Towards Identifying Contribution of Wake Turbulence on Inflow Turbulence Noise from Wind Turbines

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HAWT: Aerodynamic Noise Sources

- Various aero noise sources:
  - Turbulence interaction with blades
  - Unsteady force $\rightarrow$ noise
- Focus on inflow turbulence here
  - Important for low-frequency noise
Motivation

- Lighthill’s acoustic analogy – unsteady force $\rightarrow$ noise source

$$\frac{\partial^2 \rho'}{\partial t^2} - c_0^2 \frac{\partial^2 \rho'}{\partial x_i^2} = \frac{\partial m}{\partial t} - \frac{\partial f_i}{\partial x_i} + \frac{\partial^2}{\partial x_i \partial x_j} \left( p_{ij} + \rho u_i u_j - \rho' c_0^2 \delta_{ij} \right),$$

- Sources of inflow turbulence
  - **Atmospheric**: buoyancy & shear
  - **Turbine wakes**: shear

- Role of wake turbulence in producing noise is unclear
  - possibly pronounced under $\textit{stable}$ conditions
  - potential for OAM (other amplitude modulation)
Envisioned Prediction Approach

**Aero:** LES (SOWFA)

- **SOWFA calculations**
  - Sample wake (+atmospheric) turbulence statistics
  - Prescribe as inflow BC to aeroacoustic simulation

- **Simulate outboard section of turbine blade**
  - Ignore rotational effects, assume periodicity in span
  - Prescribe inflow turbulence (synthesized?)
  - LES + model → noise resulting from inflow turbulence-blade interaction

**Acoustics:** LES (pisoFoam)

Inflow (turbulent): from SOWFA + synthesis

Blade outboard region
Simplified (model) Problems for now

• **I:** Farm Aero
  – SOWFA calculations ... no ABL
  – Time history probes at hub height
    → Turbulence length scale + intensity
  – Lowson/Amiet noise model → far-field noise

• **II:** Rod-Airfoil interaction
  – Rod wake simulates upstream wake turbulence
  – Compute airfoil response (loads/noise) using LES
  – Acoustics analogies → far-field noise
I: FARM AERO (SOWFA)
Hypothetical Wind Farm

- Wind farm layout
  - Turbines under: no-wake, partial-wake, & full-wake

- Aero calculations using SOWFA

- Wake turbulence data extracted at hub height

D = 126 m, Probes Located at Hub Height 5 m upstream
Aerodynamic Results

- **SOWFA**: pisoFoam + actuator line model
- **At the moment**: No ABL $\rightarrow$ first row of turbines have no inflow turbulence

 Iso-vorticity surfaces

 Vorticity magnitude contours
Wake Turbulence Information

- Time history (streamwise velocity component)

- Auto-correlation: \( R_{uu}(\tau) = \frac{\langle u(t)u(t + \tau) \rangle}{\langle u^2(t) \rangle} \); where \( u = U - \langle U \rangle \)

- Integral time scale: \( T = \int_0^\infty R_{uu}(\tau) \, d\tau \)

- Integral length scale ... use Taylor’s frozen turbulence hypothesis: \( l_t = \bar{U} \times T \)
Inflow Turbulence Noise Model

• Due to Lowson ... extension of Amiet’s theory

\[
\begin{align*}
\text{SPL}_{1/3}^H &= 10 \log_{10} \left[ \left( \frac{\rho_0 c_0}{2} \right)^2 \frac{L}{r_o^2} l_t M^3 I^2 U^2 \frac{K^3}{(1 + K^2)^{-7/3}} \right] + 58.4 \\
l_t &\rightarrow \text{integral length} \\
I &\rightarrow \text{turbulence intensity} \\
U &\rightarrow \text{flow speed} \\
L &\rightarrow \text{airfoil span} \\
K &= \frac{\omega c}{(2U_{rel})} \rightarrow \text{wavenumber based on semichord } c/2
\end{align*}
\]

• Correction for low frequencies

\[
\text{SPL}_{1/3}^L = \text{SPL}_{1/3}^H + 10 \log_{10} \left( \frac{10 S^2 M K^2}{(1 - M^2)} \right) \\
\text{low freq corr}
\]

... \( S^2 \) is the compressible Sears function
Noise Results (preliminary)

- Wake turbulence: \( TI \sim 5\text{-}10\%; \) length scale \( \sim 2\text{-}10 \text{ m} \)
- Lowson’s model (in FAST) used to assess noise at IEC std. observer location
- Noise predictions for a few representative values of TI & length scales

- Perceptible impact on low-frequency noise
- However, the question of relative importance of wake/atmospheric turbulence remains
II: ROD-AIRFOIL
Model Problem: Rod-Airfoil

- Rod $\rightarrow$ turbulence generator (mimic inflow turbulence)
- Wake-airfoil interaction $\rightarrow$ noise
- Rod wake comprises of:
  - Quasi-periodic vortex shedding $\rightarrow$ tone noise
  - Vortex structure breakdown $\rightarrow$ turbulence $\rightarrow$ broadband noise
Rod Airfoil Problem Setup

- Experiment by Jacob et al. [1]

- Setup:
  - Rod airfoil in tandem
  - Airfoil (NACA 0012; \(c = 0.1\) m)
  - Rod (dia, \(d = 0.01\) m)
  - Separation, \(l = 0.1\) m

- Flow Reynolds number:
  - \(Re_d = 48,000\) (\(Re_c = 480,000\))

- Rod (cylinder) vortex shedding
  - Wake shedding \(St = 0.19\)

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Large Eddy Simulations

- Two flow solvers benchmarked against experiments
  - Compressible flow solver *Charles* by Cascade Tech.
  - Incompressible flow solver *pisoFoam* from OpenFoam

- Grid refined to resolve
  - Rod & airfoil boundary layers
  - Gap region between rod and airfoil

- Flow initialized by interpolating a 2-D solution
Flow Comparisons

- Streamwise velocity in wake
  - at $x/c = -0.255$
  - Mean and fluctuation (rms)

\[ \bar{u}, \quad u_{rms} \]
Near Field Velocity Spectral Density, $S_{uu}(\omega)$

PSD: using Wiener-Khinchin theorem:

$$S_{uu}(\omega) = \frac{\delta t}{N} \left| \sum_{n=1}^{N} u_n \exp(-i \omega n \delta t) \right|^2$$
Far-field Noise Prediction

Acoustic analogies to predict far-field noise

• Compressible flow data:
  – Ffowcs Williams-Hawkings analogy (ignore volume integral)
    
    \[ 4\pi |x| p'(x, t) = \frac{x_i}{c|x|} \frac{\partial}{\partial t} \int \left[ p'n_i + \rho u_i (u_j - U_j) n_j \right] d\Sigma \]
    
    \[ + \frac{\partial}{\partial t} \int \left[ \rho_0 u_i + \rho' (u_i - U_i) \right] n_i d\Sigma. \]

• Incompressible flow data (*no density perturbation*):
  – Amiet’s theory
  – Lighthill stress tensor + scattering problem
    • Euler equations, Boundary value, etc.
Amiet’s Theory

- Subtract surface pressure: pressure – suction sides to calculate loading → Delta P

- Compute cross PSD of loading on airfoil camber surface

\[ S_{QQ}(x_1, x_2, y_1, y_2, \omega) = \lim_{T \to \infty} \left\{ \frac{\pi}{T} E \left[ \Delta \hat{P}_T^*(x_1, y_1, \omega) \Delta \hat{P}_T(x_2, y_2, \omega) \right] \right\} \]

- Convolve cross PSD with free-space Green’s function (of convected wave eq.) to get far-field PSD

\[ S_{PP}(x, y, z, \omega) = \left( \frac{\omega z}{4\pi c_0\sigma^2} \right)^2 \int \int \int \int S_{QQ}(x_1, x_2, \eta, \omega) \exp \left\{ \frac{i\omega}{c_0} \left[ \frac{(x_1 - x_2)(M - x/\sigma)}{\beta - 2} + \frac{y\eta}{\sigma} \right] \right\} \, dx_1 \, dx_2 \, dy_1 \, dy_2 \]
Far Field Noise Power Spectral Density, $S_{pp}(\omega)$

- At $18.5c$ from mid point of leading edge along lift direction
- Charles: Ffowcs-Williams Hawkings Analogy & Amiet’s Formula
- Different span in Exp. and CFD (3:1)
  - For one-to-one comparison (if $L_{sim} < L_{corr}$):
    $$(S_{pp}(\omega))_{sim\ corrected} = (S_{pp}(\omega))_{sim} + 10 \log \left( \frac{L_{exp}}{L_{sim}} \right)$$
Far Field Noise – Peak Directivity

- Noise measurement data available on a circular arc \((r = 18.5 \, c)\)
- Dipole directivity (as expected)
- Convective amplification – increased power upstream
Conclusions and Future Work

Conclusions:

– Progressing towards assessing impact of wake turbulence on turbine noise
– Model problems solved to assess prediction accuracy
– Rod-airfoil problem $\rightarrow$ reasonable accuracy in near- and far-field spectra

Future Work:

– Wind farm calculations with ABL inflow (stable conditions)
– LES calculation of part-span blade with inflow turbulence from SOWFA calculations
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