Trailing edge noise prediction for rotating serrated blades

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Outline

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Introduction

Motivation

- Wind turbines (Oerlemans et al 2007)
- Open rotors (Node-Langlois et al AIAA-2014-2610, Kingan et al AIAA-2014-2745)

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Experiments

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- Moreau and Doolan (AIAA J. 2013)

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Experiments

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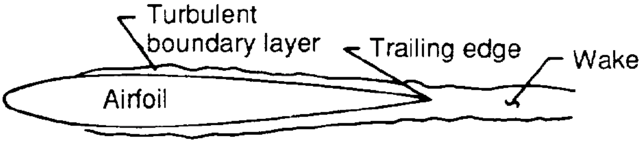
Numerical

- Jones and Sandberg (JFM 2012)
- Sanjose et al (AIAA-2014-2324)

Turbulent boundary layer trailing edge noise (TEN)

A subtle process



1. Hydrodynamic gust convecting past the trailing edge
2. Scattered into acoustics at the trailing edge
3. Acoustic field induces a distribution of dipoles near the TE
4. The dipoles radiate efficiently (M^5) to the far field

Outline

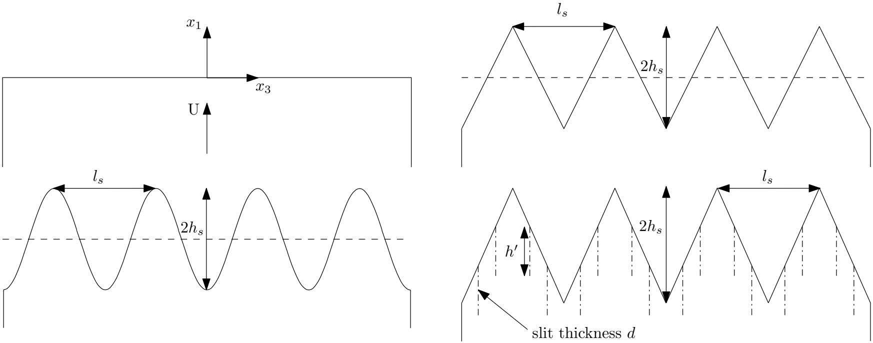
Howe (1991) & Azarpeyvand (2012)

$$S_{pp} = \quad A \qquad D \qquad \boxed{\Phi}$$

Assumptions

- High frequency ($kC > 1$)
- Frozen turbulence
- Sharp edge
- Full Kutta condition ($\Delta P_{TE} = 0$)
- Low Mach number ($M < 0.2$)

TEN modelling for isolated airfoils
Serration profiles

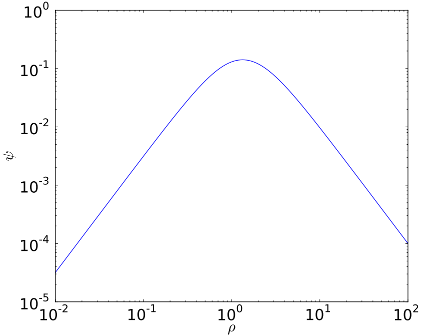


Edge spectra for serrated edges

Rewriting of Howe (1991) & Azarpeyvand et al. (2013)

$$\Phi = \psi(K_1 \delta)$$

$$\psi(\rho) = \frac{\rho^2}{[\rho^2 + 1.33^2]^2}$$

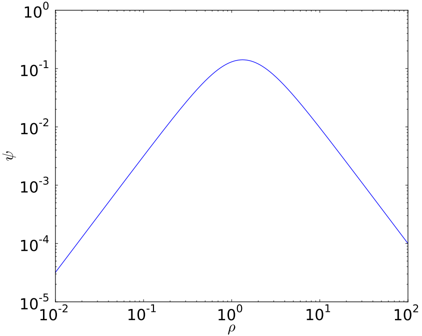


Edge spectra for serrated edges

Rewriting of Howe (1991) & Azarpeyvand et al. (2013)

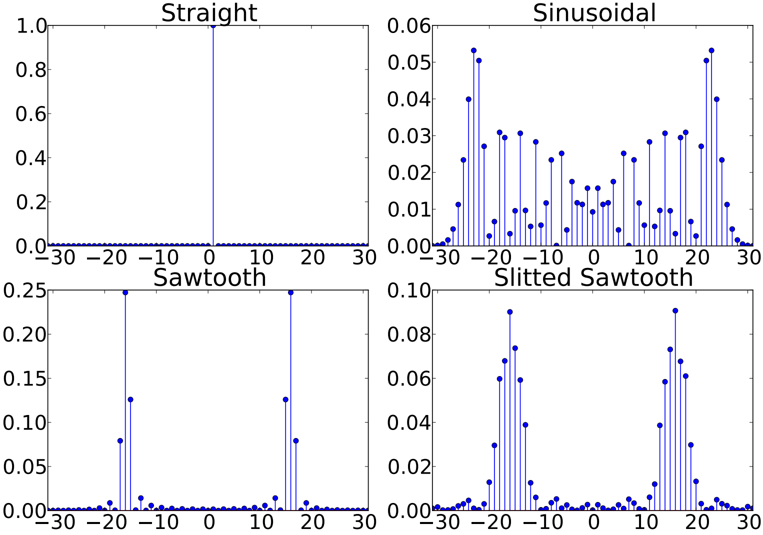
$$\Phi = \sum_n a_n(K_1 h)\ \psi(\rho_n \delta)$$

$$\psi(\rho) = \frac{\rho^2}{[\rho^2 + 1.33^2]^2} \qquad \rho_n = \sqrt{K_1^2 + n^2 k_s^2}$$

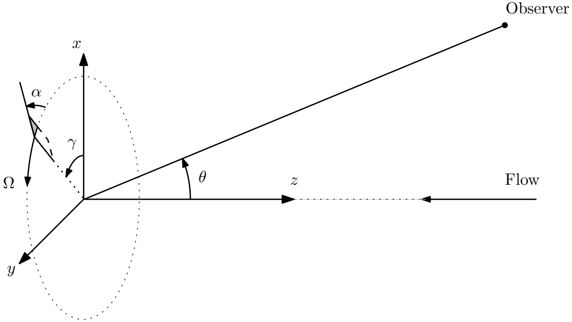


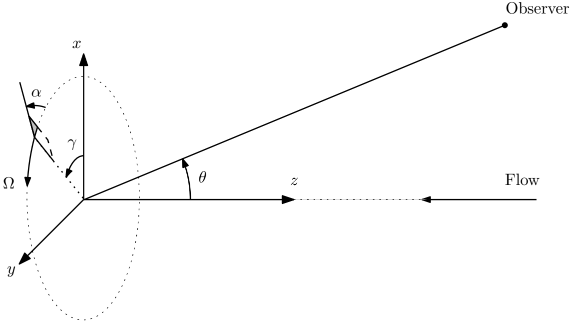
Edge spectra for serrated edges

Modal amplitudes a_n, $K_1 h_s = 25$



TEN for Rotating Airfoils





Time averaged PSD vs Instantaneous PSD

$$\overline{S}_{pp}(\omega) = \frac{1}{T}\int_0^T S_{pp}(\omega, t)dt$$

Amiet's model for rotating airfoils

$$\overline{S}_{pp}(\omega) = \frac{1}{T}\int_0^T \left(\frac{\omega'}{\omega}\right)^2 S'_{pp}(\omega', \tau)d\tau$$

Main steps:

- Ignore acceleration effects ($\omega \gg \Omega$)
- Power conservation: $S_{pp}(\omega, t)\Delta\omega = S'_{pp}(\omega', \tau)\Delta\omega'$
- Change of variable: $\frac{\partial t}{\partial \tau} = \frac{\omega'}{\omega}$

Doppler shift:

$$\frac{\omega'}{\omega} = \frac{\omega_S}{\omega_O} = 1 - \frac{\mathbf{M}_{SO}\cdot\hat{e}}{1+\mathbf{M}_{FO}\cdot\hat{e}}$$

References:

Schlinker and Amiet (1981)

Sinayoko, Kingan and Agarwal (2013)

Outline

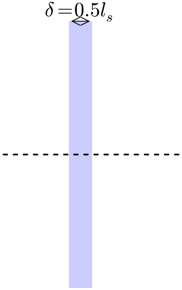
Wind turbine blade element:

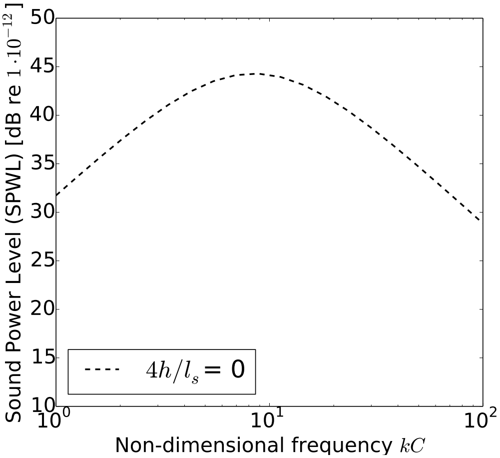
- Pitch angle: $10\,\mathrm{deg}$
- Chord: $2\mathrm{m}$
- Span: $7.25\mathrm{m}$
- Rotational speed $\Omega = 2.6\mathrm{rad/s}$ (RPM=25)
- Angle of attack: $0\,\mathrm{deg}$
- $M_{\text{blade}} = 0.165$
- $M_{\text{chord}} = 0.167$

Sawtooth serration design

Effect of serration height

Wide sawtooth $l_s = 2\delta$





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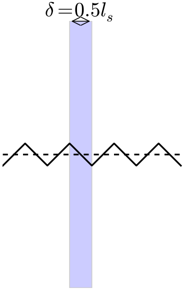

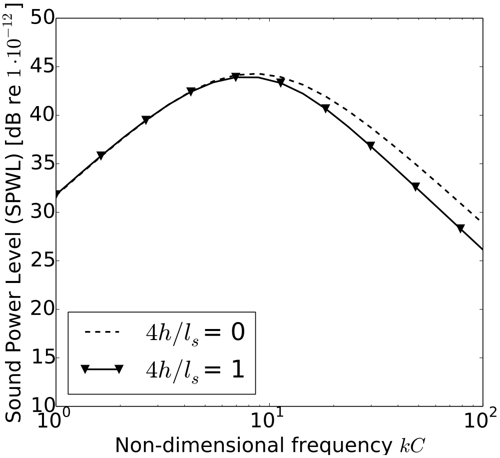

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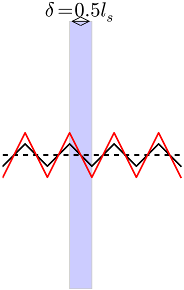

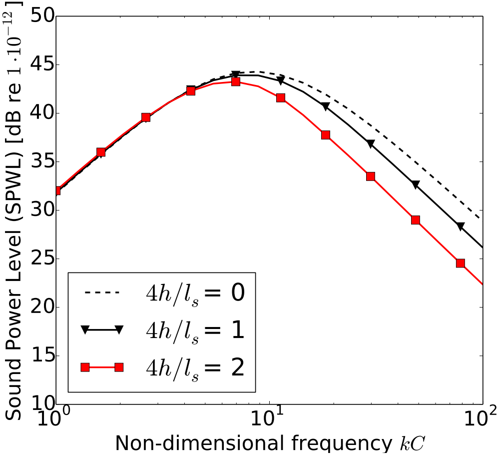

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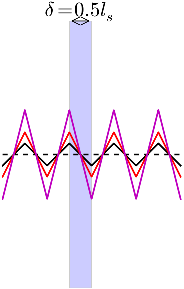

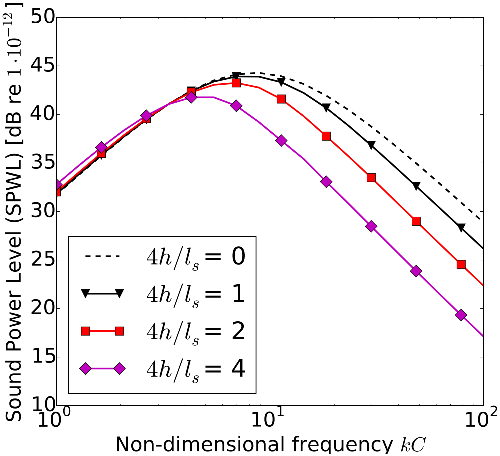

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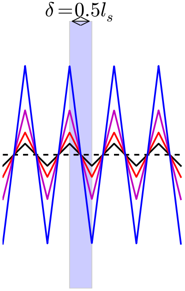

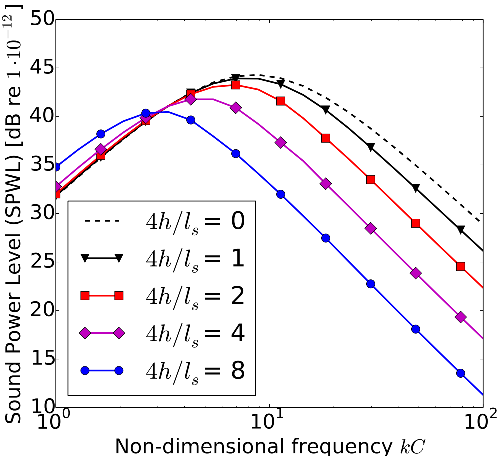

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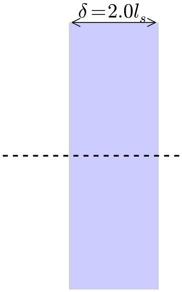
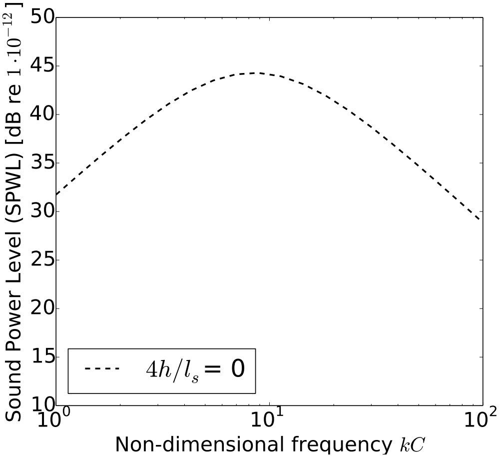
Narrow sawtooth $l_s = \delta/2$





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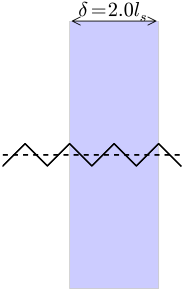

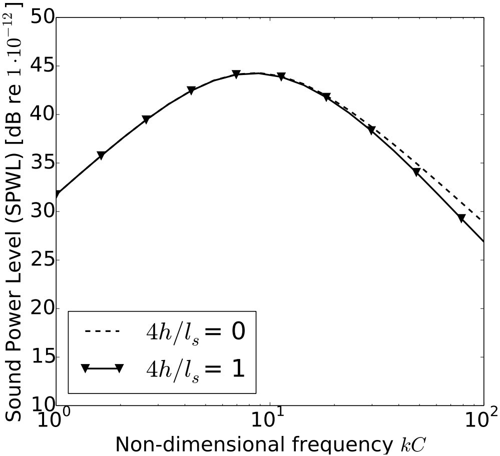

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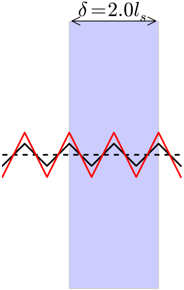

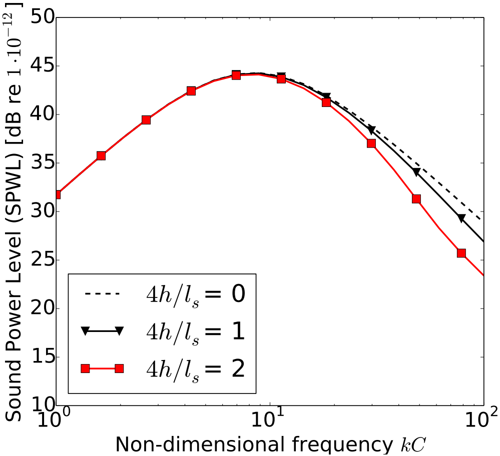

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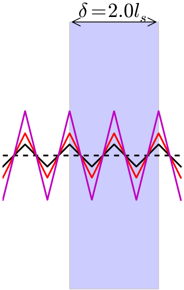

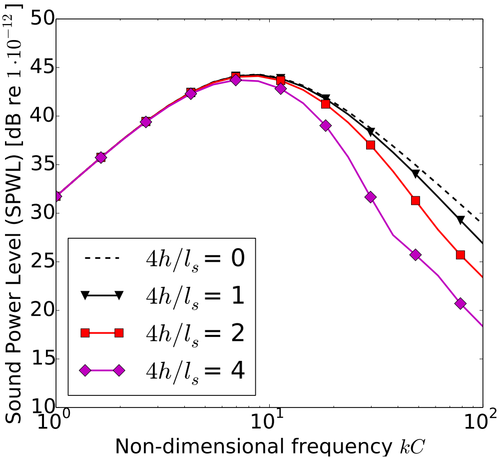

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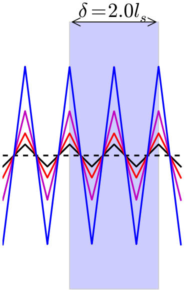
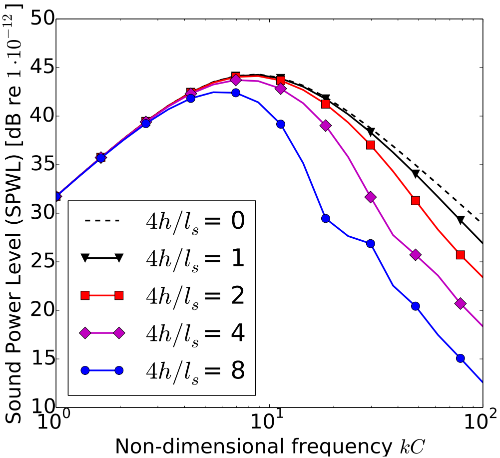
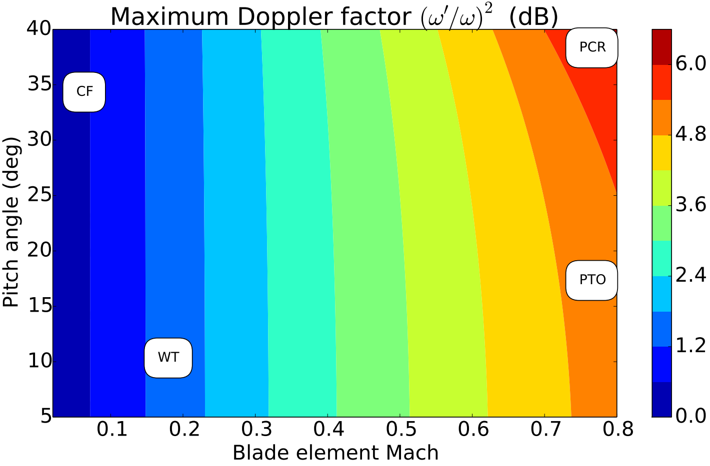




Effect of rotation on PSD

Doppler factor



WT: wind turbine

PTO: propeller take-off

CF: cooling fan

PC: propeller cruise

Outline

Generalized Amiet model for serrated edges

Theory

- Inspired by Roger et al (AIAA-2013-2108)
- Fourier series in spanwise direction.
- Pressure formulation and scattering approach
- Discretize the solution using n Fourier modes

$$\mathcal{L}\mathbf{P} = \mathbf{D}P + \mathbf{C}\frac{\partial \mathbf{P}}{\partial y_1}$$

$$\mathcal{L} = \left\{ \left(\beta^2 + \sigma^2\right) \frac{\partial^2}{\partial y_1^2} + \frac{\partial^2}{\partial y_2^2} + 2ikM\frac{\partial}{\partial y_1} \right\}.$$

1. Refine the solution iteratively

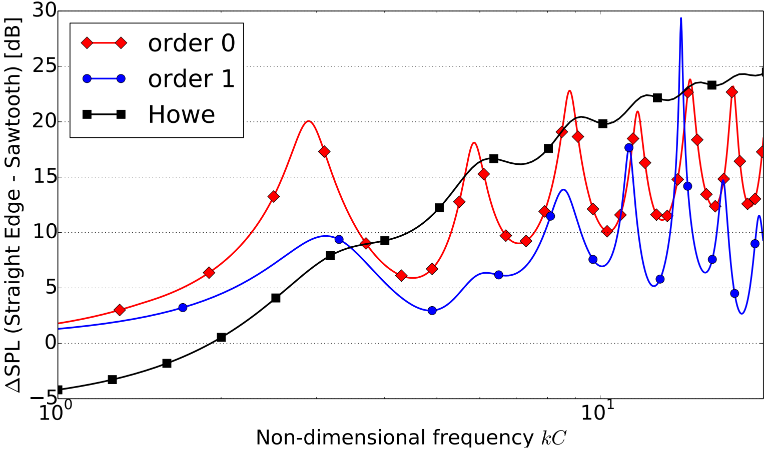
$$\mathbf{P} = \lim_{n \to +\infty} \mathbf{P}_n$$

2. Decoupled solution (order 0)

$$\mathcal{L}\mathbf{P}_0 = \mathbf{D}\mathrm{P}_0$$

3. Coupled solution (order 1)

$$\mathcal{L}\mathbf{P}_1 = \mathbf{D}\mathrm{P}_1 + \mathbf{C}\frac{\partial \mathbf{P}_0}{\partial y_1}.$$



Isolated sawtooth blade, $M = 0.1$, $l_s/\delta = 1$, $h_s/l_s = 3.75$.

Outline

Conclusions

1. Rotation effect can be incorporated easily using Amiet's approach
2. Rotation has little effect (< 1dB) for low speed fans
3. Rotation has significant effect (up to 5dB) on high speed fans
4. Preliminary results for new model improves significantly on Howe's theory

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Thank you!