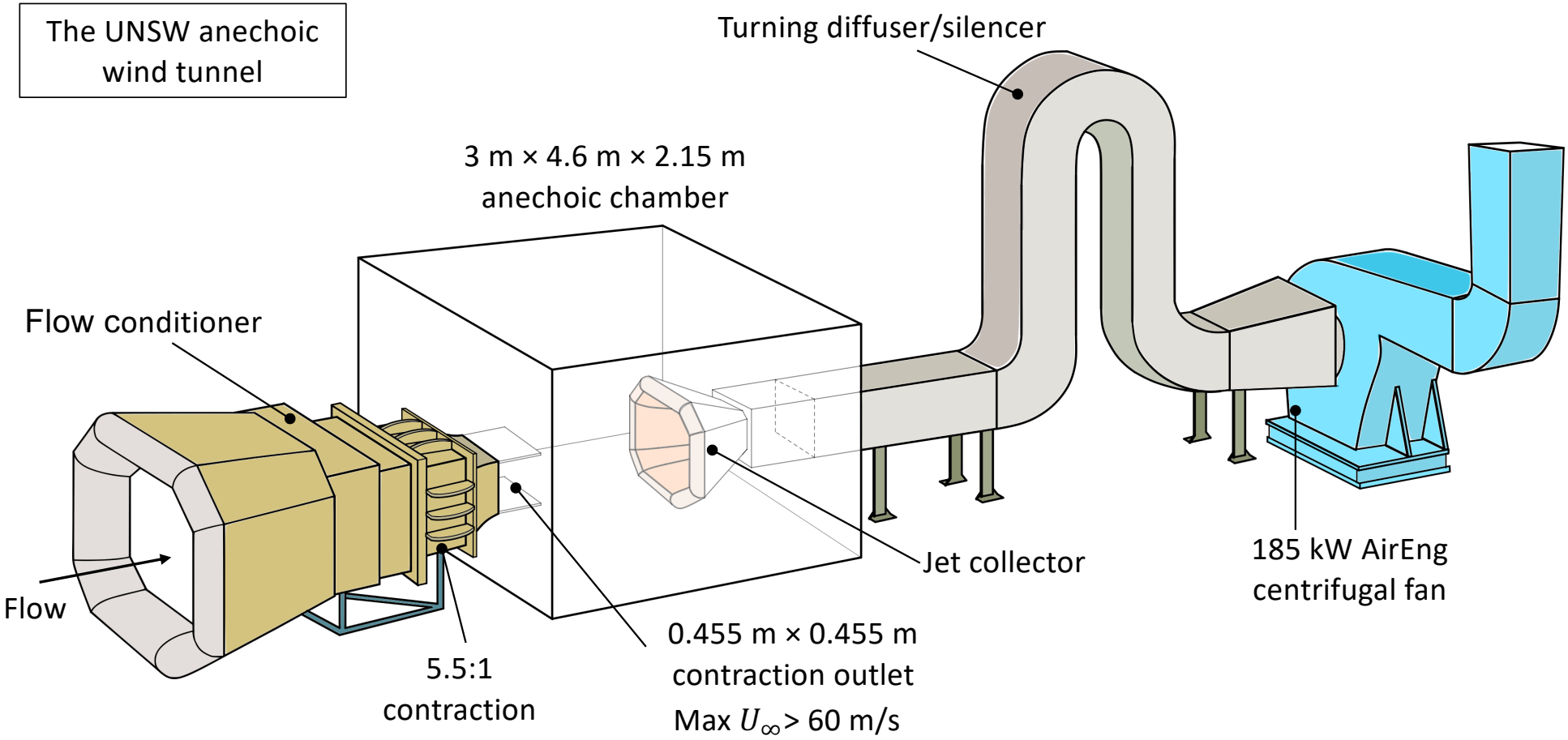


Image Courtesy of A/Prof Danielle Moreau

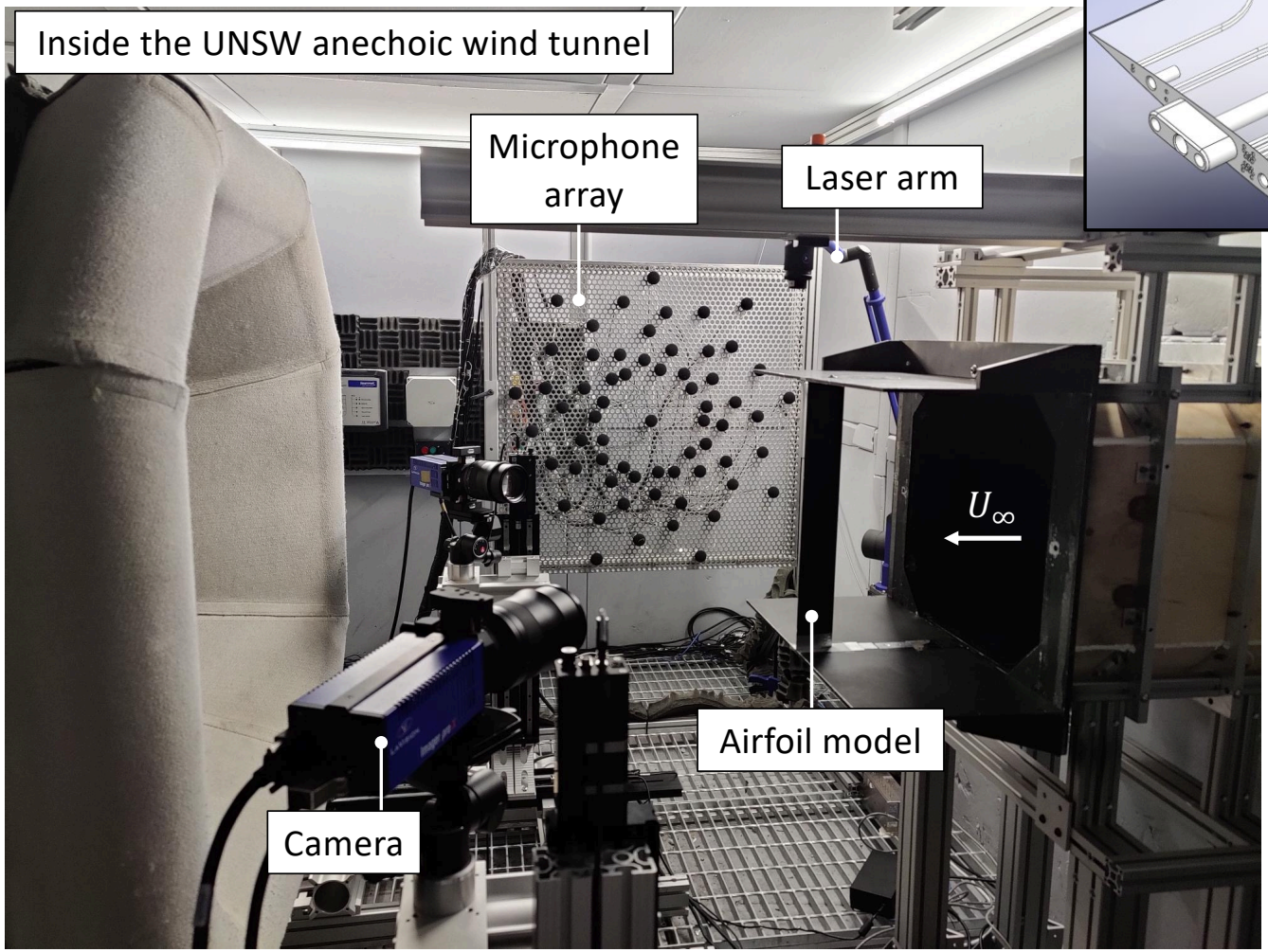
Flow noise experiments

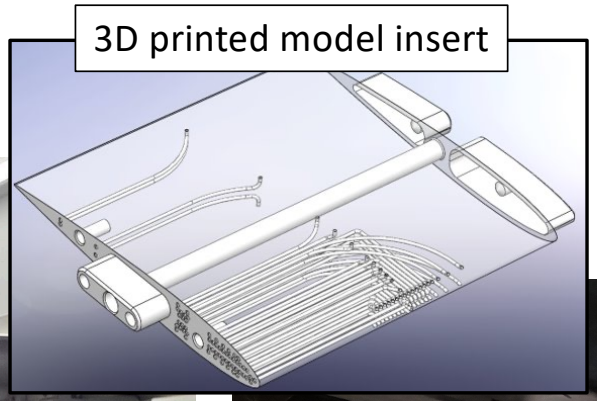
The UNSW anechoic wind tunnel

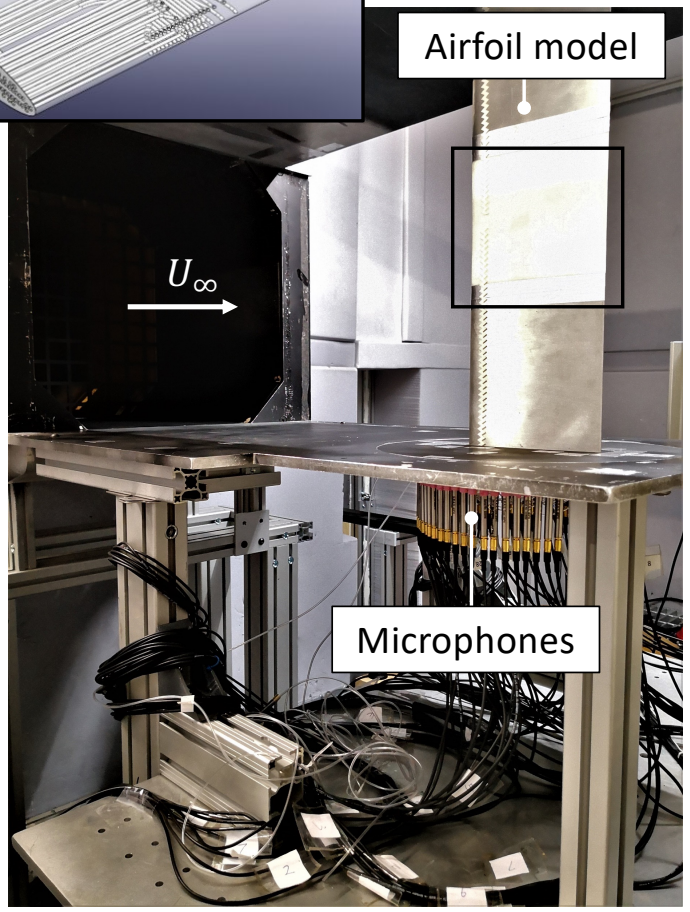


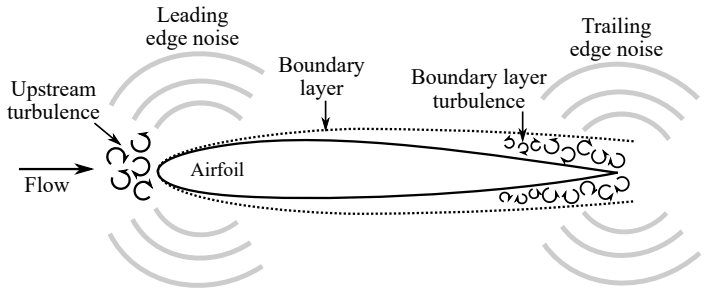
Grid Turbulence-Airfoil Interaction

Roman Kisler









Turbulence-Airfoil Interaction Noise Theory

Amiet's Theory:

$$S_{pp}(x_0, y_0 = 0, z_0, \omega) = \left(\frac{\omega z_0 \rho_0 (c/2)}{c_0 \sigma^2}\right)^2 \pi U_\infty \left(\frac{d}{2}\right) |\mathcal{L}(x, K_x, 0)|^2 \Phi_{ww}(K_x, 0) \quad (1)$$

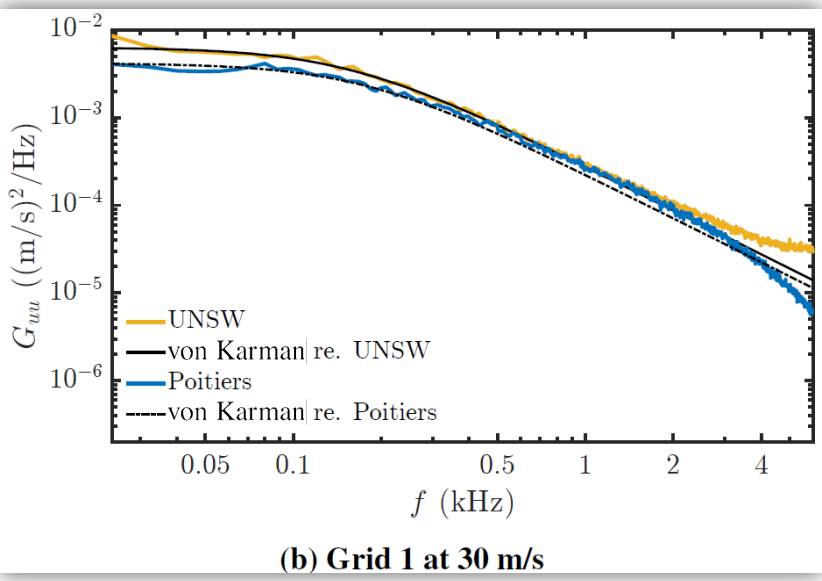
Far-field radiated sound (PSD)

Lift response function

Incoming turbulence wavenumber spectrum

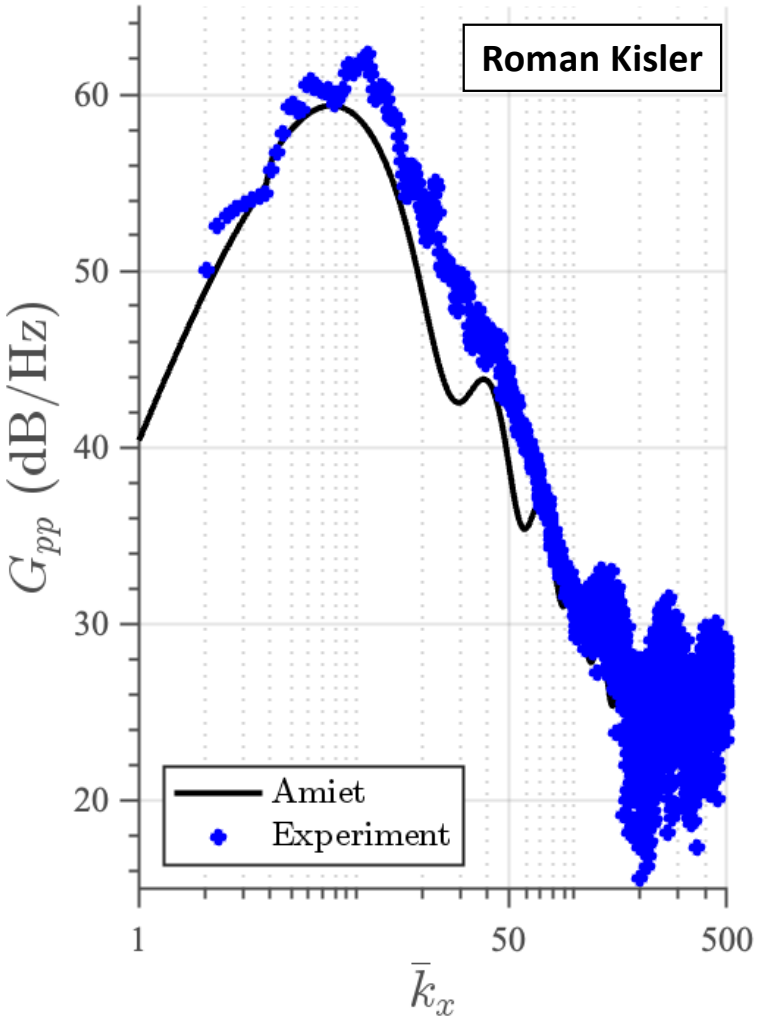
R.K. Amiet, Acoustic radiation from an airfoil in a turbulent stream, Journal of Sound and Vibration, Volume 41, Issue 4, 1975, Pages 407-420,

Grid Turbulence-Airfoil Interaction Noise



(b) Grid 1 at 30 m/s

Parameter	UNSW	
	Grid 1	Grid 2
Airfoil	NACA 0012	
Flow speed	30 m/s	
Reynolds number	3×10^5	
Turbulence intensity (streamwise)	5.1 %	4.8 %
Roach's[1] estimated TI	3.5 %	3.1 %
Integral length scale (streamwise)	25 mm	22 mm
Roach's[1] estimated length scale	18 mm	17 mm



Pressure Jump Cross-Spectra Theory (Amiet)

$$S_{pp}^{\Delta}(x,x',\eta,f) = 16\pi bU\left(\pi\rho_0 U\right)^2 \int_0^{\infty} \underbrace{g^*(\bar{x},\bar{k}_x,\bar{k}_y)g(\bar{x},\bar{k}_x,\bar{k}_y)}\underbrace{\bar{\Phi}_{ww}(\bar{K}_x,\bar{k}_y)}e^{i\bar{k}_y\left(\frac{\eta}{b}\right)}\,d\bar{k}_y$$

Convolution of transfer function and turbulence wave number spectrum

$$g(\bar{x},\bar{k}_x,\bar{k}_y) = -\frac{f(\bar{x},\bar{k}_x,\bar{k}_y)}{\pi\beta\sqrt{\pi\bar{x}\left[\sqrt{\frac{\bar{k}_y^2}{\beta^2}-\mu^2}+i\left(\mu M+\bar{k}_x\right)\right]}}e^{-\bar{x}\sqrt{\frac{\bar{k}_y^2}{\beta^2}-\mu^2}+i\mu M\bar{x}}$$

where, for cases when $\frac{\bar{k}_x}{\bar{k}_y} > \frac{M}{\beta}$,

$$f(\bar{x},\bar{k}_x,\bar{k}_y) = 1-\sqrt{\frac{\bar{x}}{2}}\left[1-\mathrm{erf}\sqrt{2(2-\bar{x}_s)\sqrt{\frac{\bar{k}_y^2}{\beta^2}-\mu^2}}\right]$$

and otherwise,

$$f(\bar{x},\bar{k}_x,\bar{k}_y) = 1-\sqrt{\frac{\bar{x}}{2}}\left\{1-(1-i)\mathrm{E}^*\left[2i\sqrt{\frac{1}{\pi}(2-\bar{x}_s)\sqrt{\mu^2-\frac{\bar{k}_y^2}{\beta^2}}}\right]\right\}$$

$$\mathrm{E}^*(x) = \frac{1}{\sqrt{2\pi}}\int_0^x e^{-i\xi}\frac{d\xi}{\sqrt{\xi}}$$

$$\bar{\Phi}_{ww}(\bar{K}_x,\bar{k}_y) = \frac{4}{9\pi}\frac{u_{\mathrm{rms}}^2}{U^2\bar{k}_e^2}\frac{(\bar{k}_x/\bar{k}_e)^2+(\bar{k}_y/\bar{k}_e)^2}{\left[1+(\bar{k}_x/\bar{k}_e)^2+(\bar{k}_y/\bar{k}_e)^2\right]^{7/3}}$$

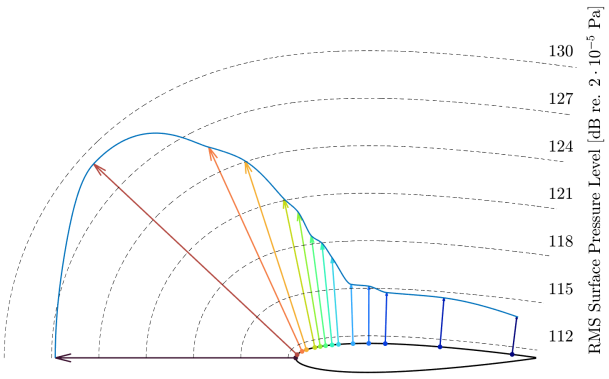
Autospectra:

$$G_{pp}^{\Delta}(x,f) = S_{pp}^{\Delta}(x,x,0,f)$$

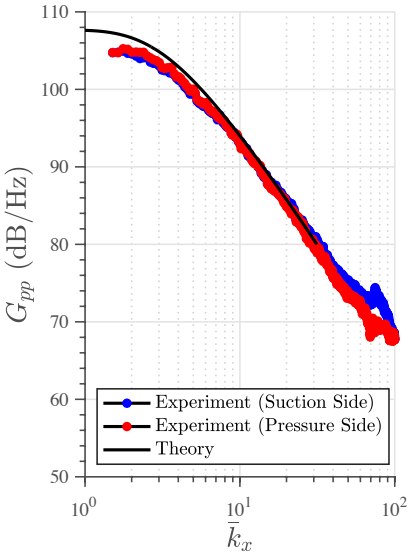
$$G_{pp}(x,f) = \frac{1}{4}G_{pp}^{\Delta}(x,f)$$

Grid Turbulence-Airfoil Interaction Airfoil Response

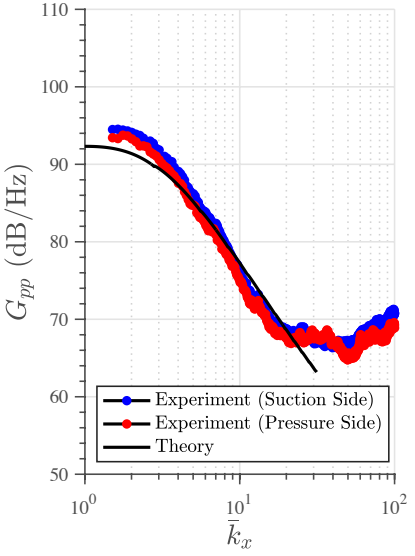
α = 0 degrees



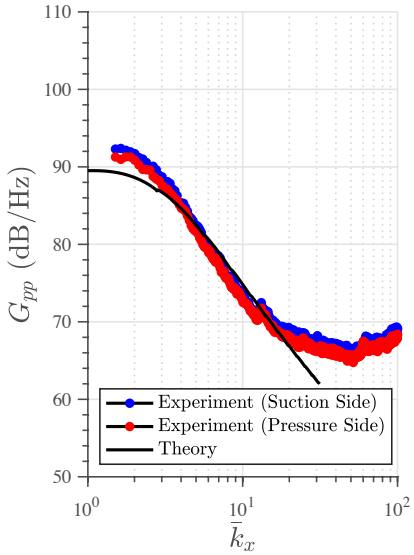
RMS Pressure Along Chord



α = 0 degrees



x/c = 0.006



x/c = 0.1022

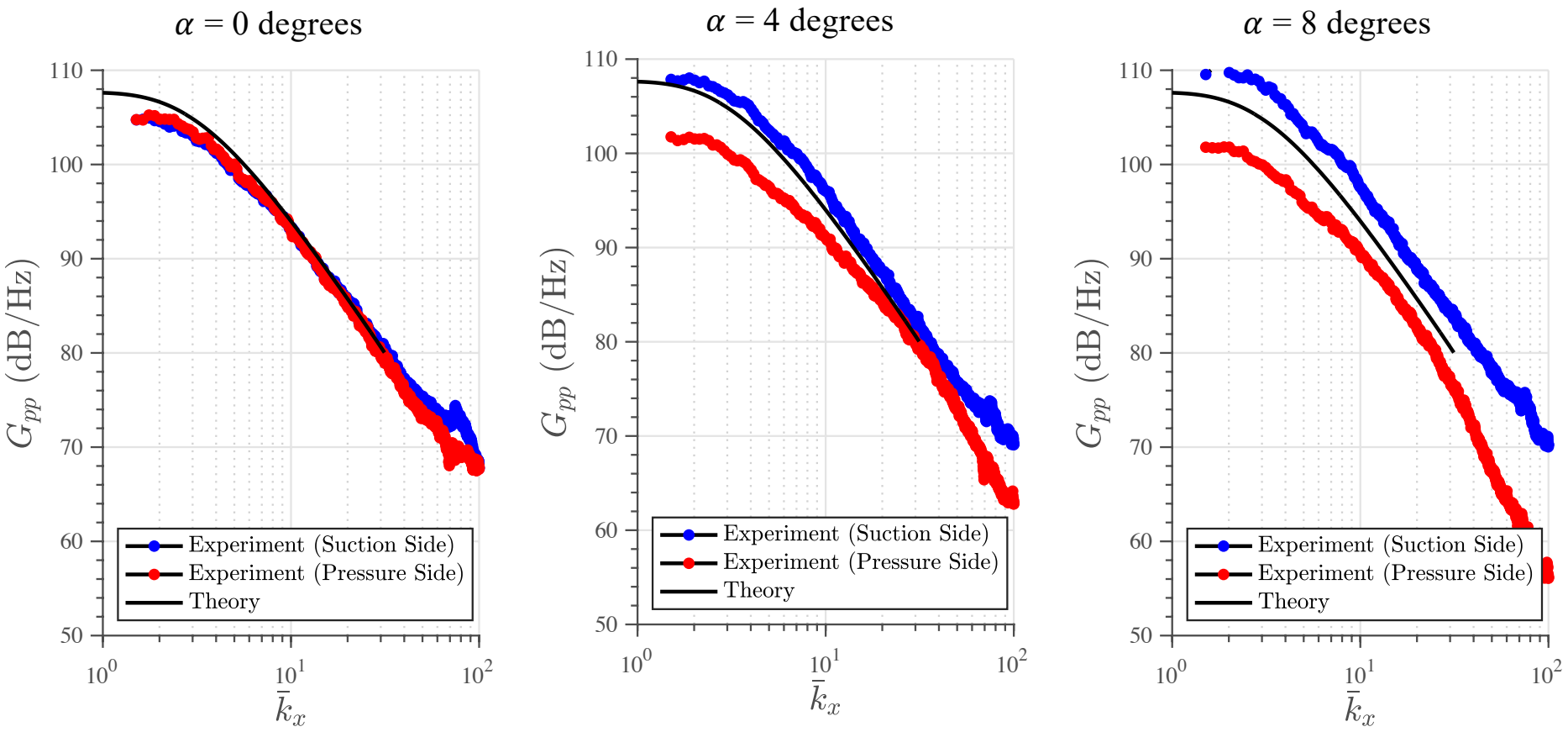
x/c = 0.1513

Theory underpredicts experiment (at low wave numbers) as you travel downstream…

Roman Kisler

Airfoil Response – Effect of Angle of Attack

$x/c = 0.006$

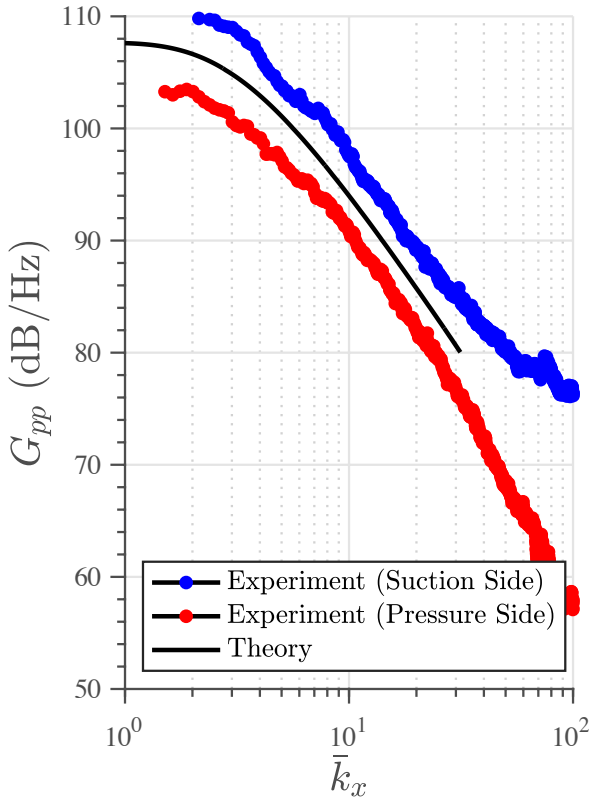


NACA 0012 in Grid Turbulence (geometric angles of attack)

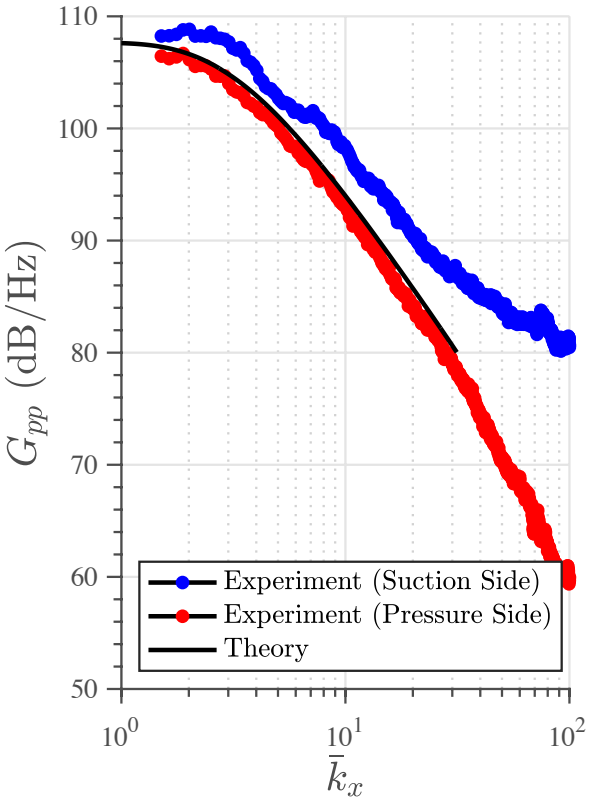
Airfoil Response – Effect of Angle of Attack

$x/c = 0.006$

α = 12 degrees

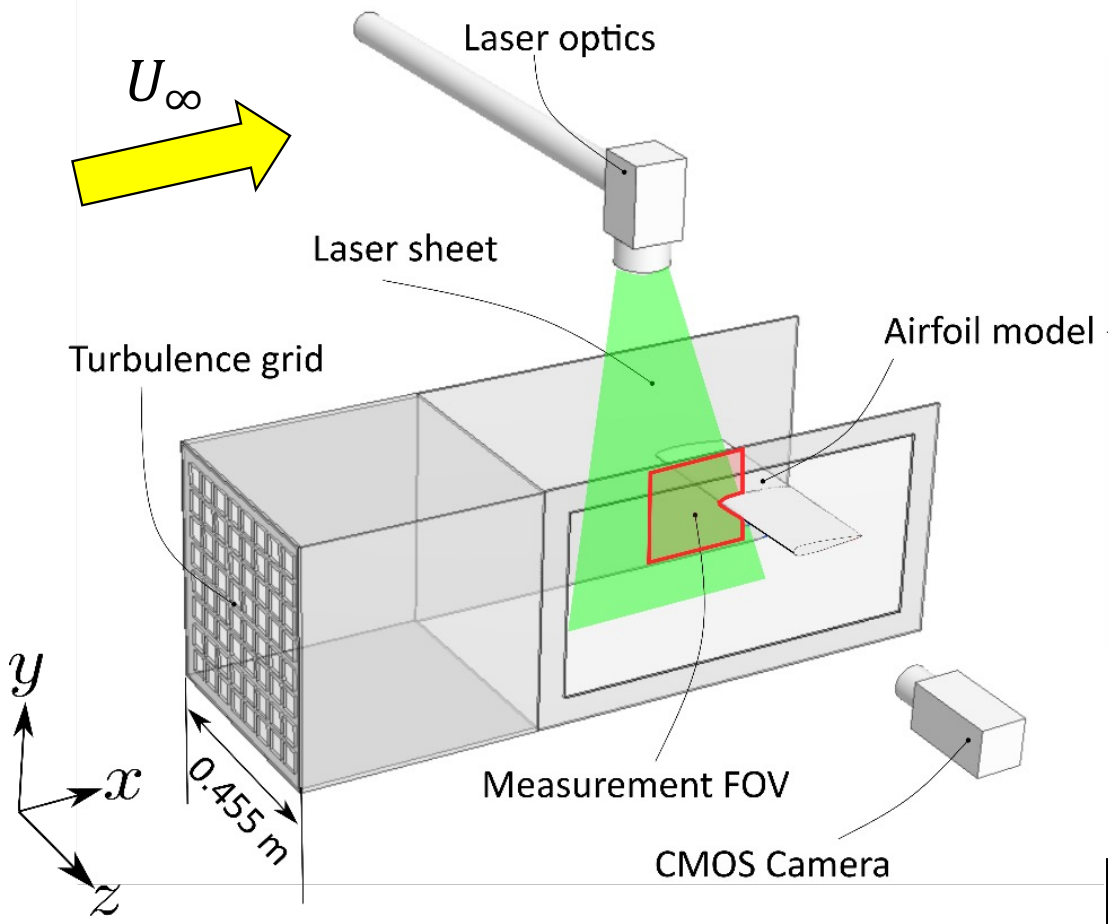


α = 16 degrees

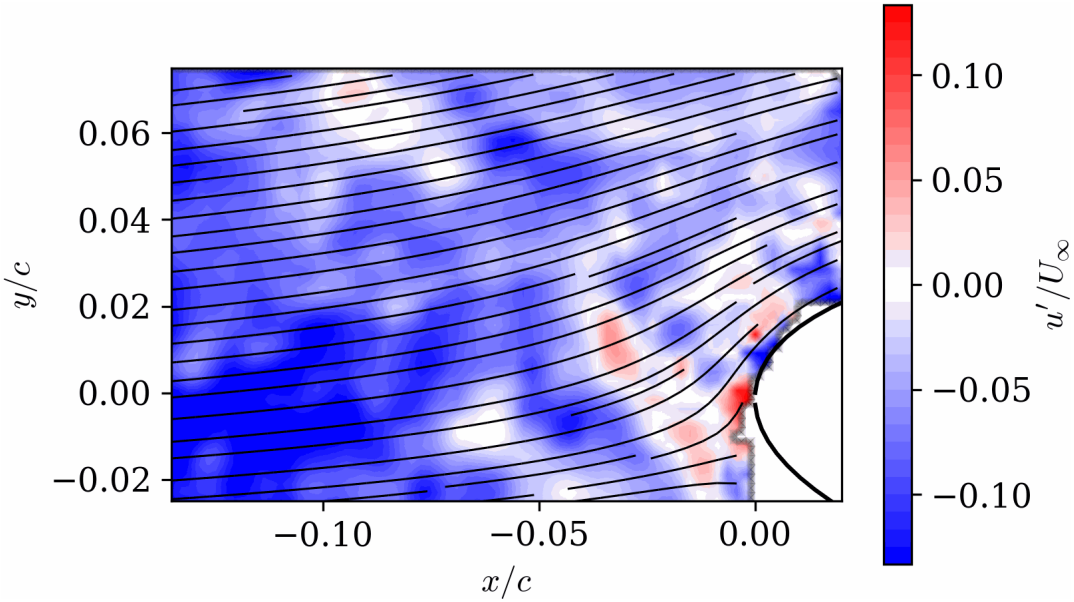


NACA 0012 in Grid Turbulence (geometric angles of attack)

High-speed PIV for LE turbulence interaction



Results for $\alpha = 5°$



Contours of instantaneous x velocity fluctuations u'

Ahmed Osama Mahgoub

Summary and Conclusions

- Low Mach number unsteady loading noise is important for future UAM ducted propulsion systems
- Turbulence-airfoil leading edge noise is a major unsteady loading source
- Amiet's theory does a reasonable job at predicting the unsteady pressure loading on airfoils at zero angle of attack
- Amiet's theory breaks down as angle of attack is increased
- This is because of the distortion of turbulence as the flow passes over the leading edge
- Increased accuracy is possible, but only by developing more sophisticated airfoil pressure response/transfer function models (that include turbulence distortion)

Thanks!

Australian Government
Australian Research Council

ARC

