CEAA2018
Svetlogorsk, Russia
21st September 2018

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Mechanisms and Modelling of Undulated Leading Edge Aerofoils

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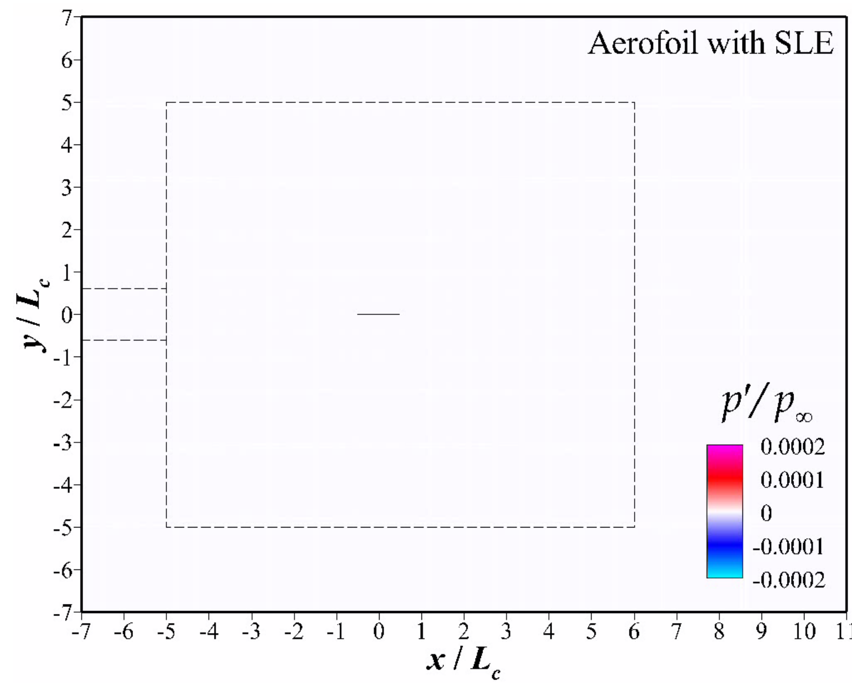
Background & Introduction

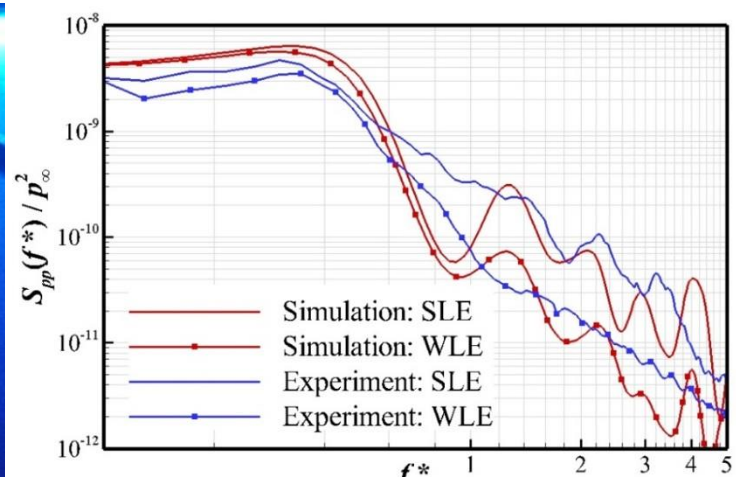
ATI Noise

- Impact on various applications
  - Relevant to wind farms, turbofan OGVs, open-rotors, etc.
  - Analytical approach:
    - Amiet (1975)
    - Myers & Kerschen (1995, 97)
    - Evers & Peake (2000)
    - Roger et al. (2010)
    - Ayton & Peake (2013, 2015)
  - Computational approach:
    - Scott & Atassi (1995)
    - Lockard & Morris (1998)
    - Hixon et al. (2005, 2006, 2011)
    - Gill et al. (2013, 2015)
    - Kim et al. (2010, 2013, 2014, 2015)

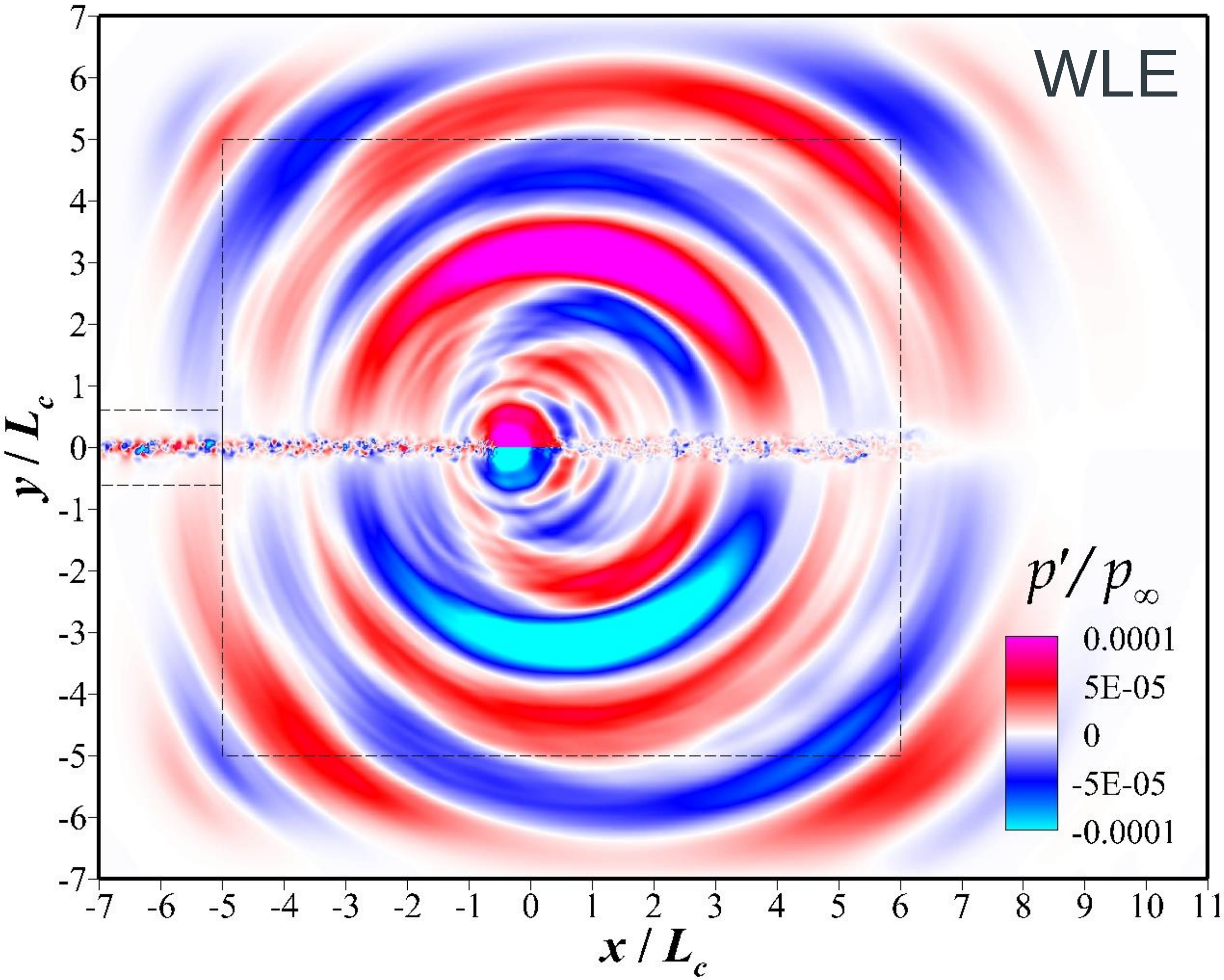


Control of ATI Noise

- Wavy (sinusoidal) LE profiles
  - Aerodynamic studies (high AoAs, mostly on time-averaged aspects)
    - Fish et al. (1995, 2008), Miklosovic et al. (2004, 2007), Johari et al. (2007), Pedro et al. (2008), Yoon et al. (2011), Hansen et al. (2011, 2016), Guerreiro et al. (2012)
  - Recent aeroacoustic studies (low AoAs with upstream disturbances)
    - Hansen et al. (2012), Lau et al. (2013), Clair et al. (2013), Narayanan et al. (2015), Kim et al. (2016), Turner & Kim (2017), Chaitanya et al. (2017)

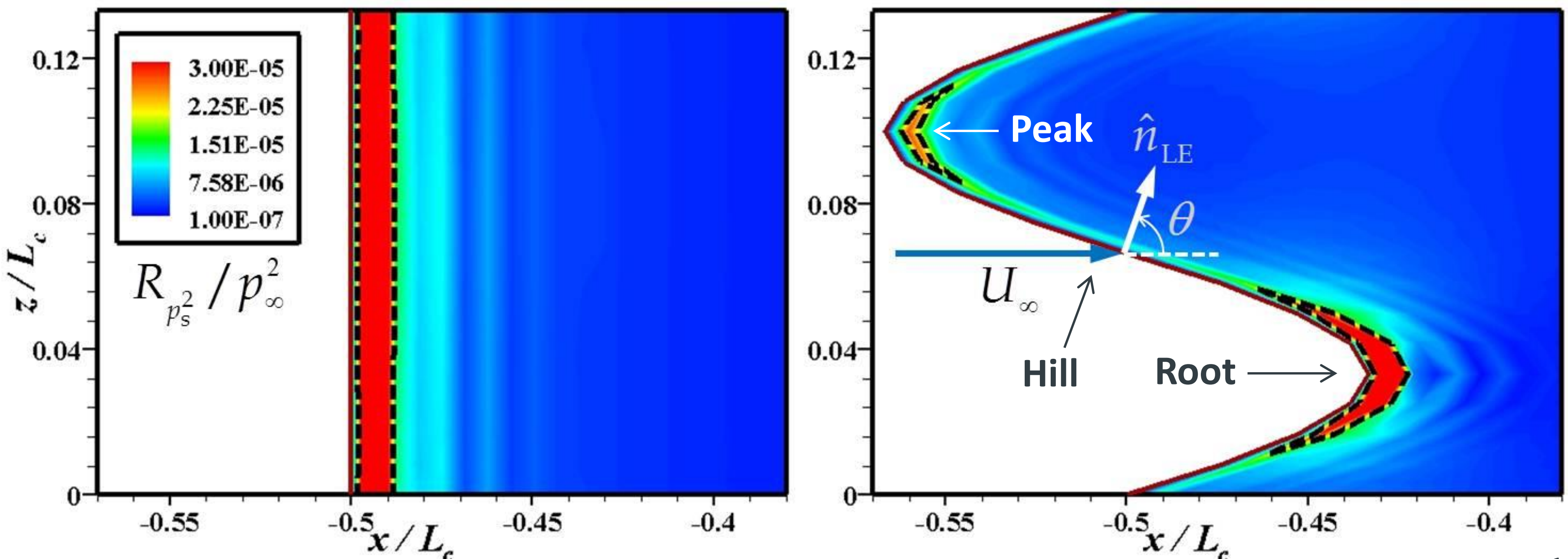


High-frequency Attenuation

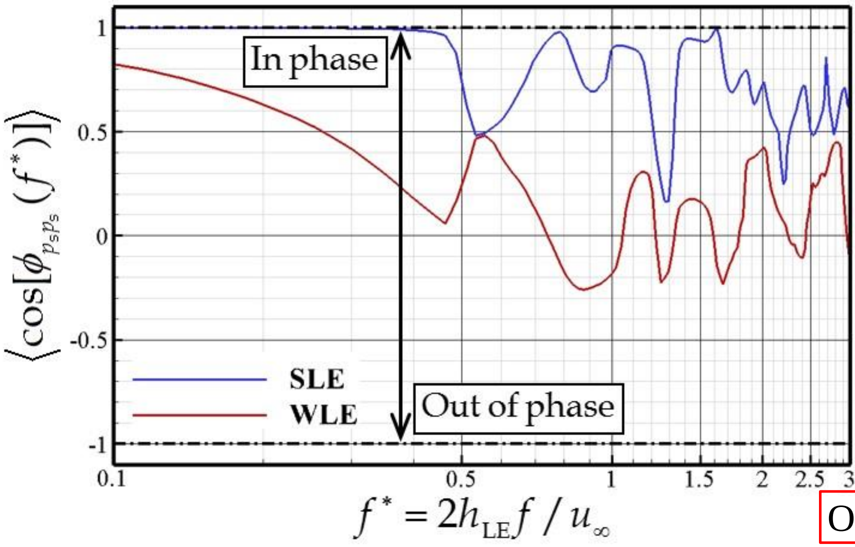


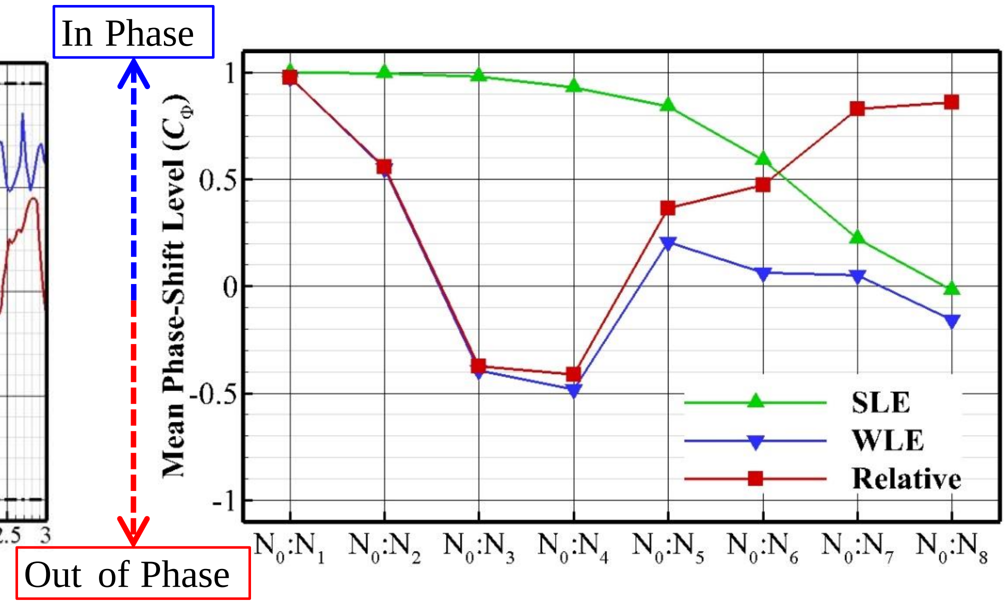
Theory 1: Source Cut-off

- High fluctuation levels in "Peak" and "Root" areas
- Almost no contribution from the "Hill" area
  - Oblique interaction: $p'_w \propto u_n = U_\infty \cos\theta$



Theory 2: Phase Interference





$$\left\langle \cos[\phi_{p_s p_s}(f^*)] \right\rangle = \frac{1}{i_{\max}} \sum_{i=1}^{i_{\max}} \cos[\phi_{p_s p_s}(\mathbf{x}_{N_0} : \mathbf{x}_{N_i}, f^*)]$$

$$C_\Phi = \frac{1}{f_b^* - f_a^*} \int_{f_a^*}^{f_b^*} \cos[\phi_{p_s p_s}(\mathbf{x}_{N_0} : \mathbf{x}_{N_i}, f^*)] df^*$$

- Kim, Haeri & Joseph (JFM 2016)

Current numerical simulations

Simplified Problem Set-up

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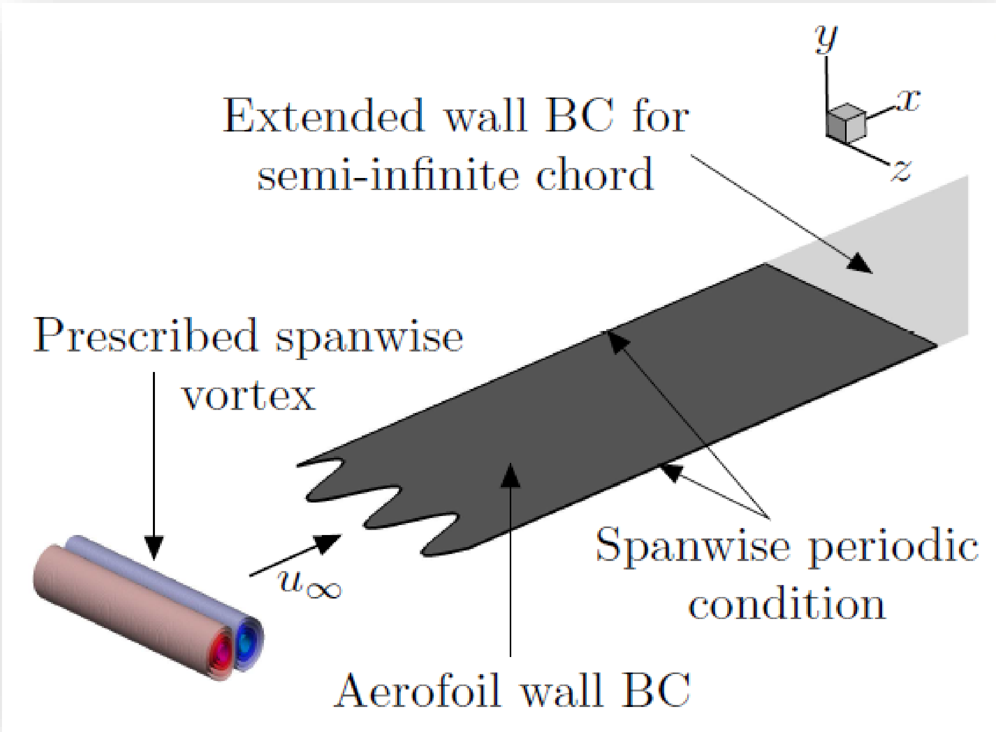
- Prescribed spanwise vortex with a modified Gaussian distribution of vorticity.

$$M_\infty = 0.24$$
$$R_v / L_c = 0.08$$
$$|v|_{\max} / U_\infty = 0.025$$



Methods Used

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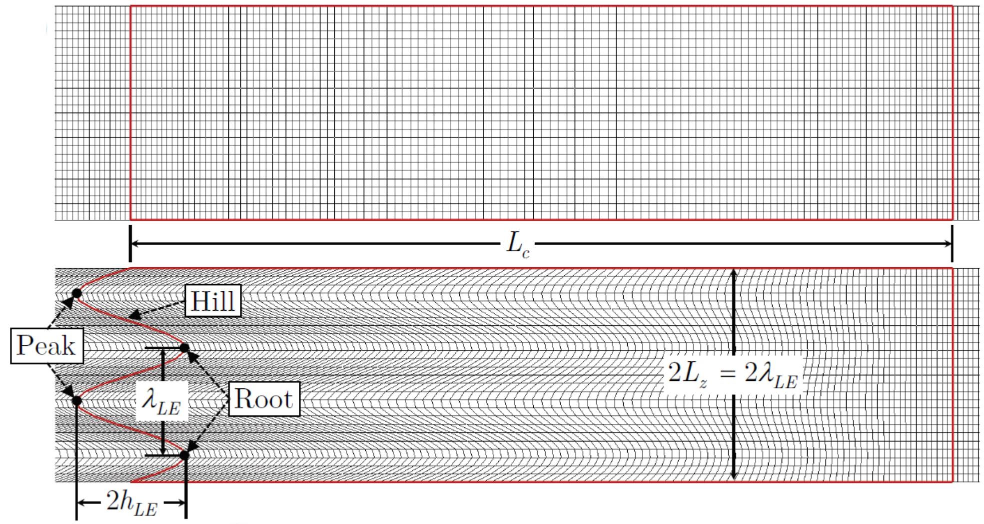
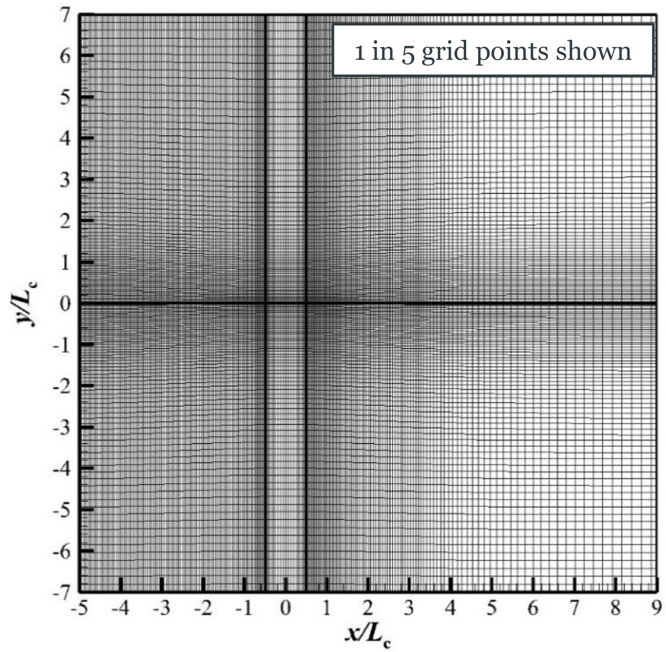
- 3D fully nonlinear Euler equations (in generalised coords.)
  - Eliminating self-noise contribution (e.g. TBL-induced TE noise)
- CANARD (Comp. Aerodyn. & Aeroaoust. Research coDe)
  - 4^{th}-order interior & 4^{th}-order boundary compact FD schemes (Kim, JCP2007)
  - 6^{th}-order compact filters with variable cut-off (Kim, C&F2010)
  - 4^{th}-order RK time integration
  - Characteristic BC & IC (Kim & Lee, AIAAJ2000, 2003, 2004)
  - Efficient sponge-layer technique (Kim et al. AIAAJ2010)
  - Massively parallel computing capability (Kim, JCP2013)

Geometry & Grid

- Inviscid flat-plate aerofoil
  - Zero thickness
  - Periodic in span
  - Single WLE wavelength
  - AR=$2h_{LE}/\lambda_{LE}$, λ_{LE} fixed
- Structure grid
  - 1600×960×64=98.3M cells
  - 400 cells across the aerofoil chord
  - MPI: 512 CPU cores
  - At least 24 cells across the vortex

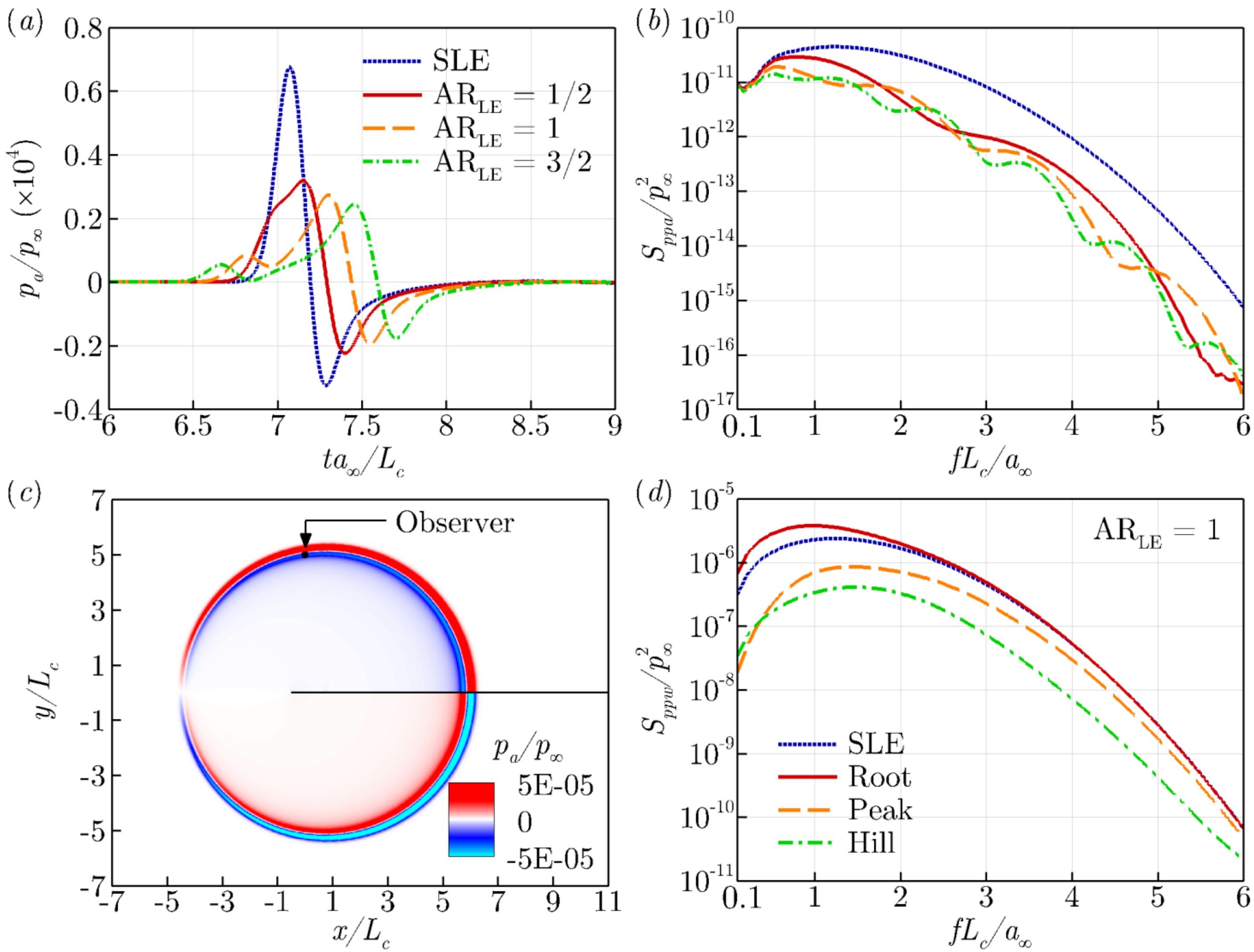




Important questions

- Why is the low frequency reduction of wall pressure fluctuations not observed in the far-field?
- Which noise reduction mechanisms is most important?
  - Reason for log-linear noise reduction trend at high frequency

Low Frequency Noise Reduction

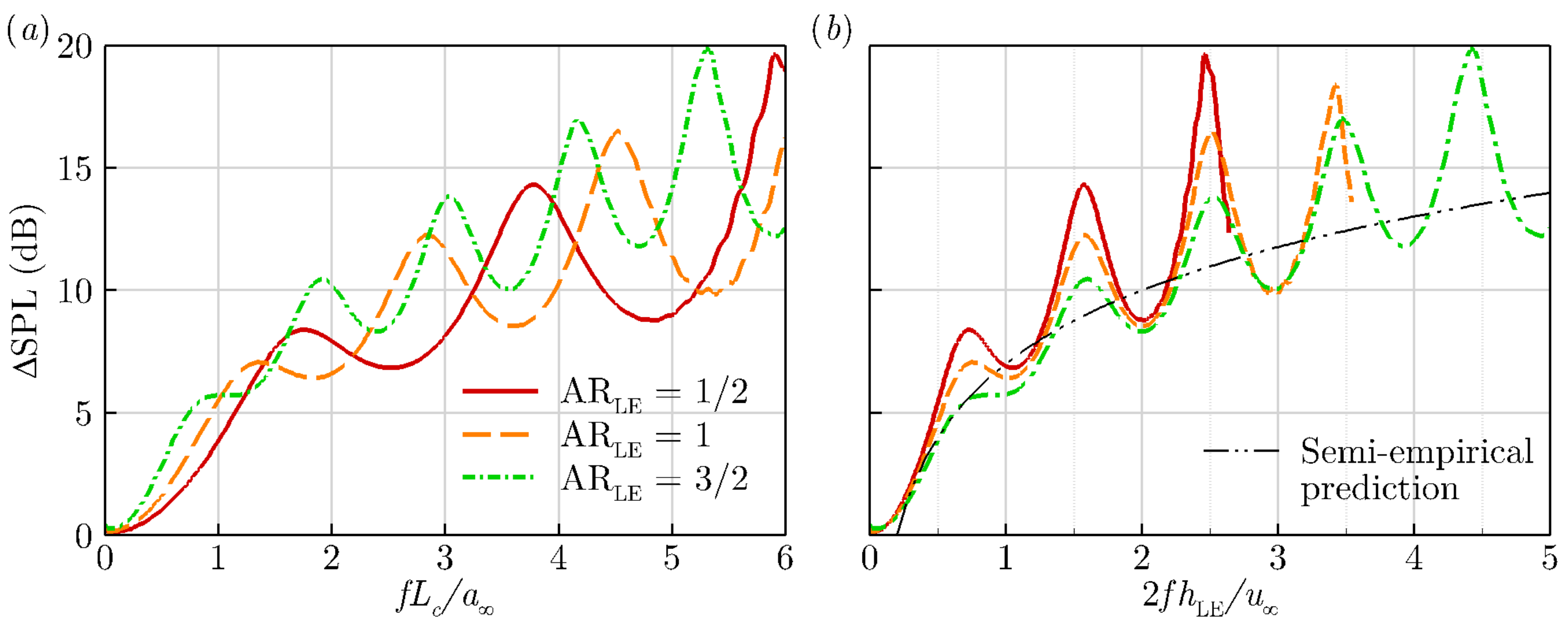


Noise reduction trends

- $10\log_{10}(10 f h_{LE}/U_\infty)$ semi-empirical trend based on the leading edge (Chaitanya et al., 2017)

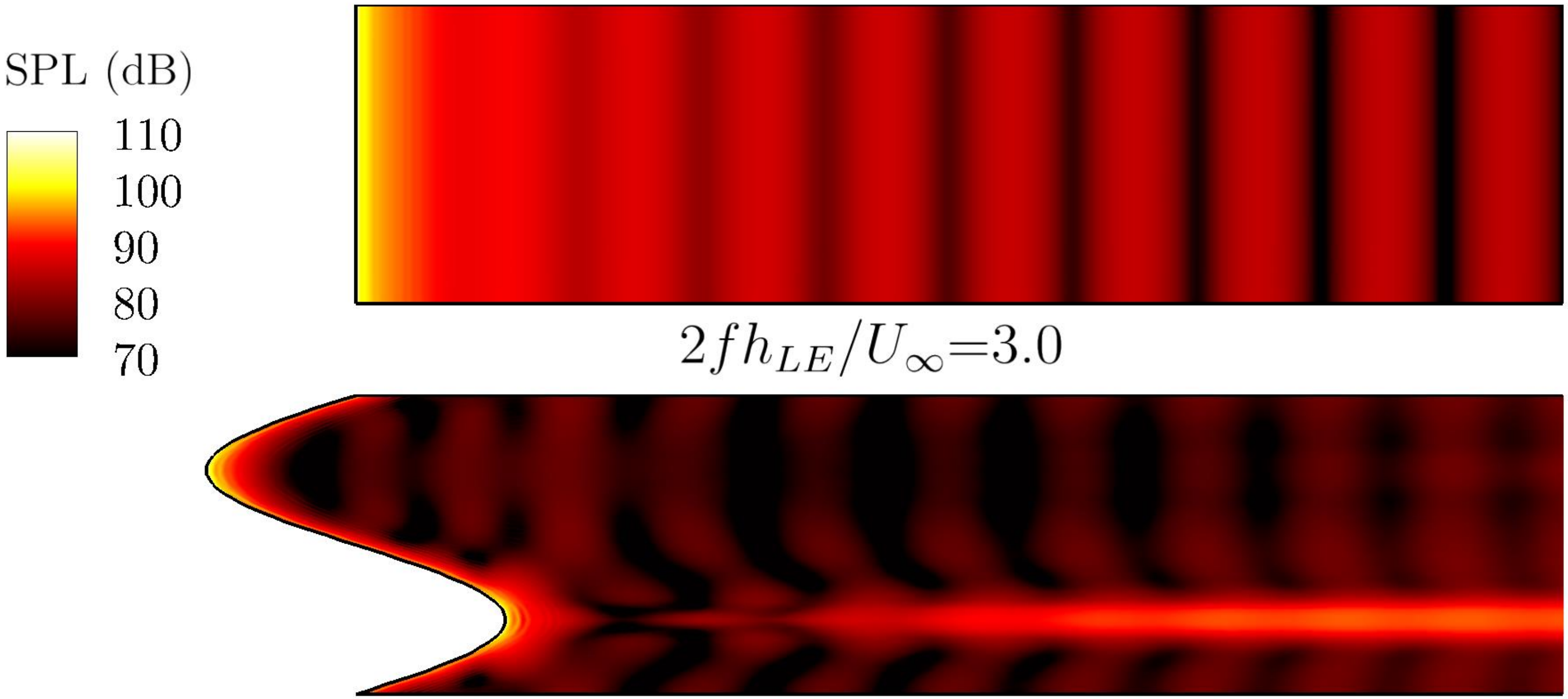
- Peak-root phase difference $\phi = 2\pi f \frac{2h_{LE}}{u_\infty}$

- Reduced interference for ↑ h_{LE} but at earlier frequency



Two-dimensional source characteristics-Magnitude

- Sound pressure level of wall pressure fluctuations



Integrated Source Magnitude

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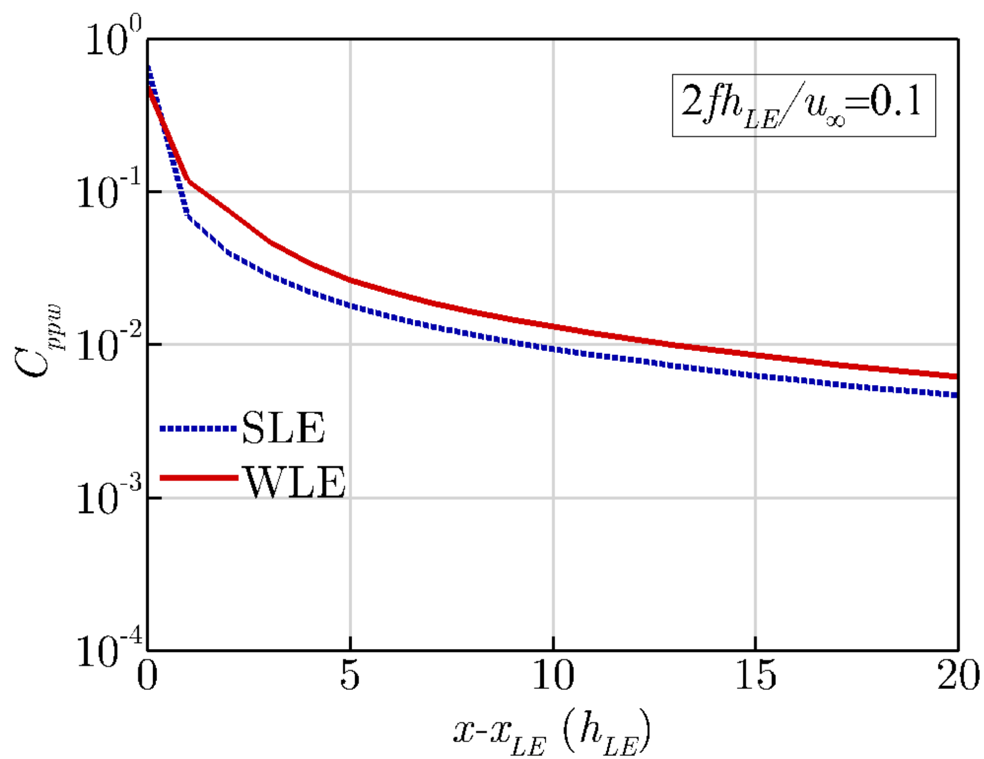
- Integrated consecutive surface strips of width h_{LE}

$$C_{ppw}(x,f) = \frac{\int_{x}^{x+\Delta x} \int_{-\frac{1}{2}\lambda_{\mathrm{LE}}}^{\frac{1}{2}\lambda_{\mathrm{LE}}} S_{ppw}(x,z,f)\mathrm{d}z\mathrm{d}x}{\int_{x_{\mathrm{LE}}}^{x_\infty} \int_{-\frac{1}{2}\lambda_{\mathrm{LE}}}^{\frac{1}{2}\lambda_{\mathrm{LE}}} S_{ppw}(x,z,f)\mathrm{d}z\mathrm{d}x} \qquad \Delta x = h_{\mathrm{LE}} \text{ and } x_\infty = 20h_{\mathrm{LE}}$$



Why is there no noise reduction at low frequencies?

Low Frequency Noise Reduction

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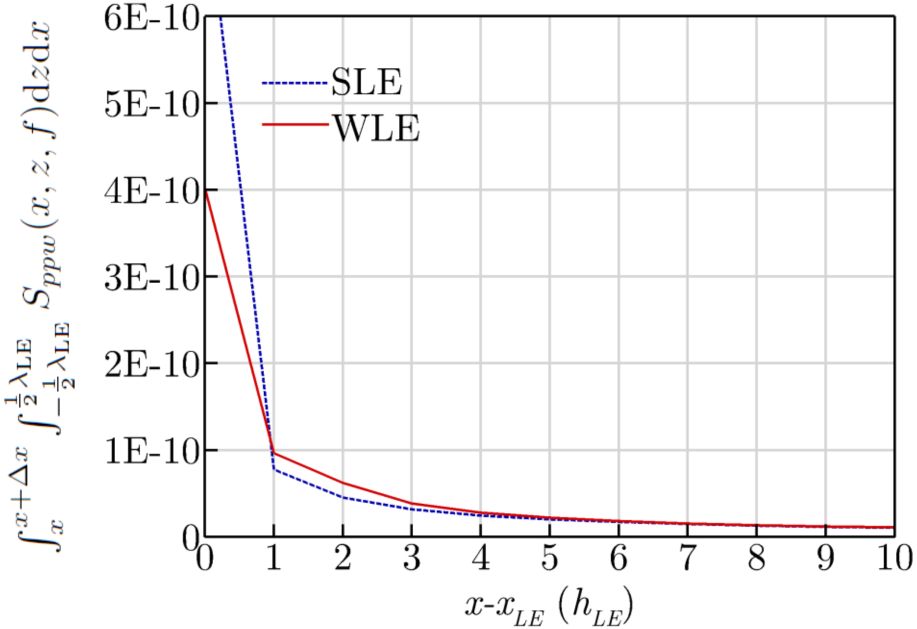
- Integrated surface strips for $2fh_{LE}/u_\infty = 0.1$



- Full surface contribution similar for SLE and WLE cases

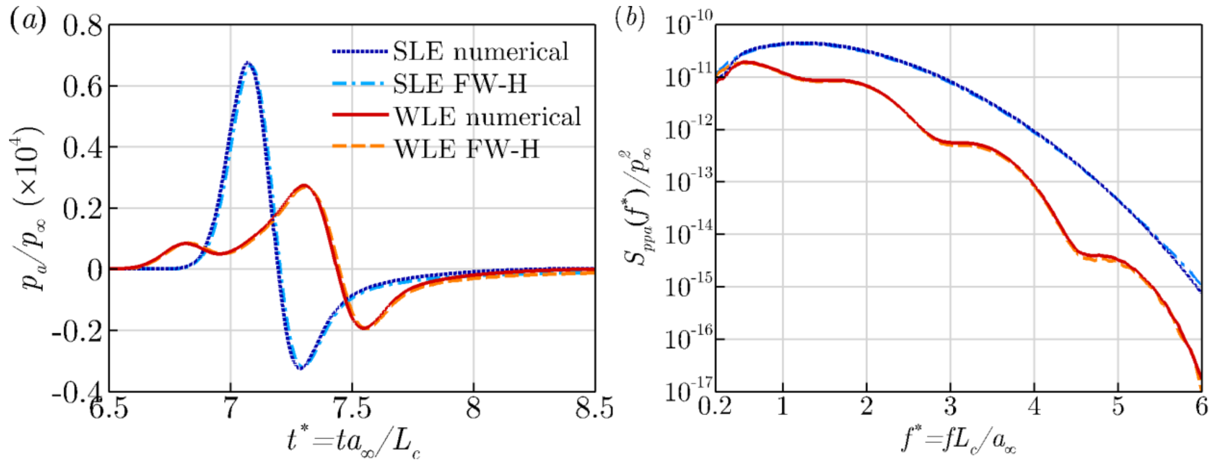
$$\frac{\int \left|\widehat{\Delta p}_{w|SLE}\right| dS}{\int \left|\widehat{\Delta p}_{w|WLE}\right| dS} = 1.04$$

Convergence of FW-H

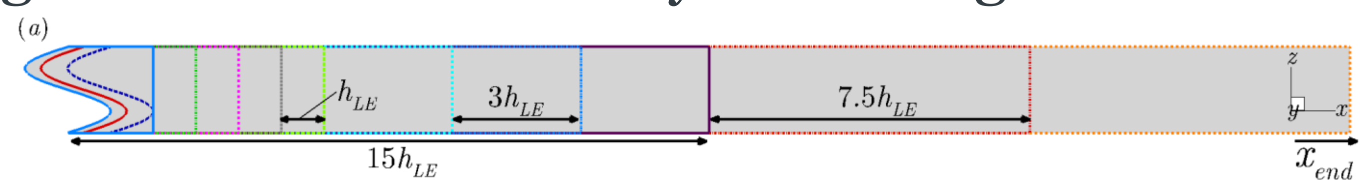
- Farassat 1A formulation for a flat plate:

$$4\pi p_a(\boldsymbol{x},t) = \int \left[\frac{\dot{p}\cos(\theta)}{cr(1-M_r)^2} + \frac{p\cos(\theta)}{r^2(1-M_r)^2} + \frac{(M_r - M^2)p\cos(\theta)}{r^2(1-M_r)^3} \right]_{ret} \mathrm{d}S$$

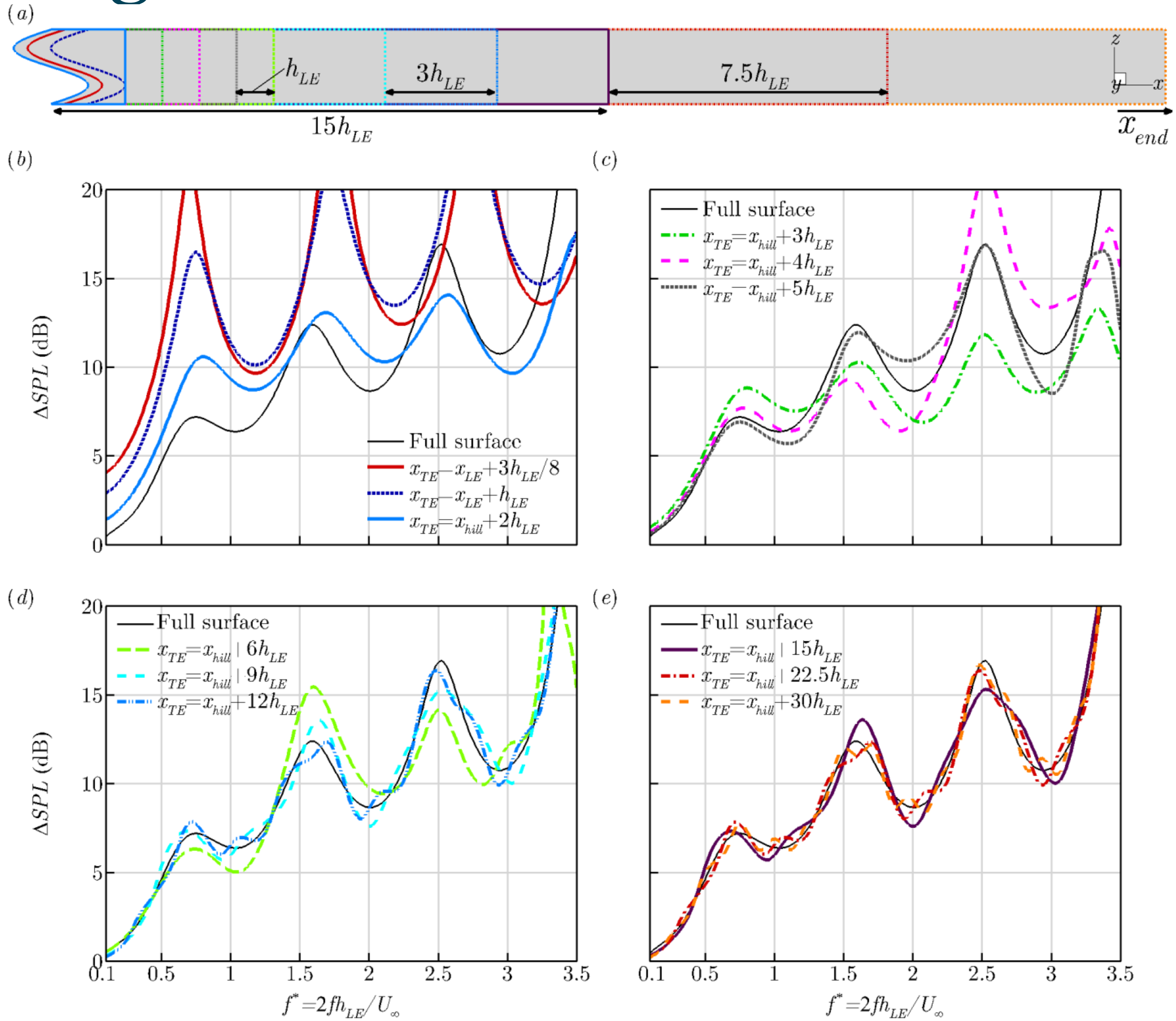
$$\cos(\theta) = \mathbf{n}\cdot\hat{\mathbf{r}} \qquad M_r = \mathbf{M}\cdot\hat{\mathbf{r}}$$



- Integration of incrementially increasing FW-H surfaces



Convergence of FW-H



Concluding Remarks

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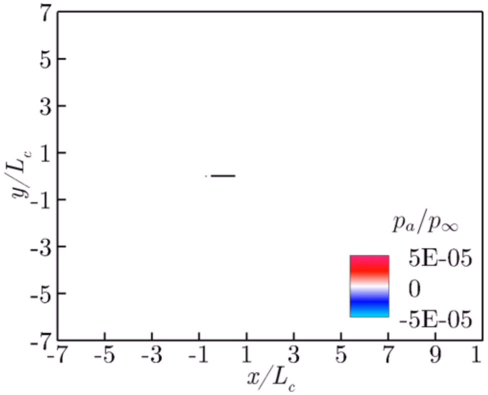
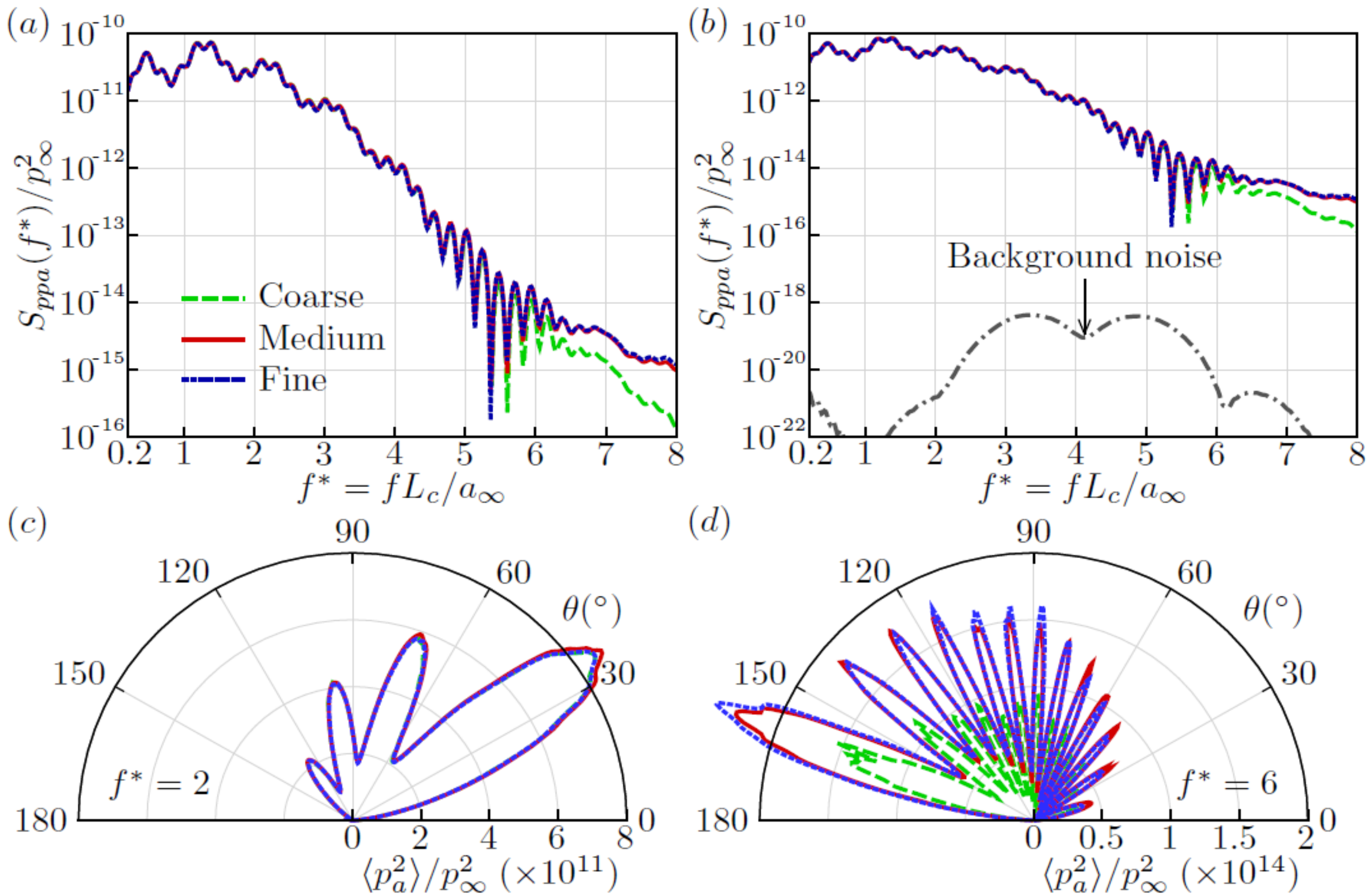
- High strength wall pressure fluctuations are not restricted to the leading edge at high frequency
  - Analysis based solely on the leading edge is not sufficient
- Inclusion of two dimensional source explains lack of noise reduction at low frequencies
- Questions remain regarding the origin of the log-linear trend
  - Evidence that both mechanisms contribute, but how much?

Grid Convergence Test





Two-dimensional source characteristics-Phase

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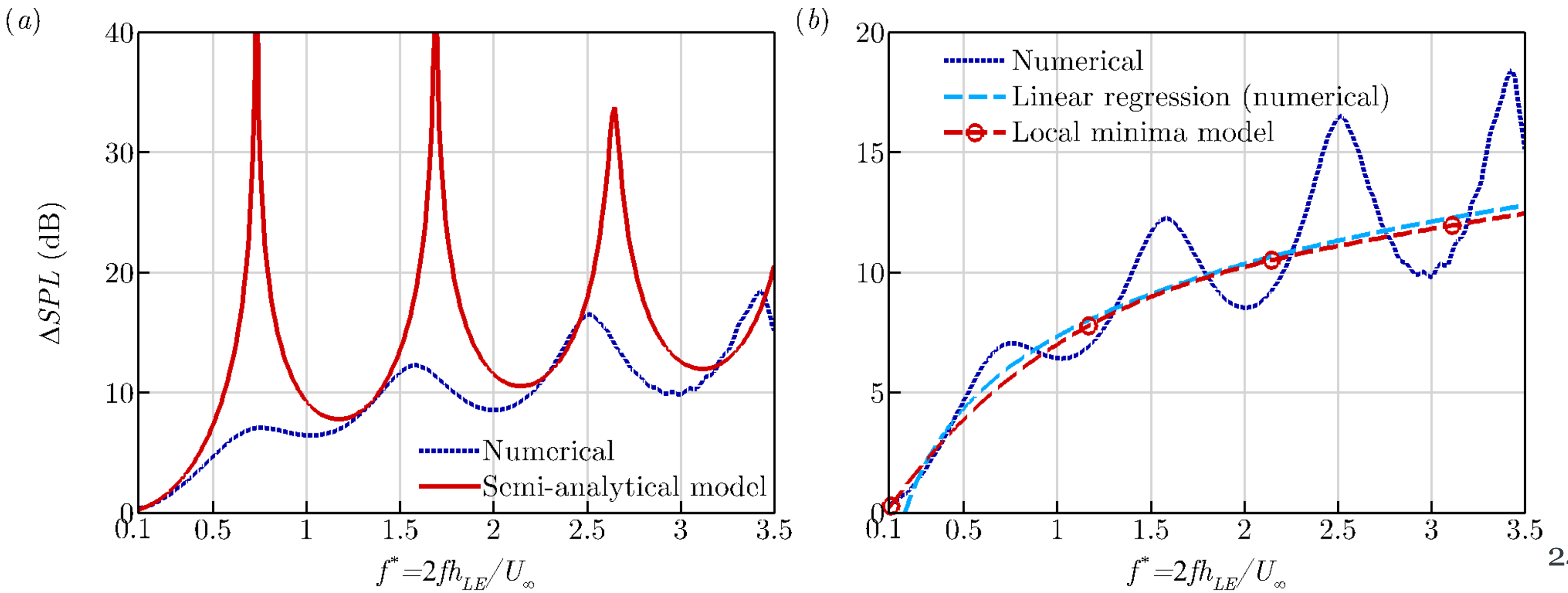
- Two-point phase spectra of wall pressure fluctuations relative to the hill

Log-linear trend in 1D

$$F(x_o, y_o, f, t) = \int_C \frac{p_m(\theta)}{r} \sin\left[2\pi f\left(\tau(\mathbf{x}) - \frac{h_{\mathrm{LE}}\sin(\theta)}{U_\infty}\right)\right] \mathrm{d}l$$



Noise reduction from source magnitude

- Source magnitude only noise reduction prediction

$$\Delta SPL(f) \approx 20\log_{10}\left[\frac{\left|\int \widehat{\Delta p}_{w,SLE}(f)dS\right|}{\left|\int \widehat{\Delta p}_{w,WLE}(f)dS\right|}\right]$$

$$\Delta SPL_{source}(f) \approx 20\log_{10}\left[\frac{\int \left|\widehat{\Delta p}_{w,SLE}(f)\right| dS}{\int \left|\widehat{\Delta p}_{w,WLE}(f)\right| dS}\right]$$