On computational aerodynamics and aeroacoustics of moving airfoils: initial results

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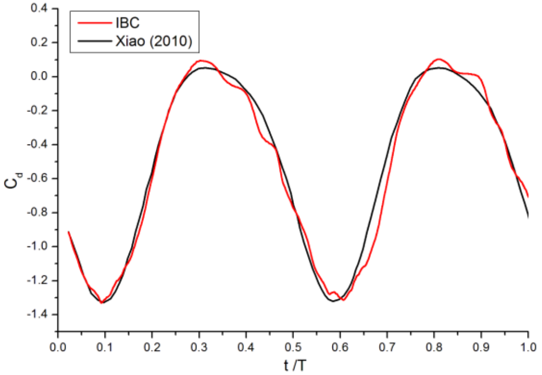
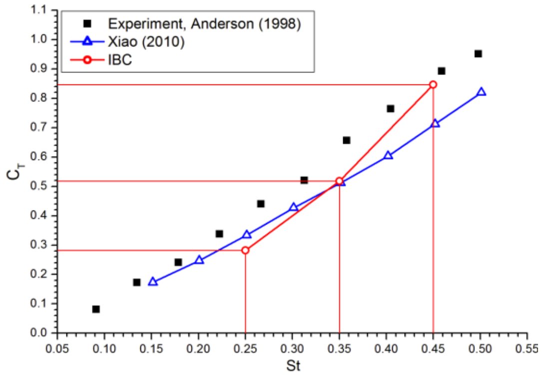
SIMULATION OF AERODYNAMICS OF MOVING BODIES

Pitching and plunging airfoil

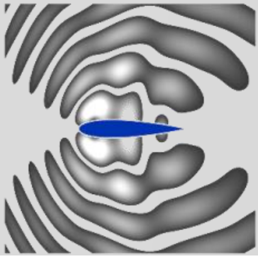


Computed drag coefficient in comparison with the numerical results from Xiao (2010)



Mean trust coefficient in comparison with experimental data from Anderson (1998)

Vorticity distribution $|\Omega_z|$



Outline

- Research background
- Leading edge noise of heaving airfoils
  - Effect of mean flow viscosity
  - Effect of anisotropic turbulence
- Summary

Introduction

- The aerodynamic flutter and dynamic stall phenomena are common in aircraft and helicopter rotors.
- Lift enhancement and thrust generation by an oscillating airfoil under certain conditions (McCroskey 1982, Freymuth 1988).
- Flow features around an oscillating airfoil varies:
  - At low Reynolds number (Re), the reversed von-Kármán vortex street or von-Kármán vortex street can be observed depending on oscillating frequency and amplitude $St_A = \frac{2\pi f A}{u_\infty}$ (Triantafyllou 1993);
  - Different of leading edge vortices can be observed under various oscillating frequency $St_c = \frac{2\pi f c}{u_\infty}$ (Lewin *et al.* 2003).

Mi-8 - Main rotor blade move in flight
https://www.youtube.com/watch?v=FlP7zSBcbuI

BBC: Super Powered Owls

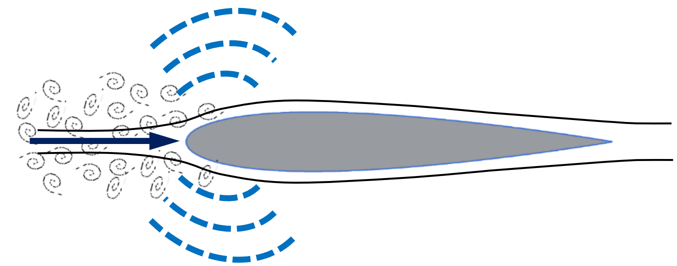
Introduction

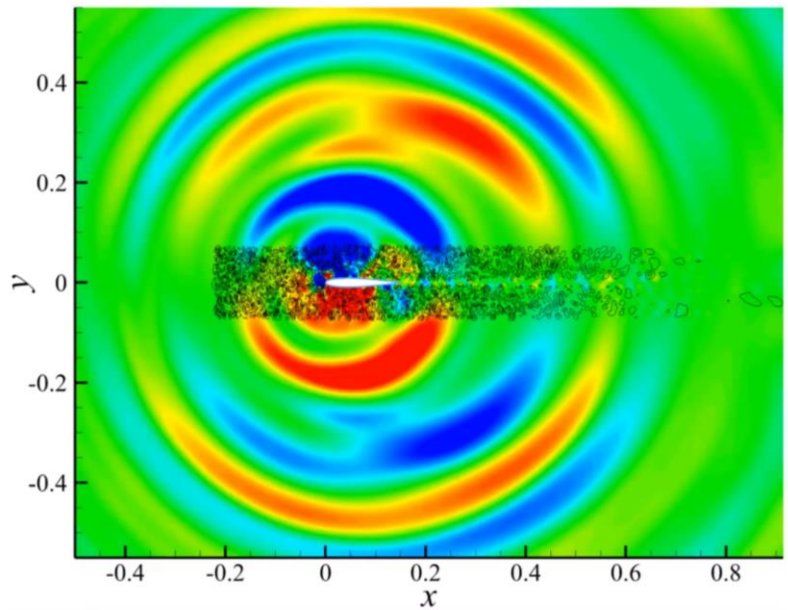
- Leading edge noise of a rigid airfoil has been studied experimentally, numerically, and analytically.

- A noise reduction effect has been observed for a thicker airfoil (Paterson and Amiet 1977).
  - The larger size of the stagnation region of the thicker airfoil was identified as the cause (Gill *et al.* 2013);

- The effects of AoA and airfoil camber was found to be small on the leading edge noise with the isotropic turbulence (Devenport *et al.* 2010, Gill *et al.* 2013).

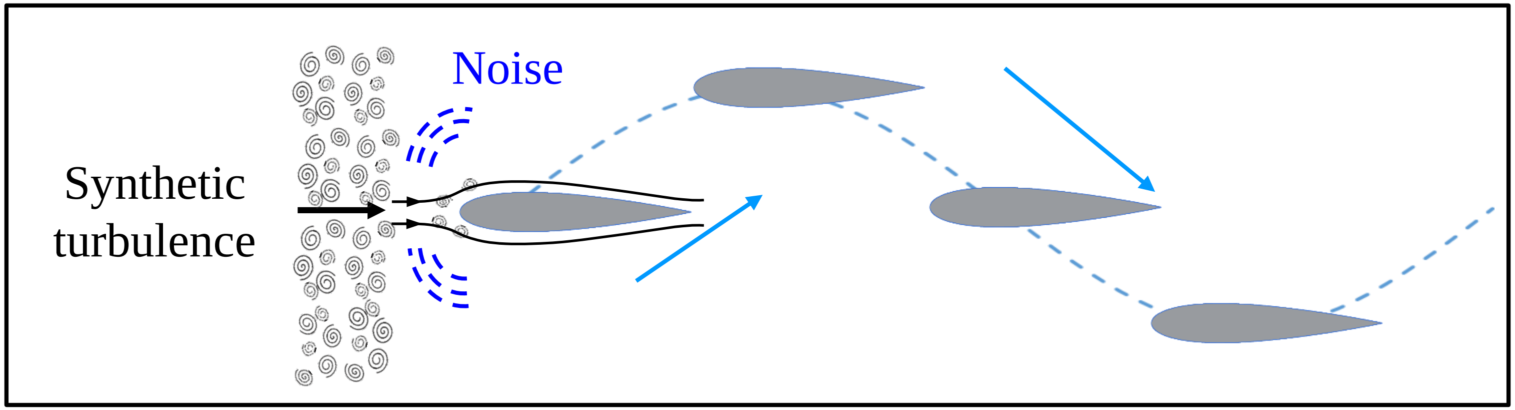
- With anisotropic turbulence, The effects of AoA was found to be more pronounced (Gea-Aguilera, 2017).





Introduction

- The leading edge noise of a heaving NACA0012 airfoil is studied.
- The mean flow solutions obtained by the Euler and the Unsteady Reynolds-Averaged Navier-Stokes (URANS) solvers are compared.
- The leading noise is predicted by the LEE with the synthetic turbulence.
- This study includes both isotropic and anisotropic turbulence.



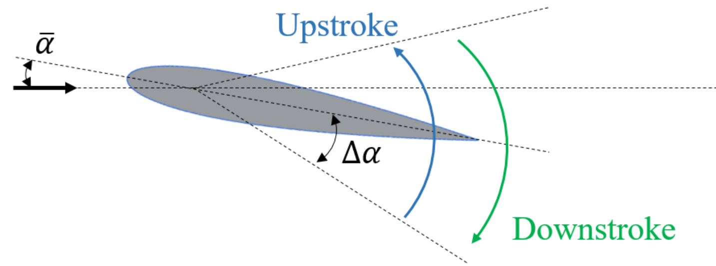
Computation of the background mean flow

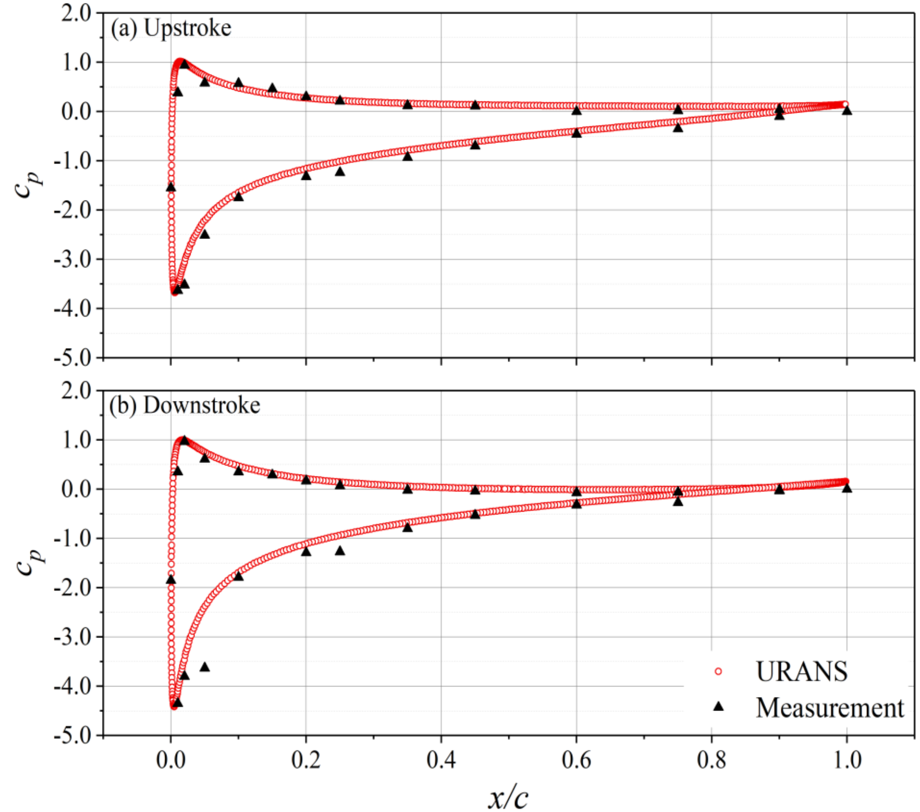
Mean flow solver validation

- The URANS solver is firstly validated with the experiment of a pitching NACA0012 airfoil from Windsor 1970.
  - $Re = 900{,}000$;
  - $\alpha = \bar{\alpha} + \Delta\alpha \cdot \sin(\omega t)$, where $\bar{\alpha} = 5.8°$, $\Delta\alpha = 6.17°$;
  - $St_A = 0.044$.

- The condition is chosen for there is no dynamic stall phenomenon.

- The comparisons are made at $\alpha = 10.16°$ for upstroke and downstroke.

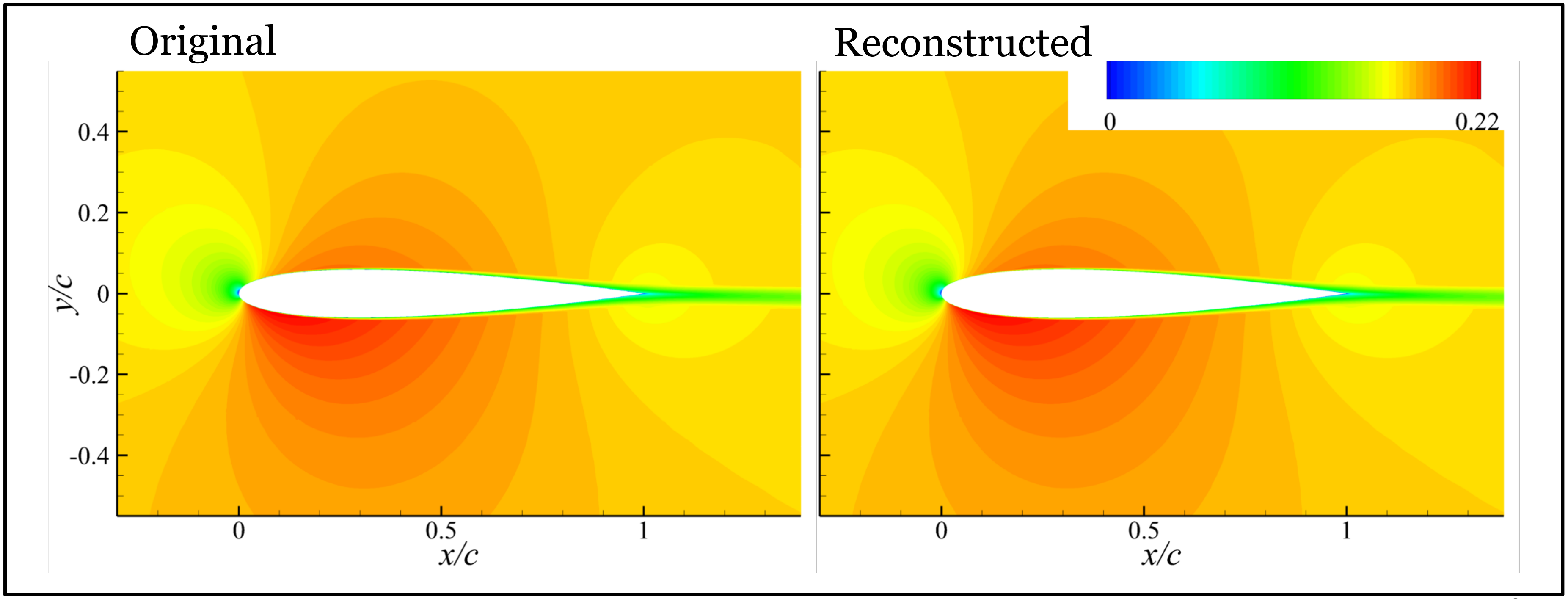




Mean flow implementation

- For the heaving case, the prescribed mean flow can be implemented into the LEE solver, under the assumption that the fluctuations will not affect the harmonic components in a significant way.

- Using its Fourier components, the mean flow can be well reproduced.



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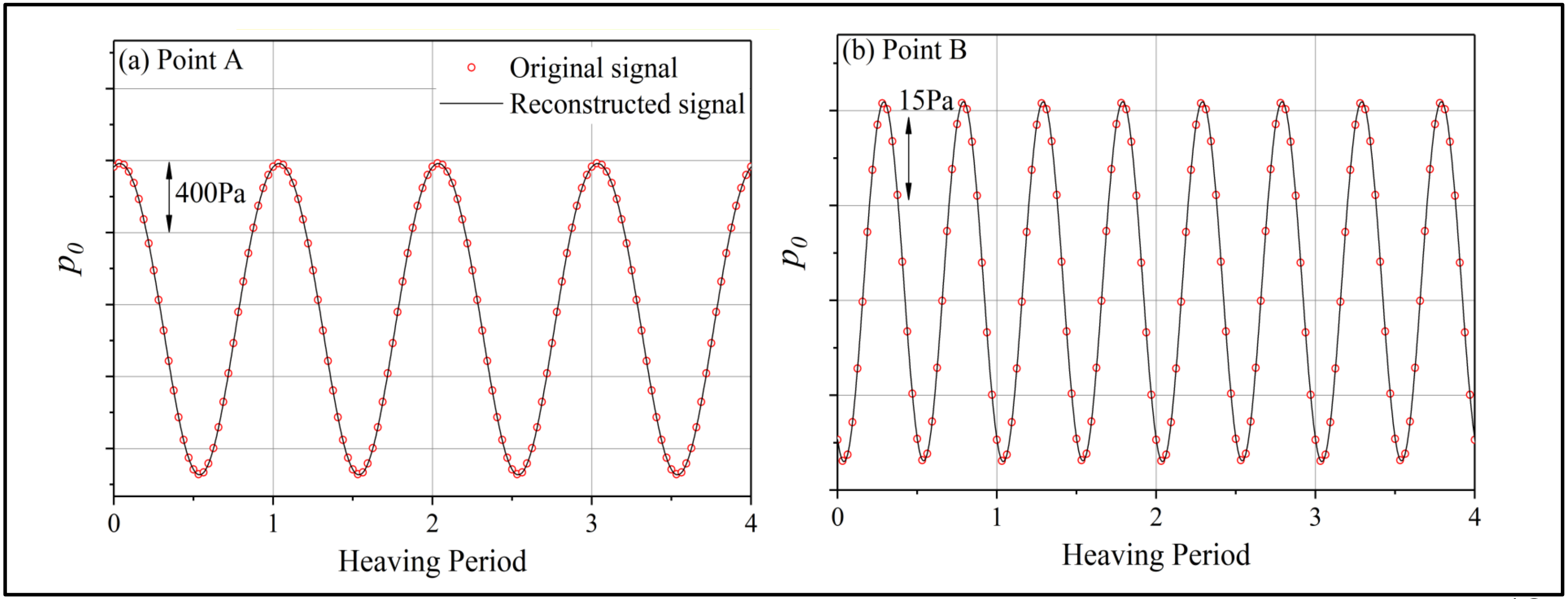
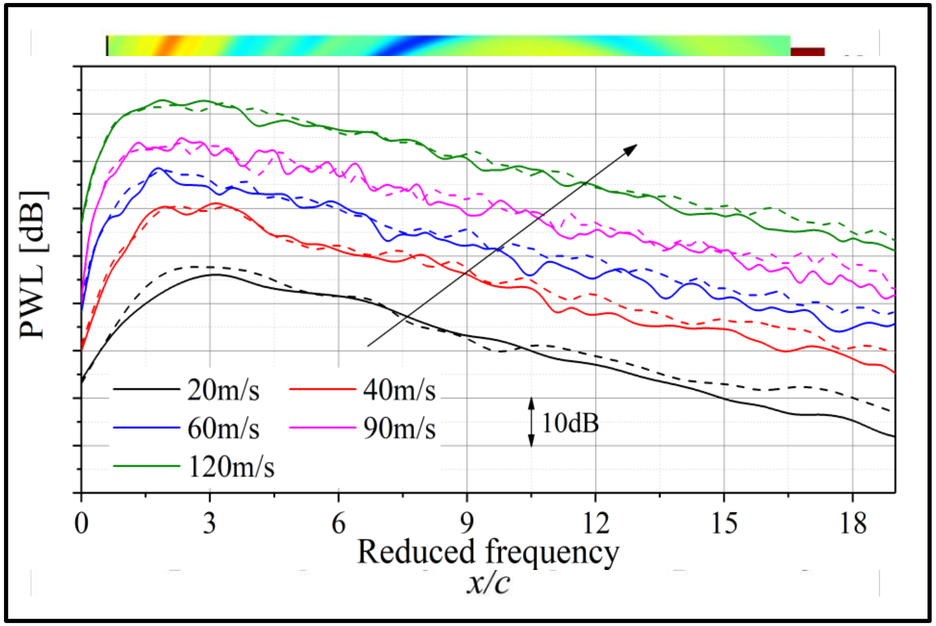


Effect of mean flow viscosity

Inviscid and viscous mean flow

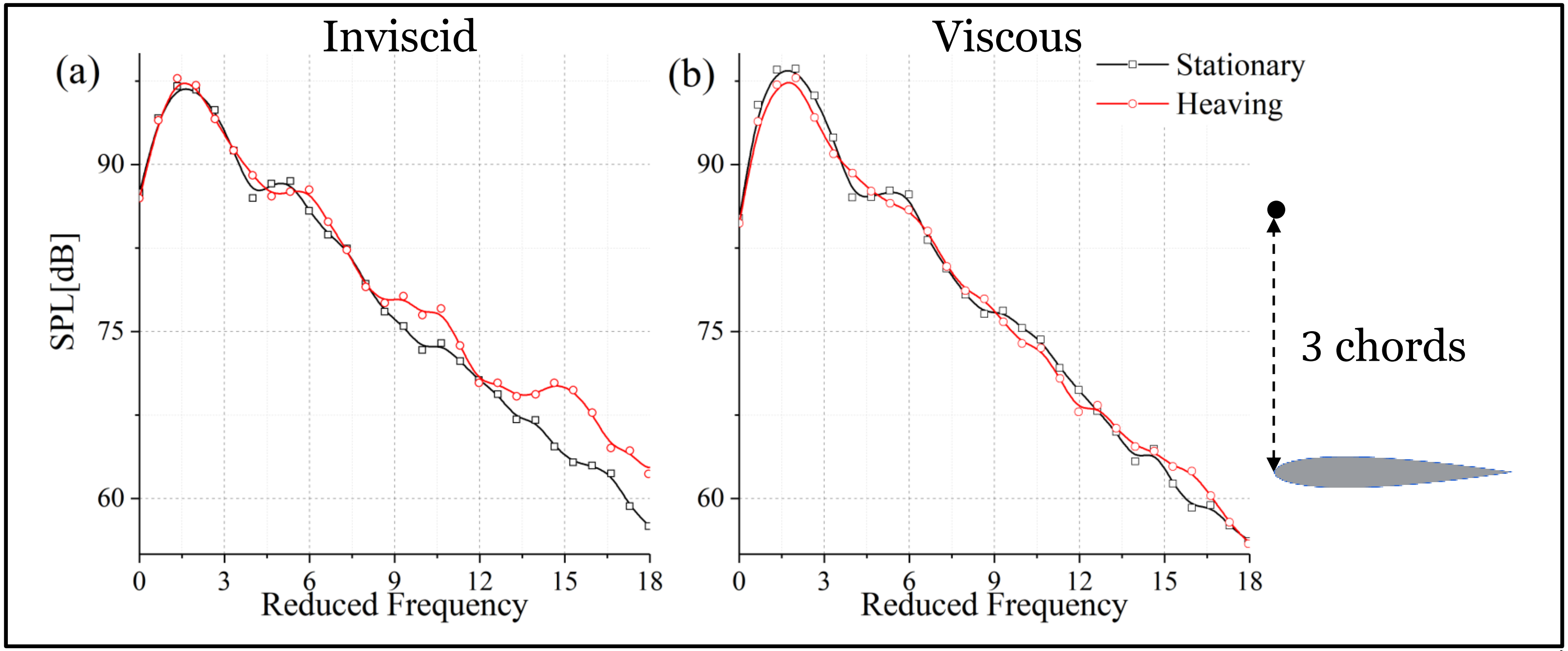
- Inviscid mean flow was used in the leading edge noise studies to avoid numerical instabilities (Gill 2015).
- The assumption of a inviscid mean flow is revisited for stationary and heaving airfoil.

- For the stationary airfoil, the difference is mainly at high reduced frequencies.
- The difference is larger for lower mean flow velocity.

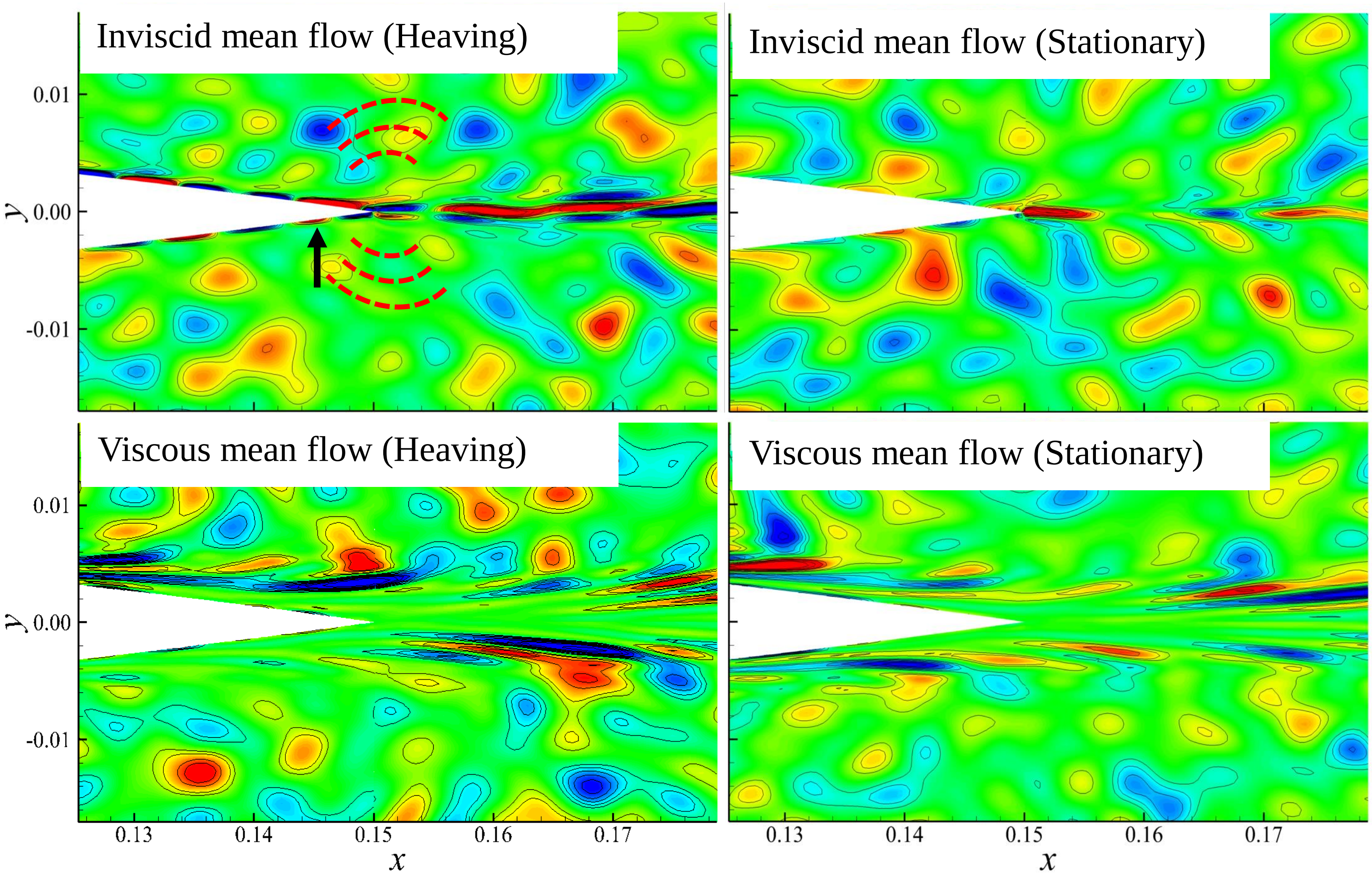


Inviscid and viscous mean flow

- For the heaving airfoil, the comparison shows that the result obtained from the inviscid mean flow is higher than that from viscous mean flow at high frequencies.



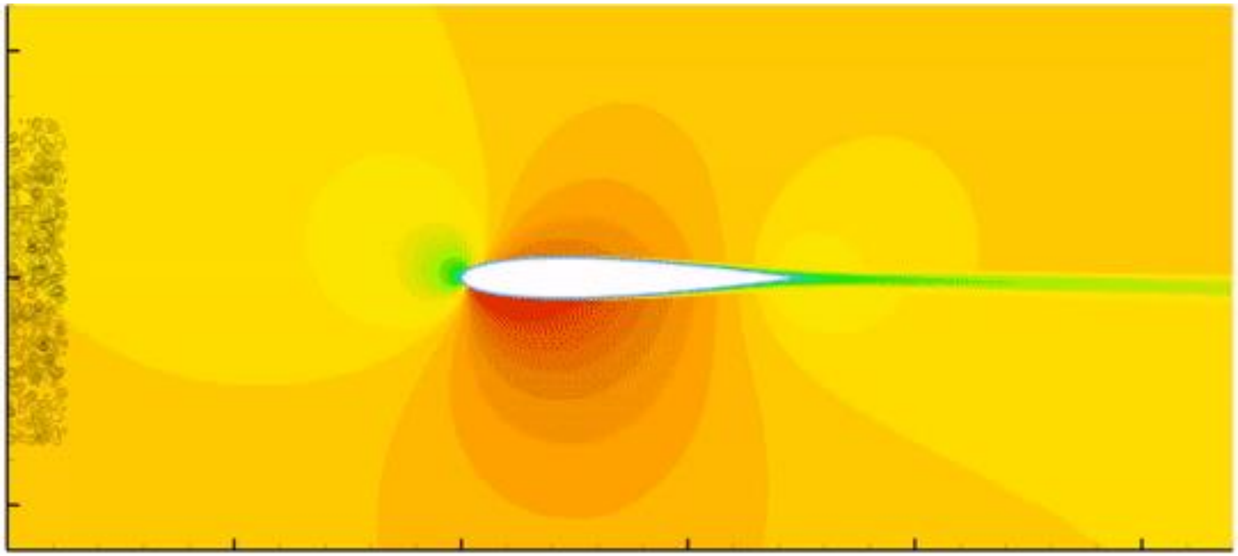
Inviscid and viscous mean flow



Effect of turbulence anisotropy

LEN with synthetic turbulence

- The synthesize quiescent turbulence based on modified digital filter method (Gea-Aguilera *et al.* 2015):
  - Gaussian energy spectrum;
- Mean flow velocity varies from 60m/s to 150m/s.



LEN with anisotropic turbulence

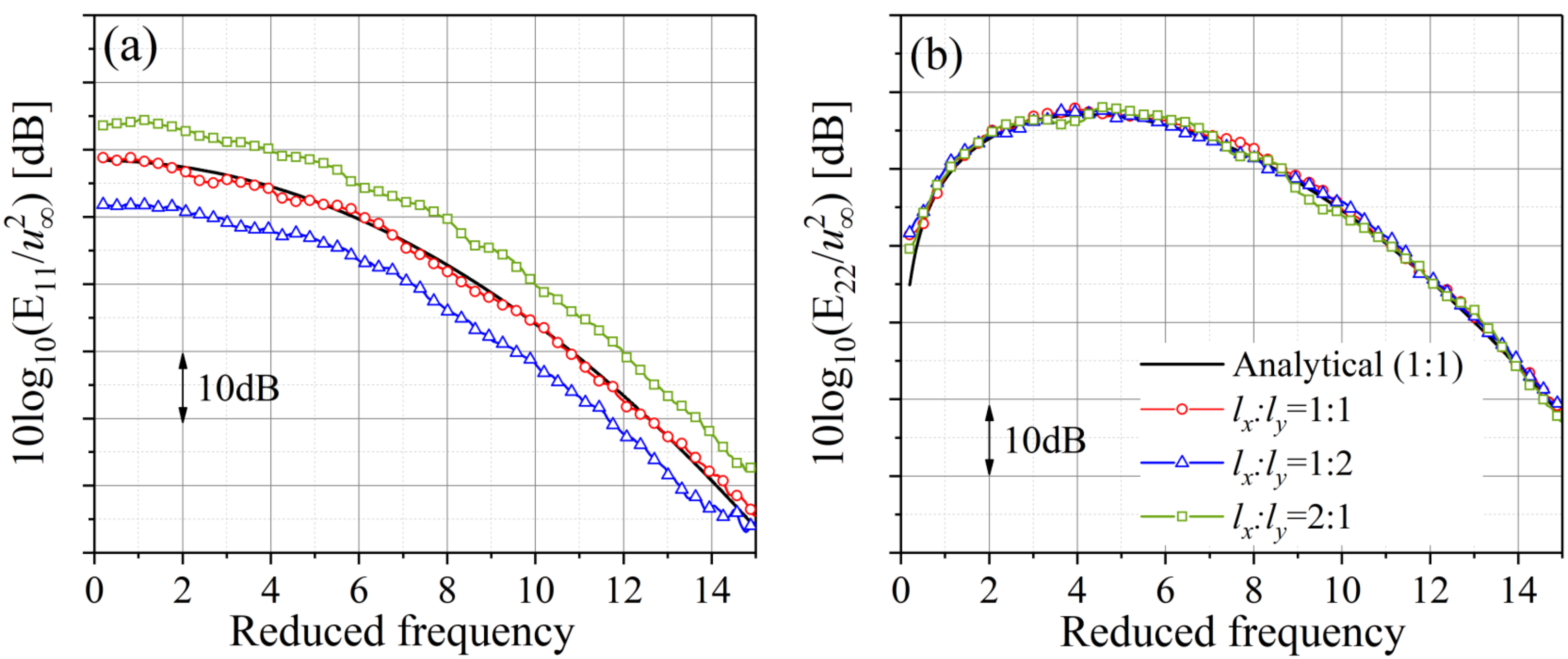
- The anisotropic Gaussian spectrum is used.

$$\langle u_t^2 \rangle = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \Phi_{11}^{2D}(k_1,k_2)\mathrm{d}k_1\mathrm{d}k_2 = u_{rms}^2 \frac{l_x}{l_y}$$

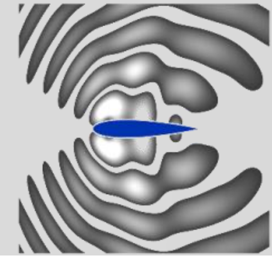
- ...nified for different

$$\langle v_t^2 \rangle = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \Phi_{22}^{2D}(k_1,k_2)\mathrm{d}k_1\mathrm{d}k_2 = u_{rms}^2 \frac{l_y}{l_x}$$

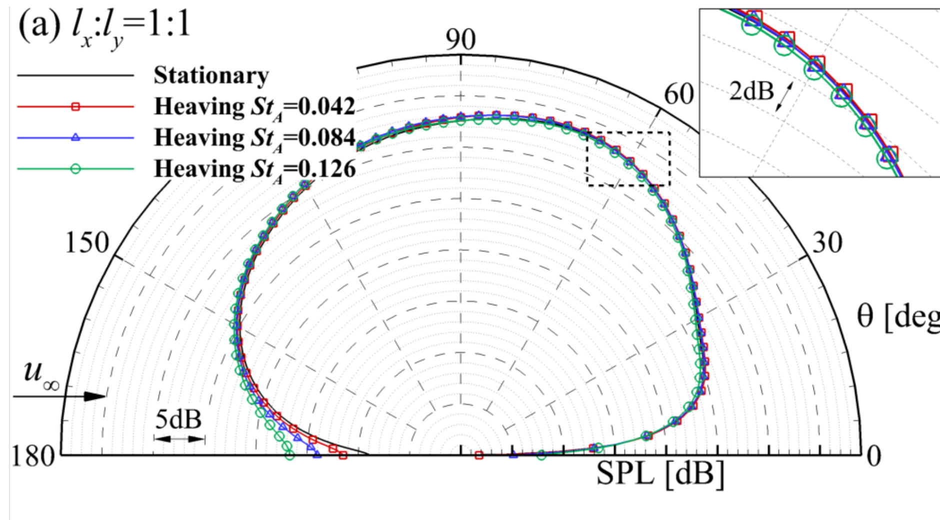
- ...e l_y changes.

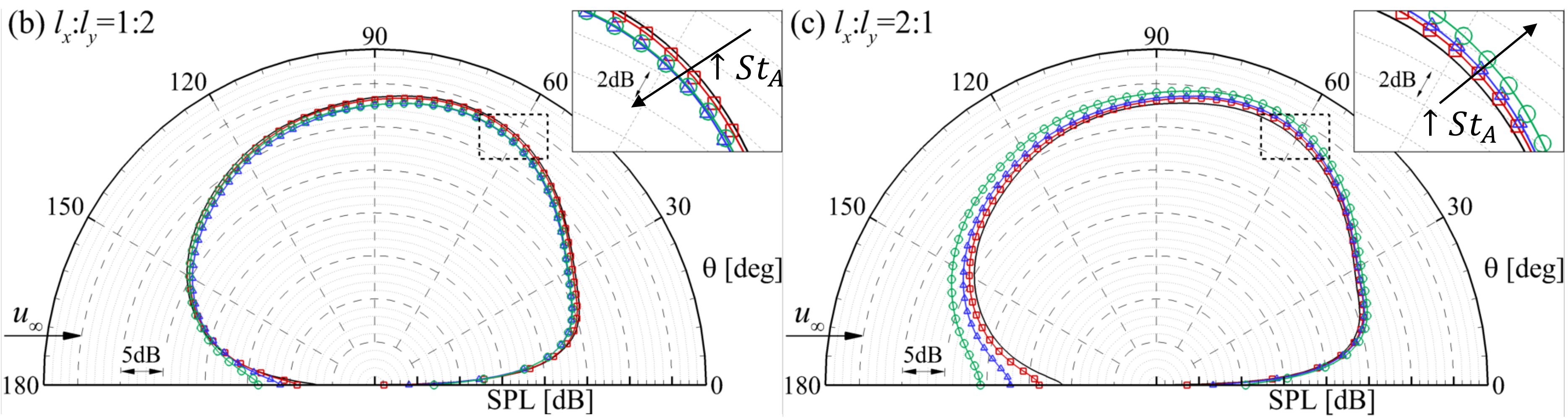


LEN with anisotropic turbulence



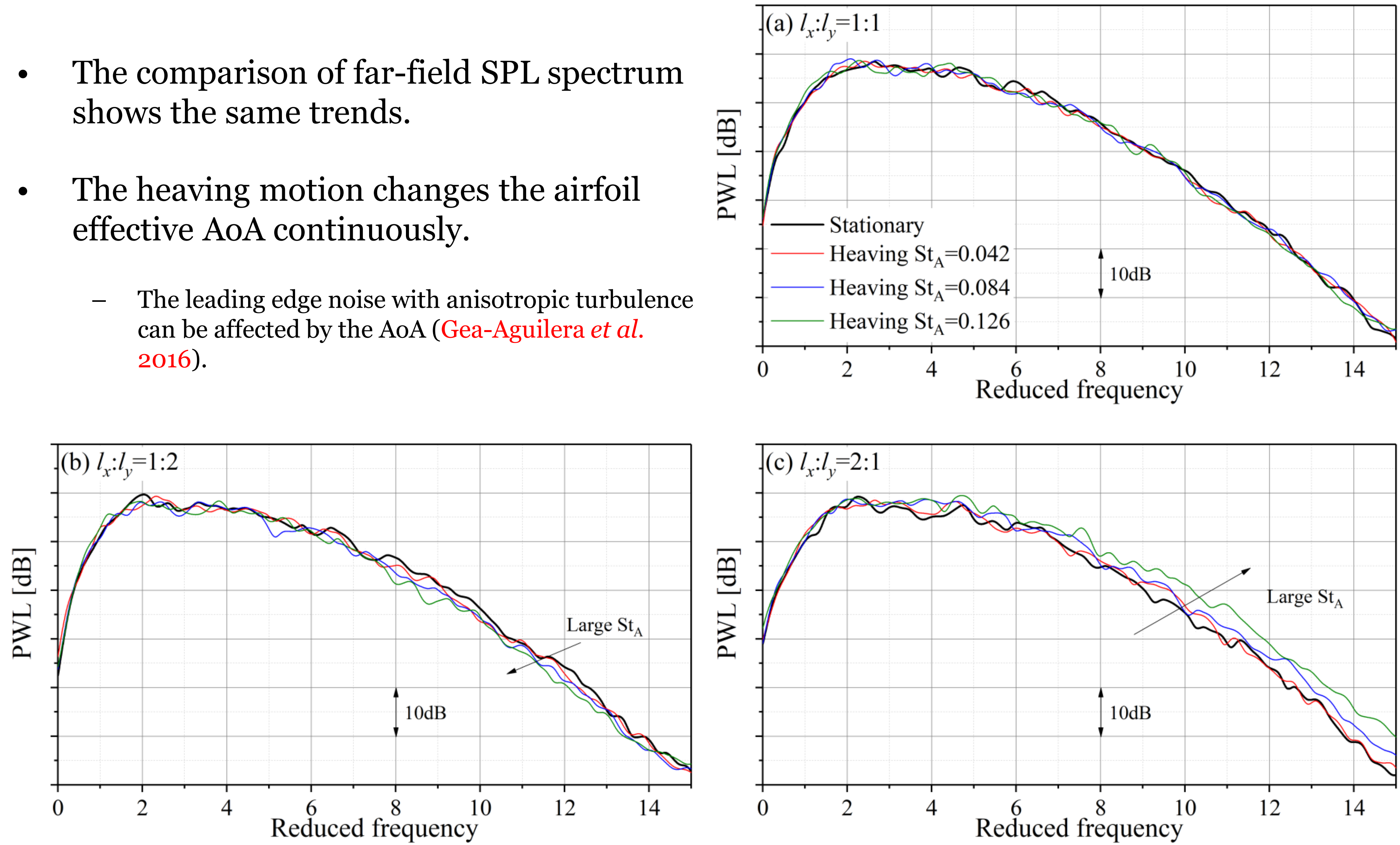
- Far-field directivities obtained under 60m/s, with different $l_x\!:l_y$ ratio are compared under different St_A.
- For $l_x\!:l_y = 1$, difference between stationary and heaving airfoil is small.
- For the two other cases, opposite trend can be observed.





LEN with anisotropic turbulence

- The comparison of far-field SPL spectrum shows the same trends.
- The heaving motion changes the airfoil effective AoA continuously.
  - The leading edge noise with anisotropic turbulence can be affected by the AoA (Gea-Aguilera *et al.* 2016).

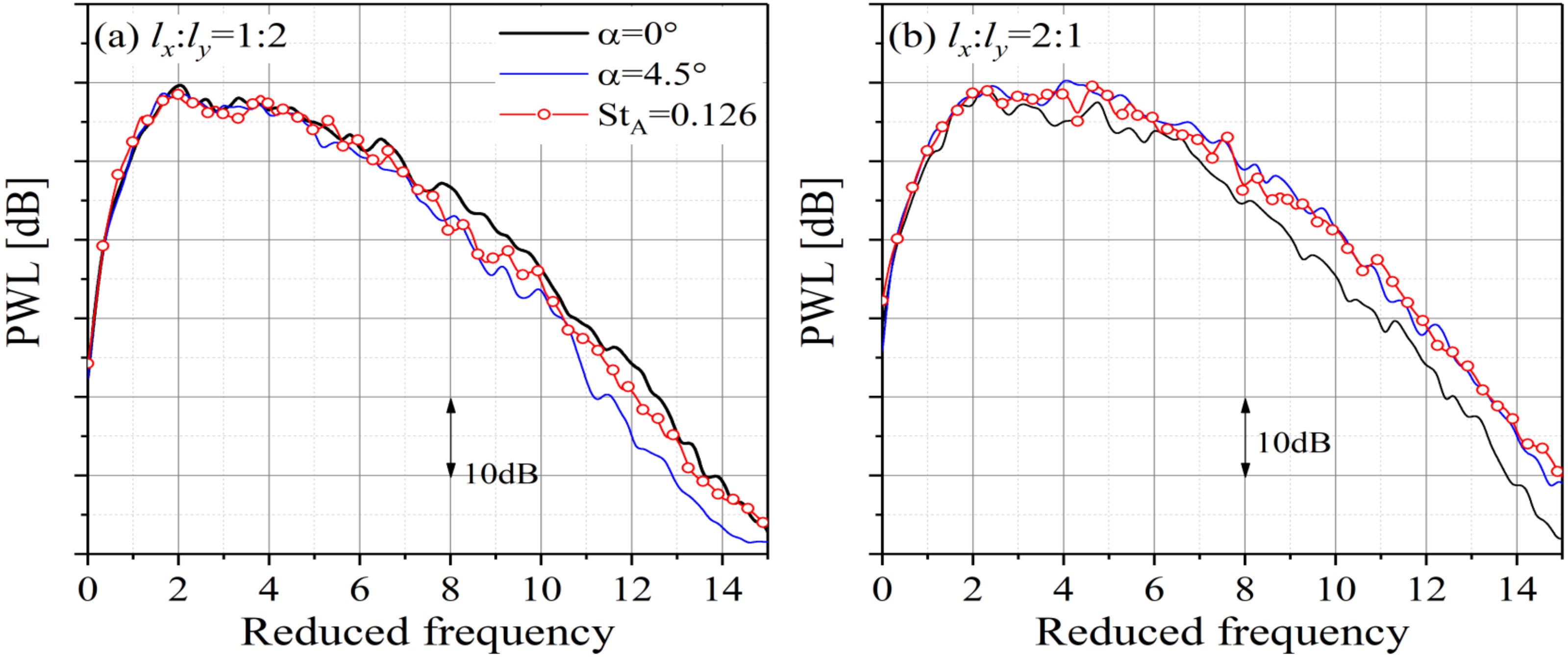


LEN with anisotropic turbulence

- The equivalent angle of attack during half heaving period can be calculated as:

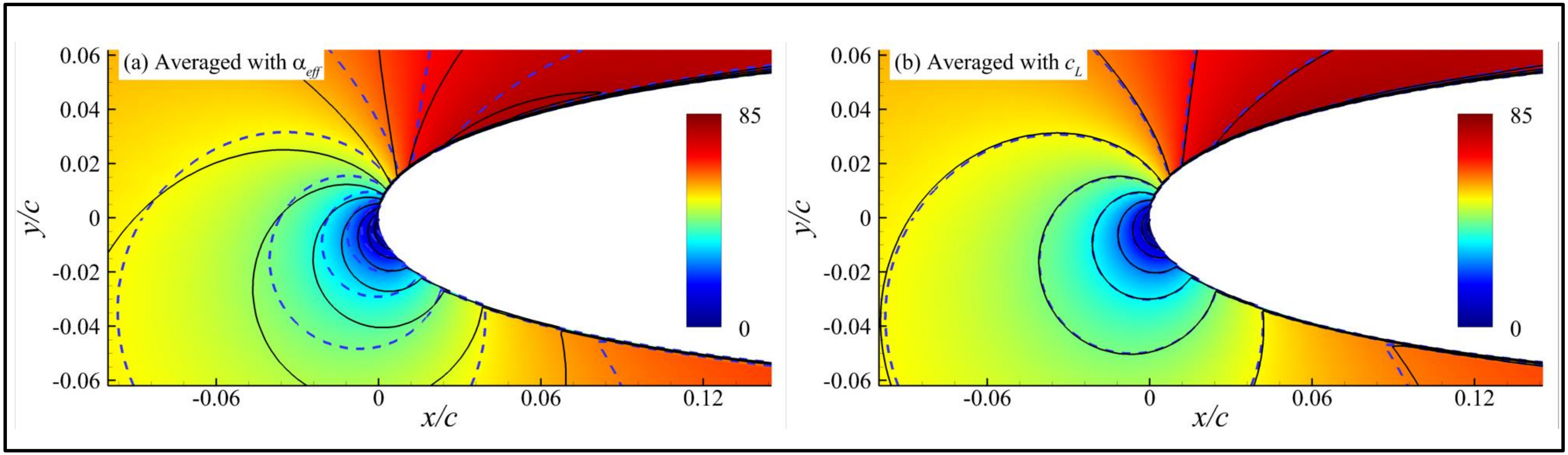
$$\alpha_{\mathrm{e}} = \frac{\int_0^{\pi} \Delta\alpha \,\mathrm{Sin}(t)\mathrm{d}t}{\pi}$$

- For $St_A = 0.126$, the $\alpha_{\mathrm{e}} = 4.5°$.



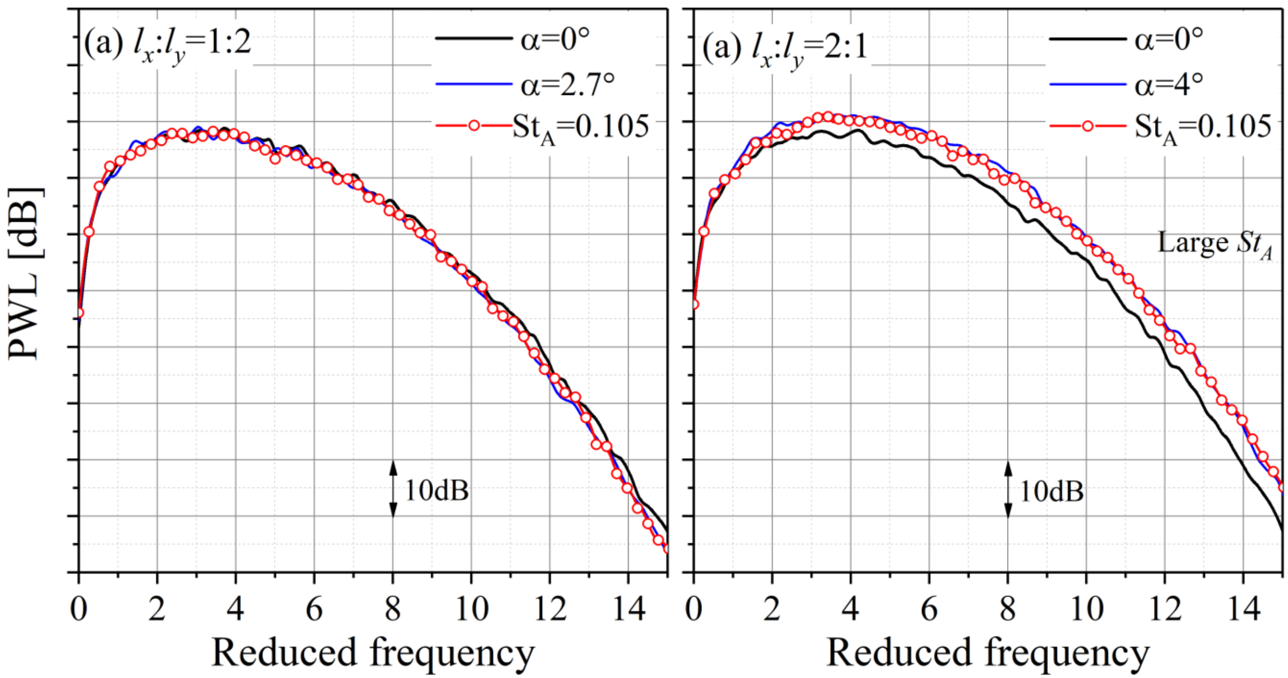
LEN with anisotropic turbulence

- The second equivalent angle of attack is calculated by averaging the lift coefficient in the half heaving period.
  - For $St_A = 0.126$, the $\alpha_{e2} = 3.0°$.
- The averaged flow field around the heaving airfoil is compared with that of the stationary airfoil under α_e and α_{e2}.

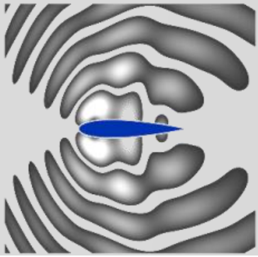


LEN with anisotropic turbulence

- For $l_x < l_y$, similar results are obtained from the heaving airfoil with $St_A = 0.126$ and the stationary airfoil with $\alpha = 3°$.
- Similarly at 150m/s, the leading edge noise from the heaving airfoil under different length scale ratio agrees well with those from stationary airfoil with $\alpha = \alpha_e$ and $\alpha = \alpha_{e2}$.



Summary



- The leading edge noise of a heaving NACA0012 airfoil is studied.
  - With both isotropic and anisotropic turbulence;
  - Under various mean flow velocity and heaving conditions;
- The inviscid mean flow assumption is revisited.
  - For stationary airfoil, the effect of inviscid mean flow is small at high u_∞;
  - For heaving airfoil, additional noise will be generated;
- For isotropic turbulence, the effect of the heaving motion is small. For anisotropic turbulence,
  - When $l_x > l_y$, the effect can be represented by the α_e;
  - When $l_y > l_x$, the effect can be represented by the α_{e2};

Thanks!

Any question?

LEN with anisotropic turbulence

- It has been demonstrated by Gill 2015 that the stagnation region around the airfoil has a significant influence on the leading edge noise by affecting the distortion of v'.

- For anisotropic turbulence with larger transverse length scale, the $\langle v_t^2 \rangle > \langle u_t^2 \rangle$.

- The hysteresis caused by the heaving motion implies that the stagnation region of the heaving airfoil could be different.

- During the heaving, the maximum c_L doesn't correspond to the maximum α.