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Review of NACA 0012 Turbulent Trailing Edge Noise Data at Zero Angle of Attack

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Summary

Turbulent trailing edge noise is one of the most important sources of noise from wind turbines. Most of the understanding concerning the physics of turbulent trailing edge noise comes from experimental data obtained using NACA 0012 airfoil profiles in anechoic wind tunnel facilities. Further, nearly all semi-empirical models used for design purposes are based or validated against this data set. This paper compares turbulent trailing edge data for NACA 0012 airfoils from a variety of wind tunnel facilities as well as some modern computational studies. Even though the comparison is limited to zero angle of attack, the results are able to show the limitations of the current data set and the accuracy of two semi-empirical noise models. There is reasonable agreement across different data sets at moderate Reynolds numbers, but there is limited agreement at higher Reynolds numbers. With the design Reynolds number for modern and future wind turbine blades now exceeding the Reynolds number of the test data, there is a need to perform new experiments and update our existing prediction models.

1. Introduction

Turbulent airfoil trailing edge noise is the dominant aerodynamic wind turbine noise source above the low-frequency range (200 Hz and above, Oerlemans et al. (2007), Doolan et al. (2012)). Much effort is taken to measure (Moreau et al., 2011a, 2011b, 2012) and predict (Doolan et al. 2010, Albarricin et al., 2012) turbulent trailing edge noise in order to design quieter airfoil shapes or to ensure that new designs do not create excessive noise.

Numerical predictions of trailing edge noise need validation against data obtained under controlled laboratory conditions. Most of the data suitable for this purpose is normally taken from a NASA study in the 1980s (Brooks et al., 1989), where NACA 0012 airfoils were placed in an anechoic wind tunnel at various Reynolds numbers, Mach numbers and angles of attack. The data obtained in this study forms the basis for the much-used Brooks, Pope and Marcolini (BPM) semi-empirical noise model that is used for wind turbine noise predictions and is incorporated into the NAFNoise prediction method (Moriarty, 2003). The NASA experimental noise data also forms the basis of validation of other more sophisticated numerical predictions of trailing edge noise (Wolf et al., 2012, Marsden et al. 2008, Ewert and Schroder, 2004).

While the NASA experimental noise data is important, there are only a few other studies available that allow comparison to confirm its accuracy and to quantify cross-facility effects. Further, the Reynolds number at which the NASA data was obtained is limited to approximately 1.5×10^6, which is lower than the design Reynolds number of many modern and planned wind turbine blades.

As part of an on-going effort to review airfoil trailing edge noise data for improved physical understanding and for numerical validation purposes, this paper compares turbulent trailing edge data for NACA 0012 airfoils from a variety of wind tunnel facilities as well as some modern computational studies. The comparison is limited to zero angle of attack but is able to show important differences in the available data and justifies the need for further experimental measurement to support future wind turbine development.

2. Trailing Edge Noise

Turbulent trailing edge noise is created when turbulent fluid flow passes the sharp trailing edge of an airfoil. The sudden impedance change at the edge enhances the efficiency of the aerodynamic sources close to the surface of the airfoil resulting in sound that can be heard by an observer in the far-field (Ffowcs Williams and Hall, 1970).

A typical example of a 1/3 octave band turbulent trailing edge noise spectrum is shown in Figure 1, measured in the DLR AWB anechoic wind tunnel (Herr, 2007, Herr et al., 2010, Herr and Reichenberger, 2011). There is usually noise radiated at a peak frequency (defined as f_{peak}) with level SPL_{peak}, as indicated in the figure. In this paper, Re indicates Reynolds number and M indicates Mach number.

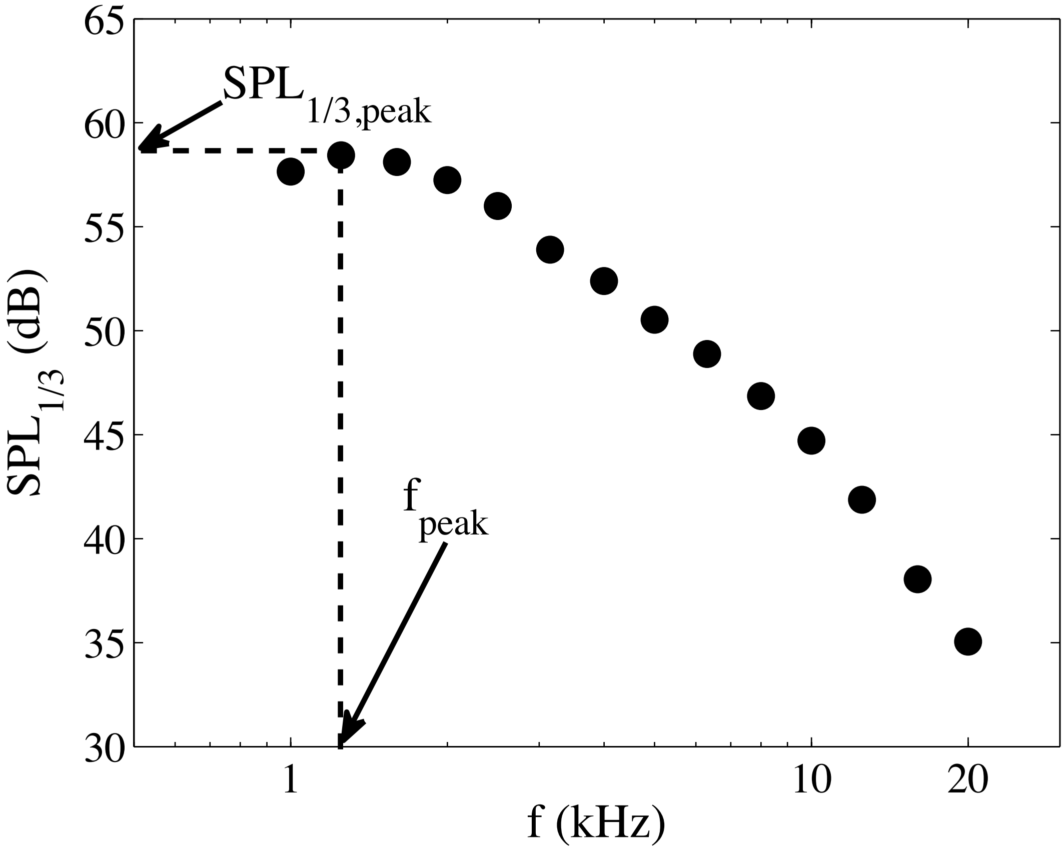

Figure 1. Typical 1/3 octave turbulent trailing noise spectrum (Herr, 2007, Herr et al., 2010, Herr and Reichenberger, 2011), M = 0.174, Re = 1.54 x 10^6.

A convenient and standard way (Brooks et al., 1989) of presenting trailing edge noise data that enables comparison across different facilities and at different scales is by non-dimensionalising the frequency (f) as a Strouhal number (St) and to scale the SPL in terms of Mach number, observer distance (r_e), airfoil span (L) and trailing edge boundary layer displacement thickness (δ*).

$$St = \frac{f\delta^*}{U_\infty} \tag{1}$$

$$\text{Scaled SPL} = \text{SPL}_{1/3} - 10\log_{10}\left(M^5 \frac{\delta^* L}{r_e^2}\right) \tag{2}$$

Free stream velocity is U_∞.

3. Data Comparison

Table 1 summarises the experimental and numerical studies compared in this paper. For brevity, the reader is referred to each cited paper in the table for details of experimental and numerical techniques used. The identifier in parenthesis in the first column is used in the legends of the figures in the rest of paper. In all cases, the boundary layer is tripped and turbulent at the trailing edge. The exception is the numerical case of Marsden et al. (2008), which is untripped, but is included as the boundary layer on both sides of the airfoil has transitioned to a turbulent state upstream of the trailing edge.

Table 1. Summary of data sets used for comparison. Shaded entries are numerical studies.

Author (Identifier)	**Mach Number**	**Re/10^6**
Brooks and Hodgson (1981) (NASA 81)	0.11-0.2	1.6-2.9
Brooks et al. (1989) (NASA 89)	0.09-0.21	0.069-1.47
Herrig et al. (2008) (IAG)	0.117-0.204	0.533-2.80
Herr, 2007, Herr et al., 2010, Herr and Reichenberger, 2011 (DLR)	0.117-0.175	1.1-1.6
Bahr et al. (2011) (UFL)	0.153-0.173	0.96-1.08
Devenport et al. (2010) (VT)	0.046-0.189	0.99-4.96
Wolf et al. (2012) (Wolf LES)	0.115	0.408
Marsden et al. (2008) (Marsden LES)	0.22	0.5

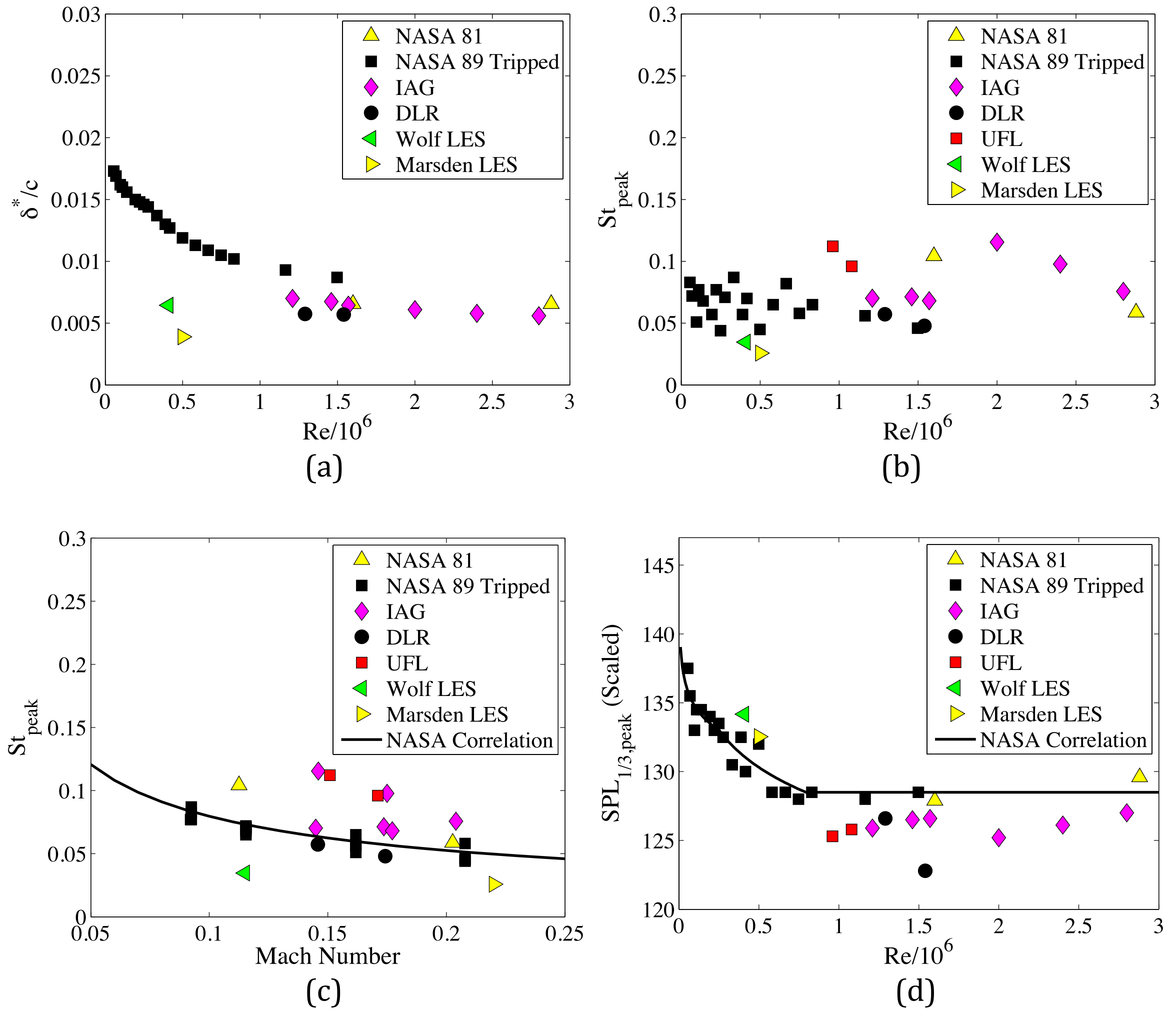

Figure 2. Variation of integral and peak data values. (a) Displacement thickness; (b) St_{peak} vs. Re; (c) St_{peak} vs. Mach number; (d) SPL_{peak} vs. Re.

The variation of measured displacement thickness with Reynolds number is shown in Fig. 2(a). The NASA 89 data is higher in the small area of overlap with other data sets. Further, the numerical data under predicts the displacement thickness significantly.

The peak radiating Strouhal number shows random variation with Reynolds number (Fig. 2(b)). Brooks et al. (1989) found an empirical Mach number relationship that describes peak radiating Strouhal number and this forms part of the BPM model. Figure 2(c) displays peak Strouhal number against Mach number, with the NASA correlation shown as a line. The NASA empirical fit appears to be facility specific.

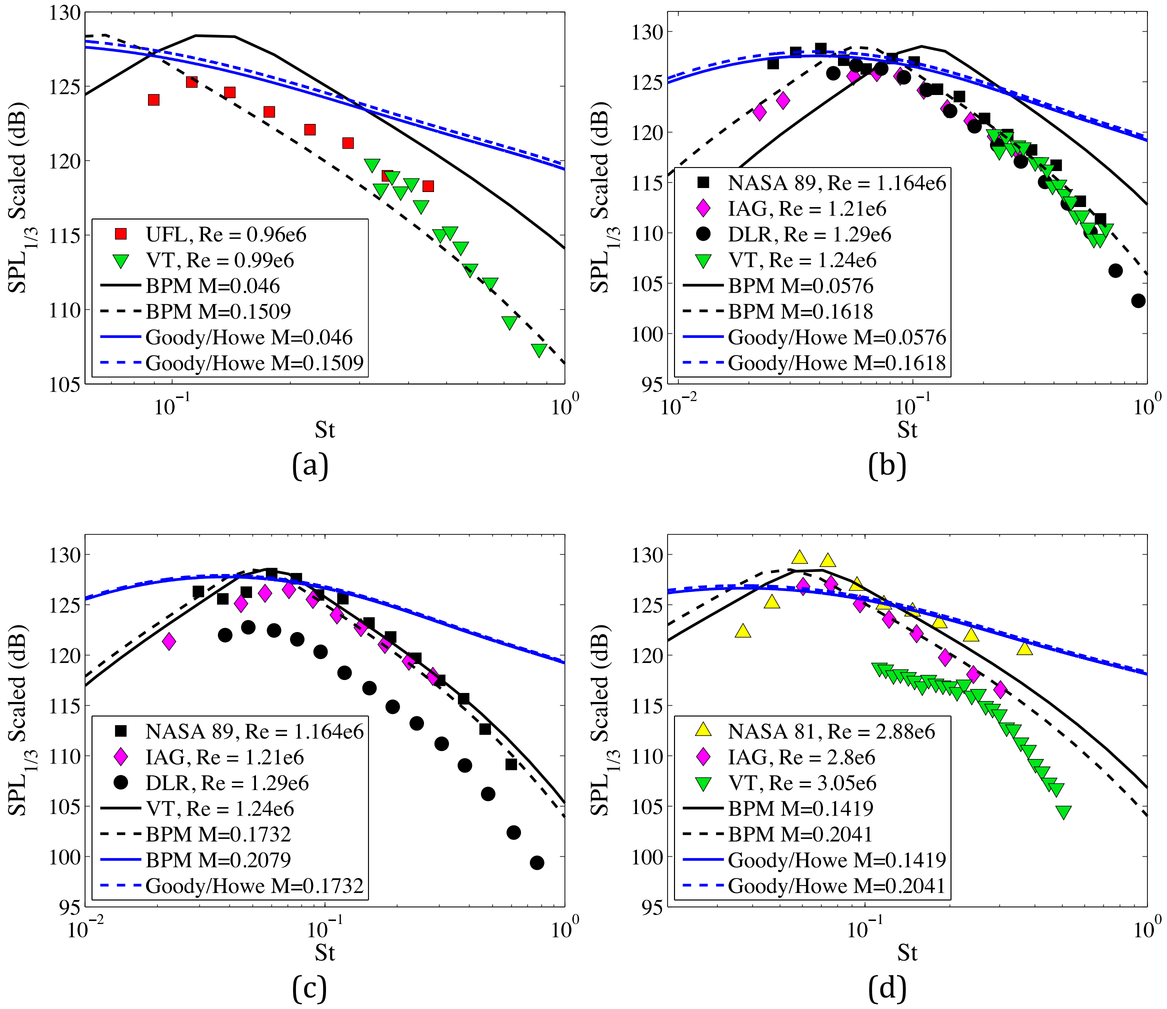

Figure 3. Comparison of scaled 1/3 octave noise data from various facilities with semi-empirical noise predictions. (a) Re ≈ 1 x 10^6; (b) Re ≈ 1.2-1.3 x 10^6; (c) Re ≈ 1.5 x 10^6 and (d) Re ≈ 3 x 10^6.

Peak scaled radiating 1/3 octave SPL is shown to vary in an approximately inverse relationship with Reynolds number until a Reynolds number of about 1 x 10^6 (Fig. 2(d)). This empirical finding also forms part of the BPM model and the NASA correlation for peak level is shown as a line. Below Re = 1 x 10^6, most data lies within a few dB of this line, even the numerical data when scaled using their erroneous displacement thickness predictions (see Fig. 2(a)). After Re = 1 x 10^6, the experimental data from other facilities deviate from the NASA correlation. It appears that the limited amount of data from other facilities is 3-6 dB below the NASA correlation.

Scaled 1/3 octave spectra (according to Eqs. 1 and 2) from various studies at similar Reynolds numbers are compared in Fig. 3. Also shown in Fig. 3 are semi-empirical noise predictions. Two models are included for comparison: NASA's BPM model (Brooks et al., 1989) and Howe's model (Howe, 1998) using Goody's model (Goody, 2004) for the turbulent wall pressure spectrum (Goody/Howe in Fig. 3).

The BPM model has a Mach number dependency (independent of the Reynolds number), due to their experimental observation that peak Strouhal number was shown to depend on Mach number (Fig. 2(c)). Therefore two BPM predictions were performed for each Reynolds number or subfigure in Fig. 3. A lower Mach number corresponding to the smallest experimental Mach number at that Reynolds number and a higher Mach number corresponding to the largest experimental Mach number. To be consistent, the Goody/Howe model was used with the same Mach and Reynolds numbers as the BPM model.

At Re ≈ 1 x 10^6 (Fig. 3(a)), data from Bahr et al. (2011) (UFL) are compared with the results from Devenport et al. (2010) (VT). The VT results are limited to higher Strouhal numbers due to the beamforming technique used to gather the noise data. The two data sets are complimentary, with the UFL and VT data overlapping at the mid-Strouhal numbers (St ~ 0.3-0.4). The experimental data shows no Mach number dependency in contrast to the BPM model. The lower Mach number BPM prediction compares well with the experimental data, while the higher Mach number does not. The Goody/Howe model does not show a Mach number dependency, but is unable to achieve the correct slope or level, over predicting SPL at all Strouhal numbers.

There is remarkable collapse of experimental data at Re ≈ 1.2-1.3 x 10^6 (Fig. 3(b)). There is some deviation of the experimental data sets at lower Strouhal number; however, the peak level and frequency compares reasonably well. Again, the lower Mach number BPM prediction compares well with the scaled experimental data, while the higher Mach number prediction does not. The Goody/Howe model achieves a reasonable prediction of the peak level and Strouhal number, but has incorrect slope at lower and higher Strouhal numbers.

The NASA 89 and IAG scaled noise experimental data collapse at Re ≈ 1.5 x 10^6 (Fig. 3(c)); however, the DLR data is approximately 6 dB lower. As the Mach number range of the experimental data in Fig. 3(c) is small, both BPM predictions compare well with the IAG data and the NASA data it was derived from. The Goody/Howe model is able to approximate the peak, but the slope of the spectrum at lower and higher Strouhal numbers is incorrect.

As the Reynolds number is increased to Re ≈ 3 x 10^6 (Fig. 3(d)), which is beyond the NASA 89 Reynolds number range and the range that the BPM model was derived, the experimental data sets show poorer agreement. The NASA 81 and IAG data agree within a few dB at lower Strouhal number and the peak radiating Strouhal numbers agree. However these data sets deviate significantly as the Strouhal number is increased. Further, the VT data does not agree with either experimental data set and is sometimes over 10 dB lower.

The BPM model agrees reasonably well with the NASA 81 and IAG data at Re ≈ 3 x 10^6 (Fig. 3(d)), but does not compare well against the VT data. The Goody/Howe model matches fairly well with NASA 81 data at high St (above St = 0.1) but is unable to match the remainder of the data shown in Fig. 3(d).

4. Conclusions

Noise and boundary layer thickness data from a number of experimental and numerical studies have been compared for the NACA 0012 airfoil at zero angle of attack and a range of Reynolds and Mach numbers. The major conclusions are:

1. There is significant variation between experimental and numerical prediction of boundary layer thickness. The experimental data compares better across facilities, but there are still some inconsistencies.
2. There is no observed variation of peak radiating Strouhal number with Reynolds number. The Mach number dependency observed in the NASA facility (Brooks et al., 1989) is not observed in other facilities or numerical simulations.
3. Above Re = 1 x 10^6, most experimental scaled SPL data falls below the NASA empirical correlation by up to 6 dB. Below Re = 1 x 10^6, the only available comparison can be made with numerical simulation, which scales remarkably well, considering the inaccuracies in their boundary layer thickness predictions.
4. Data at available comparable Reynolds numbers collapse well at and around Re ≈ 1 x 10^6; however, at higher Reynolds number, there are few available studies. At Re ≈ 3 x 10^6, three experiments are compared, with the data showing poor agreement at higher Strouhal number.
5. The BPM model compares well with most data sets if a low value of free stream Mach number is used. The Mach number dependency of the BPM model does not appear to be appropriate, while the experimental data suggests that, provided other variables are properly scaled, the noise spectrum has Reynolds number dependence only.
6. The Goody/Howe model compares poorly with the available experimental data, but this may be due to the assumptions made concerning the skin friction coefficient and other turbulent flow parameters at the trailing edge. If a better estimate of these values were available, then the Goody/Howe model may provide a better estimate. Importantly, the Goody/Howe model does not show the Mach number dependency of the BPM model.
7. There are no experimental data sets to compare with the NASA data below Re ≈ 1 x 10^6 and there are very few above Re ≈ 1.5 x 10^6 and only a single data point above Re = 3 x 10^6 (from Devenport et al. (2010), not shown in this paper). Given the discrepancies observed in this comparative study, more data is required to better understand the error of our observations, improve our modelling capability and to assist noise evaluations for turbine blades designed to operate at high Reynolds numbers.

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