On predicting wind turbine noise and amplitude modulation using Amiet's theory

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Introduction

Motivation

Long term objective: Develop an efficient numerical tool for designing low noise wind turbine blades.

Introduction

Strategy

1. Propagation: develop and validate noise prediction code based on Amiet's theory for:
   - time averaged spectra
   - amplitude modulation
   - trailing edge noise and inflow noise
2. Source: assess existing semi-analytical models against experimental data
3. Blade optimization

$\rightarrow$ Current study focuses on first step

Paper key objectives

- Review Amiet's theory and hightlight key challenges
- Present our first comparison against measured data
- Showcase the key advantages of the theory

Outline

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1. Amiet's theory and prediction methodology
2. Results
3. Conclusions

Amiet's theory for solated airfoils

- Amiet 1974, 1975, 1976
- Leading edge noise

$$S'_{pp}(\omega, \boldsymbol{x}) = B \ |\Psi_{LE}(\mathbf{K}, k_c)|^2 \ \Phi_{ww}(\mathbf{K})$$

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$$S'_{pp}(\omega, \mathbf{x}) = B\ |\Psi_{LE}(\mathbf{K}, k_c)|^2\ \Phi_{ww}(\mathbf{K})$$

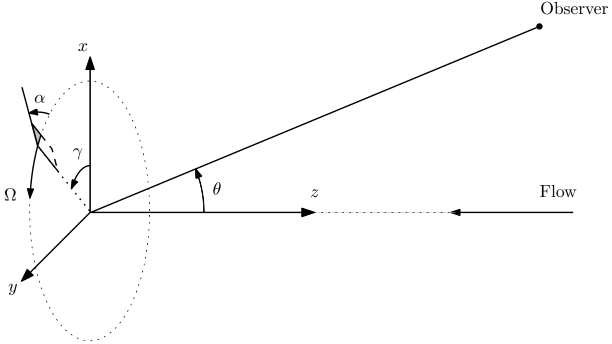
- Trailing edge noise

$$S'_{pp}(\omega, \mathbf{x}) = A\ |\Psi_{TE}(\mathbf{K}, k_c)|^2\ l_S(\mathbf{K})\ S_{qq}(\omega)$$

Key pitfalls

1. Common definitions of $|\Psi_{TE}|^2$ become singular for certain observer angles.
2. Frequency spectrum $S_{qq}(\omega)$ is wall pressure spectrum.

Split blade into blade elements of size l_S.



Amiet's theory for rotating blades

- Split blade into segments larger than l_S
- For each segment, use isolated airfoil theory to estimate the instantaneous PSD $S_{pp}(\omega, t, \mathbf{x})$

$$\Delta\omega S_{pp}(\omega, t, \mathbf{x}) = \Delta\omega' S'_{pp}(\omega', t', \mathbf{x'})$$
$$\Delta\omega' = D\Delta\omega$$
$$S_{pp}(\omega, t, \mathbf{x}) = DS'_{pp}(\omega', t', \mathbf{x'})$$

- Integrate over one period $T = 2\pi/\Omega$

$$S_{pp}(\omega) = \frac{1}{T}\int_0^T S_{pp}(\omega, t)dt$$
$$dt = Ddt'$$
$$S_{pp}(\omega, \mathbf{x}) = \frac{1}{T}\int_0^T D^2 S_{pp}(\omega, t', \mathbf{x'})dt'$$

- Assume blade in rectilinear motion to derive Doppler shift D:

$$D = 1 - \mathbf{M_{BO}} \cdot \boldsymbol{\sigma}/(1 + \mathbf{M_{FB}} \cdot \boldsymbol{\sigma})$$

Key pitfalls and remarks

1. Amiet's theory provides both averaged PSD and instantaneous PSD.
2. Doppler shift exponent is 1 for instantaneous PSD and 2 for stationary PSD

$$S_{pp}(\omega, t, \boldsymbol{x}) = D S'_{pp}(\omega', t', \boldsymbol{x}')$$
$$S_{pp}(\omega, \boldsymbol{x}) = \frac{1}{T}\int_0^T D^2 S_{pp}(\omega, t', \boldsymbol{x}') dt'$$

3. Pitfall: in blade frame, observer position $\boldsymbol{x}'$ is relative to the retarded source position

$$\boldsymbol{x_e} = \boldsymbol{x_s} + \boldsymbol{M_{FO}} c_0 T_e$$

Validation and details in *Sinayoko, Kingan and Agarwal (2014)*.

Aerodynamics

Chordwise Mach number M_{ch} and angle of attack AoA needed for each blade segment.

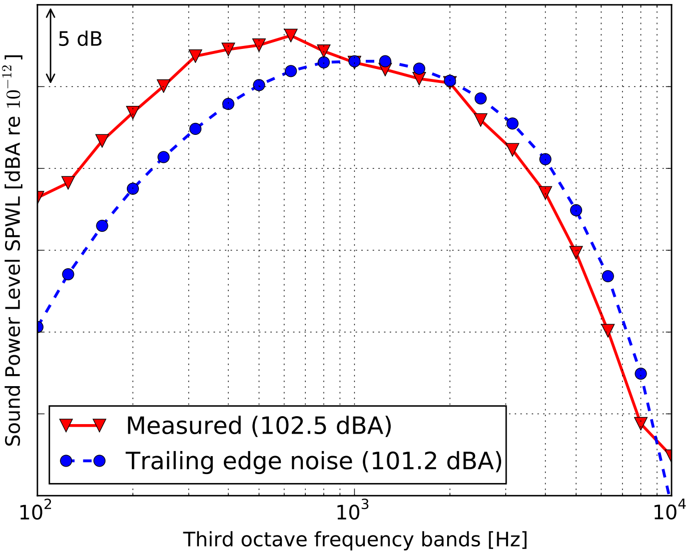
1. Use Blade Element Momentum code PYRO to get M_{ch} and AoA given wind speed and rotation speed;
2. Use Xfoil or measurements to get lift and drag coefficients needed by PYRO;
3. Use Xfoil to get boundary layer thickness δ^* needed for S_{qq} model.

Outline

Test case

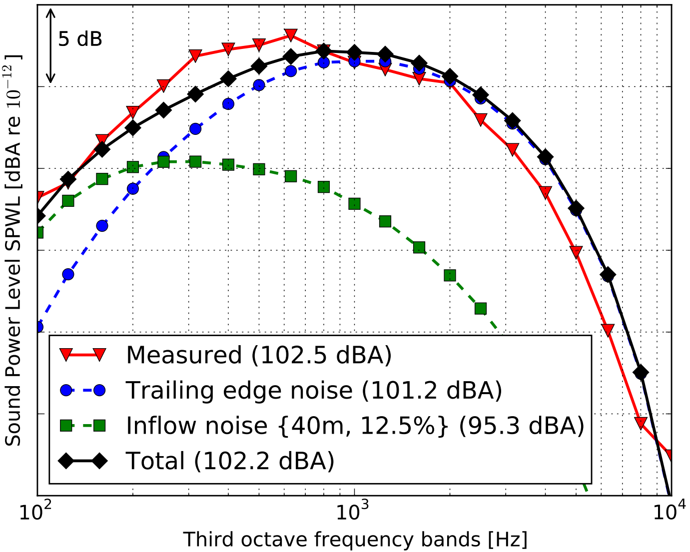
- Blade geometry: DAN-AERO (Masden et al 2010)
- Tower: 58 m
- Rotor radius: 40 m
- Wind speed: 8.5 m/s
- Rotation speed: 18.14 RPM
- Absorption coefficients: ISO-96-132 with 10°C and 70% humidity

Results



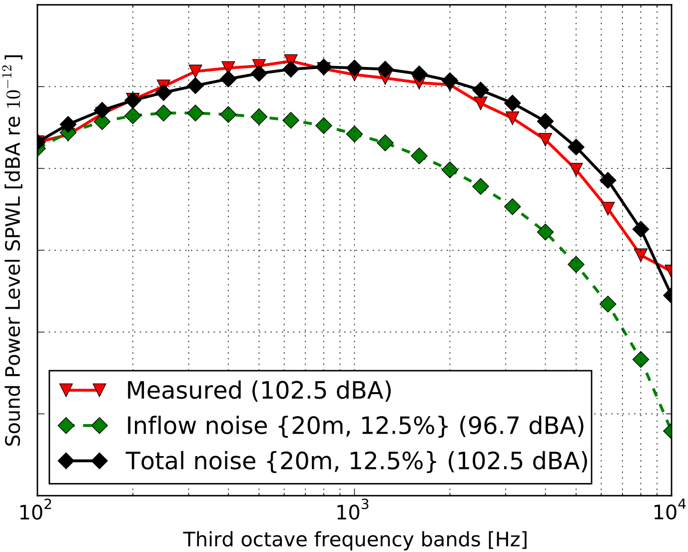
5 dB
Sound Power Level SPWL [dBA re 10^{-12}]
Measured (102.5 dBA)
Trailing edge noise (101.2 dBA)
10^2
10^3
10^4
Third octave frequency bands [Hz]

Results



5 dB
Sound Power Level SPWL [dBA re 10^{-12}]
Measured (102.5 dBA)
Trailing edge noise (101.2 dBA)
Inflow noise {40m, 12.5%} (95.3 dBA)
Total (102.2 dBA)
10^2
10^3
10^4
Third octave frequency bands [Hz]

Effect of integral length scale



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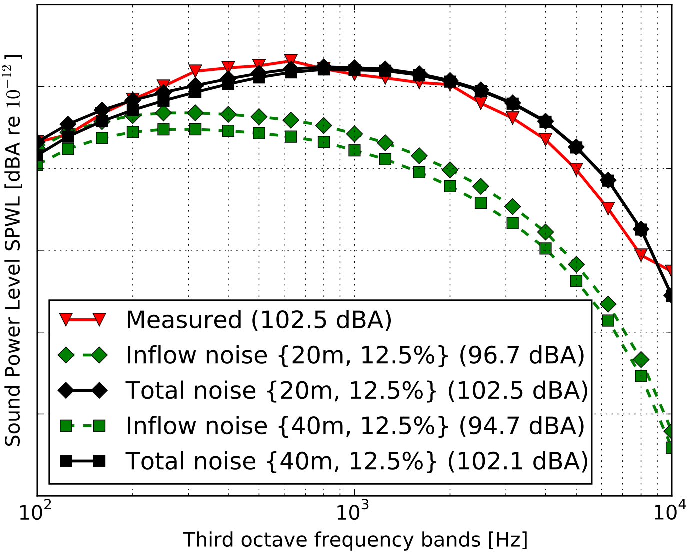

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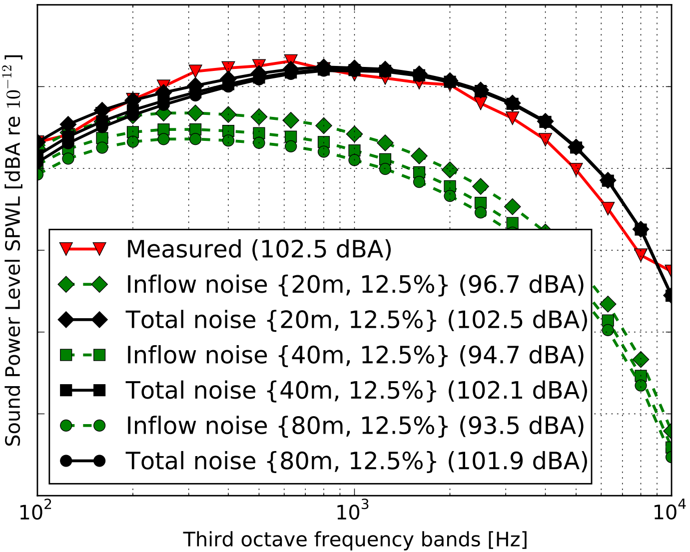

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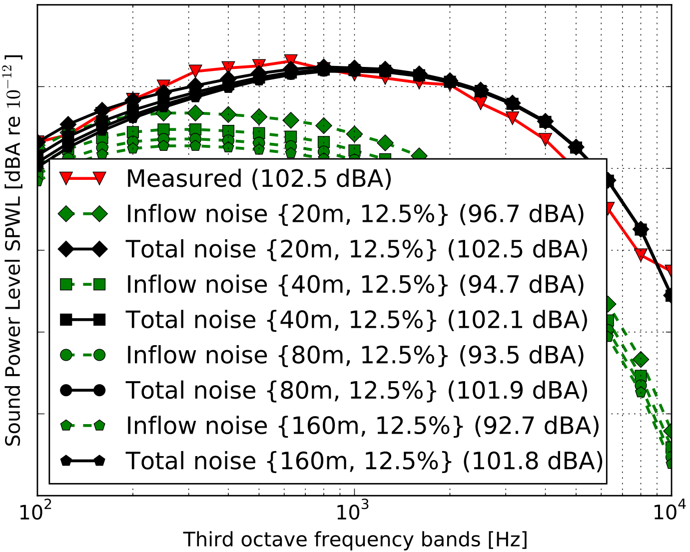
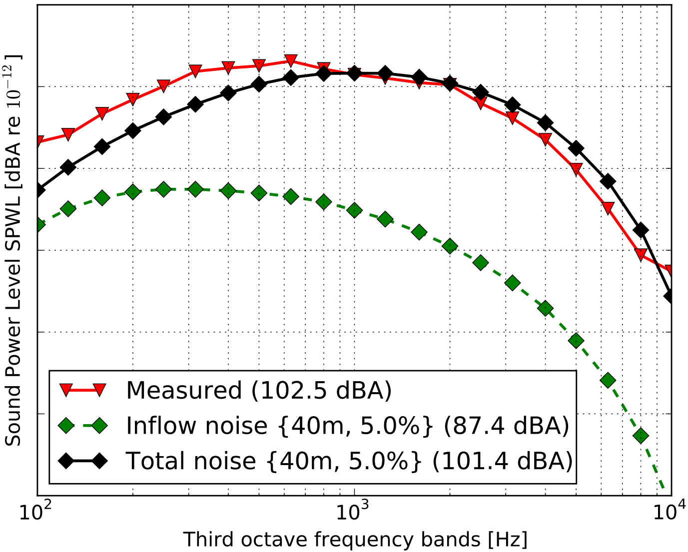


Effect of turbulence intensity scale



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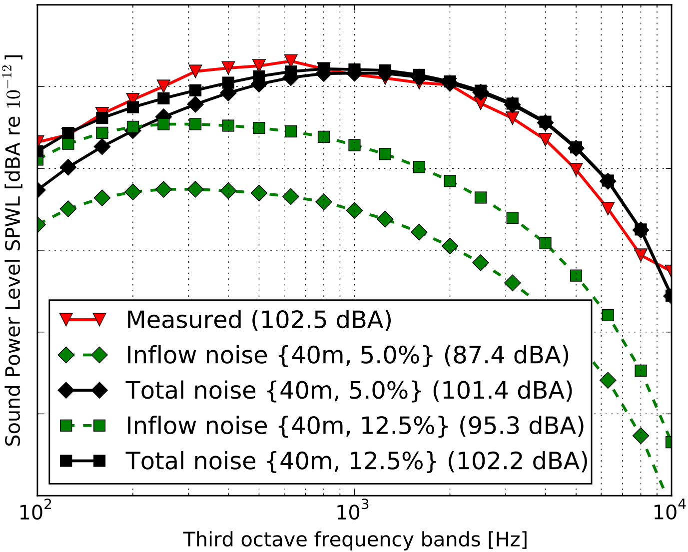

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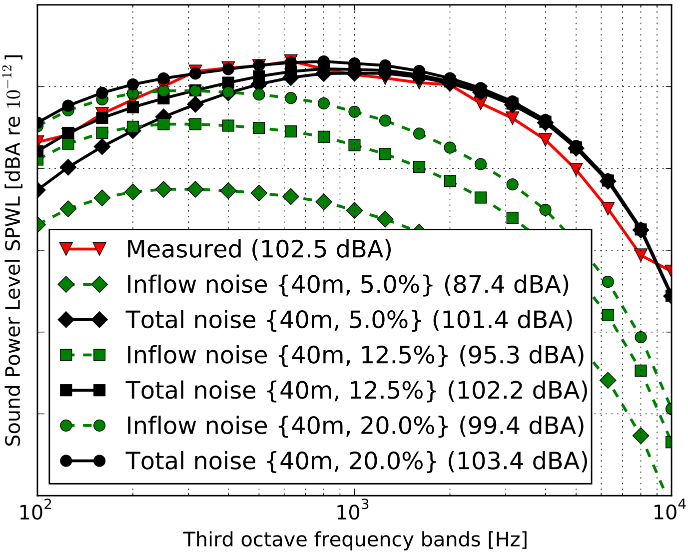
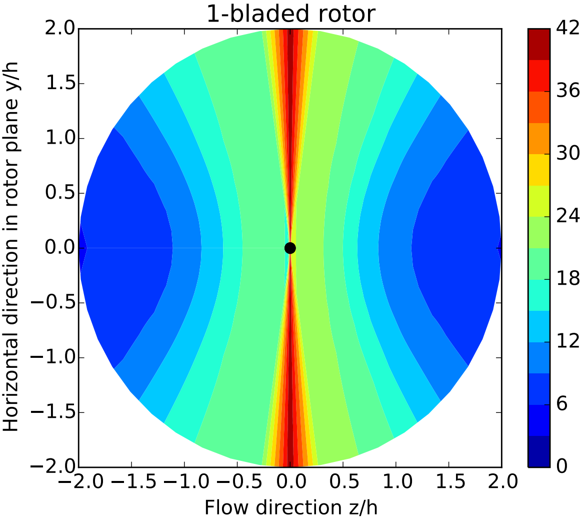


Amplitude modulation



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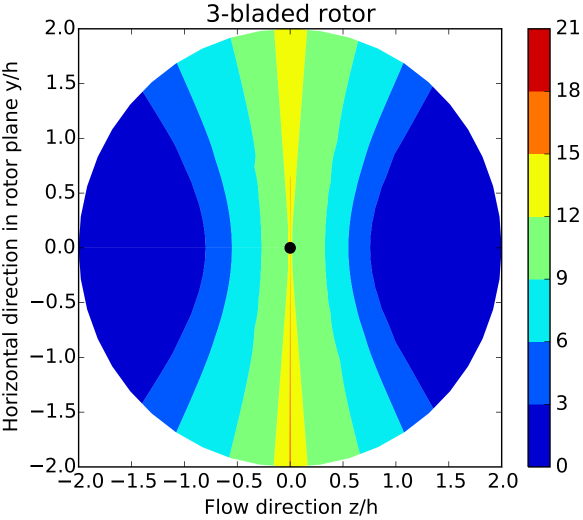

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Conclusions

Achievements

1. Reviewed Amiet's theory
2. Code for predicting wind turbine noise using Amiet's theory
3. Inflow noise dominates at low frequencies
4. Total noise is:
    - Sensitive to axial turbulence intensity level (+2 dBA from 5% to 20%)
    - Insensititive to integral length scale (-0.7 dBA from 20m to 160m)

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Future work

- Investigate alternative trailing edge frequency spectra;
- Develop new source modelling techniques if needed;
- Improve AM predictions in rotor plane;
- Optimize a wind turbine blade for low noise and/or low AM.

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Further information

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