TURBULENCE DISTORTION EFFECT ON LEADING EDGE NOISE FROM WIND TURBINE BLADES

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1 Introduction

Turbulence distortions is a potential source for production of flow induced noise and rely on the turbulence properties of aerodynamic flow field. Particularly in wind energy applications, the broadband leading-edge noise from rotating blades becomes significant when the turbulence intensity (TI) and integral length scale factors vary with mean flow velocity and rms velocity fluctuations. The noise radiated at leading edge of blade varies significantly with turbulence characteristics of velocity spectrum that describes the turbulent kinetic energy envelope. In this work, leading edge noise predicted by modified rapid turbulence distortion (RDT) model proposed by [1] is applied and compared with noise levels predicted by Grosveld, Moriarty and Lowson turbulent inflow models for a 2MW model wind turbine blade. For low frequencies in sound spectra, 50 Hz < f < 200 Hz the sound power predicted by both models agreed within 2-5% with experiment data of a SWT 2.3 MW wind turbine blade which has tip speed of ~83 m/s. However, for mid-band frequencies 250 Hz < f < 1 kHz, the modified rapid distortion model scales the turbulence properties in velocity spectrum more accurately leading to better estimation of noise levels. The modified RDT model has been computed for different turbulence intensities and found that as turbulence intensity increased the standard error for noise was reduced by at least 1 dB in low frequency region of sound spectrum. This trend is not observed with other models and on contrary it was found to increase.

2 Method

2.1 Modified rapid distortion theory (RDT)

To understand sudden changes to turbulence characteristics in flow field, rapid distortion theory (RDT) model developed by [2] provides an insight on how turbulence velocity or pressure fluctuations in homogeneous isotropic incompressible flows. It essentially uses a wavenumber analysis to calculate the surface pressure fluctuation to approximate the smaller scale of eddies which distorts the flow field relative to mean velocity field with changing boundary conditions under homogeneous isotropic turbulence. According to [3] in order to obtain rapidly distorted turbulent velocity spectra by applying RDT method, following conditions are necessary:

- Turbulence intensity in atmosphere must be very negligible compared to normalized local turbulence values in flow field.
- The integral length scales need to be smaller compared to length scale of eddies developed in the turbulent boundary layer.
- Reynolds number associated with turbulent flow velocity field is significantly large compared to mean flow velocity.

For unsteady incompressible flows, the leading edge noise is affected by the strength of turbulence or distortion in turbulence field which can be measured by velocity gradients in leading edge of boundary layer on aerofoil. [4, 5] studied the effect of angle of attack and different aerofoil geometry specifications, e.g. thickness, LE radius and camber on the leading edge turbulence interaction noise based on [6] noise prediction model. They found that model overpredicts the far field leading edge noise at high frequencies with respect to measured noise due to small thickness assumption for aerofoil and ignores the turbulence distortion effects. Hence the corrected model for velocity spectrum takes account of velocity perturbations that cause turbulence distortion near LE boundary layer, even at higher wave numbers and thus predicted the LE turbulence interaction noise more accurately. Later, [1] has done further modifications related to length scale proposed by [3, 7] to study the local turbulence properties and derived the improved rapidly distorted turbulent energy spectra, ϕ_{ww} for velocity field as given by Eq. (1):

$$\phi_{ww}(k_x, k_y) = \frac{91}{36\pi}\frac{\overline{u^2}}{k_e^2}\frac{\left(\frac{k_x}{k_e}\right)^2 + \left(\frac{k_y}{k_e}\right)^2}{\left(1+\left(\frac{k_x}{k_e}\right)^2 + \left(\frac{k_y}{k_e}\right)^2\right)^{\frac{19}{6}}}. \tag{1}$$

The expression obtained by Eq. (1) is substituted in the modified turbulent inflow noise model proposed by Lowson method for sound pressure. The final expression for sound pressure estimation derived by [1] in his validation study resulted in change of the empirical constant from 78.4 to 89.95 and given by Eq. (2):

$$SPL_{1/3} = 10\cdot\log\left(\frac{\rho^2 c^2 lL}{2r_e^2}\frac{M^3U^2I^2\left(\frac{k_x}{k_e}\right)^3 \overline{D}_L}{\left(1+\left(\frac{k_x}{k_e}\right)^2\right)^{\frac{19}{6}}}\right) + 85.95, \tag{2}$$

where k_x and k_y are the wave numbers of turbulent velocity fluctuations along blade chord and span directions respectively. k_e is the wave number corresponding to energy containing turbulent eddies in velocity spectra. $\overline{u^2}$ is the *rms* value of turbulent velocity fluctuations in energy spectra.

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3 Results

Fig. 1 illustrates the comparison of sound power predicted by modified RDT, Grosveld, Lowson and Moriarty models for a wind speed of 12 m/s at turbulence intensity of 10%. It can be noted that for frequencies, $f < 60$ Hz, the Grosveld model showed a less conservative prediction for L_w with a maximum value of 110 dB and closely agrees the trend predicted by modified RDT model. However, for $f > 60$ Hz, the noise outputs agree better with Moriarty & Migliore and Lowson noise models. Also, sound levels predicted by Moriarty & Migliore and Lowson models show a difference of ~3 dB between 20 Hz < f < 60 Hz. For frequencies between 100 Hz and 1 kHz in the noise spectra, the slope of curves for Grosveld, Lowson and Moriarty models show a similar trend and agree strongly with each other. However, the RDT model shows a steeper slope for noise curve in that region. Also, the validation of turbulent inflow noise predicted by four semi empirical models has been done with experiment noise data of Siemens SWT 2.3 MW – 93. For low frequencies, $f < 100$ Hz, the standard Lowson, Moriarty & Migliore, and RDT model showed strong agreement with experiment data, but the Grosveld model deviated by 3 dB because the turbulent velocity energy spectra for Moriarty & Migliore and RDT models was modified based on standard Lowson method and was not implemented in Grosveld model. Further, it can be seen that experiment data shows a sound power peak near f~1 kHz which is due to the trailing edge noise from blade. So, for subsonic turbulent flows, the turbulent inflow noise exhibits M^6 dependence and radiates sound as a dipole in rotor plane.

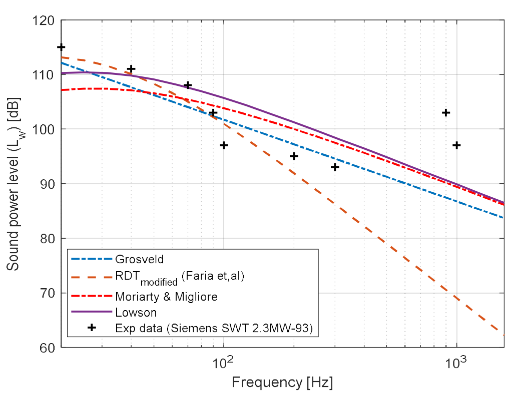

Figure 1: Comparison of the turbulent inflow noise predicted from the Grosveld, Moriarty, Lowson, and modified RDT models at mean wind speed of 12 m/s, at turbulence intensity of 10%, and validated with experiment data of Siemens SWT 2.3 MW-93 model.

4 Discussion

The sound power, L_w for turbulent inflow noise computed by all four models shows relative difference in low frequency part of spectra, at different turbulent intensity levels. For this reason, standard error for sound power, L_w has been evaluated for each of TI levels used in the study. Table 1 show that the standard error for L_w in the frequency range, 20 Hz < f < 315 Hz is reduced with increasing values of TI at mean wind speed of 10 m/s. This suggests that all four models predict similar trends for TI noise levels and agree with experiment data shown in Fig 1.

Table 1: Comparison of standard error in sound power level, L_w predicted at different turbulent intensities for mean wind speed of 10m/s

TI, %	1/3rd octave frequency, [Hz]							
	20	31.5	63	80	125	160	200	250
6.0	2.35	1.71	1.29	1.36	1.76	2.08	2.41	2.75
8.0	1.88	1.24	0.79	0.90	1.39	1.75	2.09	2.45
10.0	1.55	0.94	0.50	0.65	1.21	1.58	1.93	2.29
12.0	1.32	0.80	0.48	0.63	1.17	1.52	1.86	2.22
14.0	1.18	0.79	0.63	0.76	1.21	1.54	1.86	2.20

5 Conclusion

The present study investigated the turbulence distortion effect based on the modified RDT model to predict turbulent inflow noise for wind turbine blades. The modified RDT model predicted the turbulent inflow noise curve more accurately in the low frequency region of sound spectra and agreed well with experiment data, compared to Moriarty and Migliore, Grosveld and Lowson models. The mechanism for broadband turbulence interaction noise at leading edge of turbine blade is thus dependent on turbulence velocity spectra characteristics considered in each of model. Model comparisons also show that maximum standard error for sound power is ~2.8 dB at 250 Hz in sound spectra.

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Reference

[1] Faria, M. A., Saab, J. Y., Rodriguez, S., Pimenta, M. M., A rapid distortion theory based airfoil turbulent inflow noise prediction method, *Journal of Brazilian society of mechanical sciences and engineering*, 42: 397, 2020

[2] Hunt, J. C., A theory of turbulent flow round two-dimensional bluff bodies, *Journal of fluid mechanics*, 61(4), 625-706, 1973

[3] Goldstein, M.E., Afsar M.Z., Leib, S.J., Nonhomogeneous rapid distortion theory on transversely sheared mean flows, *Journal of fluid mechanics,* 736: pp, 532-569, 2013

[4] Moreau, S., and Roger M., Effect of angle of attack and airfoil shape on turbulence-interaction noise, *11th AIAA/CEAS aeroacoustics conference*, 2005

[5] dos Santos, F.L., Botero-Bolivar, L., Venner, C., and de Santana, L. D., Modelling the turbulence spectrum dissipation range for leading edge noise prediction, *AIAA Journal*, 2022

[6] Amiet, R., Acoustic radiation from an airfoil in turbulent stream, *Journal of sound and vibration.* 41: 407-420, 1975

[7] Christophe, J., Application of hybrid methods to high frequency aero-acoustics, *Dissertation, Von Karman institute for Fluid dynamics*, 2011