Computational aeroacoustic prediction of trailing edge noise for small wind turbines

Alison Zilstra and David A Johnson
Wind Energy Group, University of Waterloo, Waterloo, Ontario, Canada, N2L 3G1
E-mail: alison.zilstra@uwaterloo.ca

Abstract. The study of aeroacoustic noise generated by small wind turbines is important to increase acceptance and implementation of the technology. Small wind turbines have unique challenges due to the low Reynolds number (Re) flow the blades experience, which introduces a potential for tonal noise. Computational aeroacoustics can be applied during the design stage of the turbine blades to improve acoustic performance. This work aims to validate a fully analytical aeroacoustic model by analyzing a SD 7037 blade segment at static angles of attack, with comparison to experimental flow and acoustic data. The Ffowcs-Williams and Hawking (FW-H) acoustic model is used in combination with Large Eddy Simulation (LES). The following simulation parameters were examined: mesh quality, mesh density, inlet turbulence and spanwise boundary condition. These parameters change the boundary layer (BL) transition process and the formation of the laminar separation bubble on the suction side of the blade segment, both of which impact the aeroacoustic noise prediction. It was found that improvement in mesh quality and density on the surface of the blade segment resulted in improved BL simulation and tonal noise prediction. Alteration of the inlet turbulence and spanwise boundary condition did not have as large of an effect.

1. Introduction
Small wind turbines (SWTs) play an important role in the transition to renewable energy by providing power in remote areas not connected to the power grid, which are often dependent on diesel generators, and offsetting fossil fuel dominated grid usage of a household. However, the aerodynamic design of SWTs presents a specific set of problems because they operate under low Reynolds number (Re) flow. One of the issues that requires additional investigation is the noise generated by the trailing edge (TE) of the blades under the low Re flow, which is capable of producing tonal noise. As noise pollution becomes more of a concern, aeroacoustic design is a necessary step within the design process. Increasing computational power and validation of computational fluid dynamics (CFD) software opens the possibility of computational aeroacoustic (CAA) analysis of small wind turbine blades. CAA simulations require precise transient simulations to accurately predict the acoustic behaviour of a blade, but the methods are not yet fully validated for the complex conditions that can arise during low Re flow. The objective of this work is to determine the ability of CAA to predict the tonal noise produced by low Re flow over a wind turbine blade, and to determine the viability of CAA as an aeroacoustic design tool. This is achieved through CAA analysis of an airfoil designed for small wind turbines, SD 7037, with experimental validation of the flow and acoustics provided by previous researchers at the Wind Energy Group (WEG) at the University of Waterloo [1][2].
2. Background

2.1. Small Wind Turbine Noise

Small wind turbines are defined as having a swept area of less than 200m$^2$, and can be further broken down into micro turbines with around 1.5m blades (< 0.5kW), mid-range at 2.5m (0.5 to 5kW) and mini at 5m up to 8m (20 to 50kW) [3]. Sample Re ranges for the micro and mid-range turbines are $8 \times 10^3$ to $2 \times 10^5$ and $1.5 \times 10^4$ to $3.5 \times 10^5$, respectively. An important note is that these turbines pass through a wide range of low Re between the cut-in and rated wind speeds, which can cause the blades to produce different levels of aeroacoustic noise. Wind turbines of all sizes also emit noise from the nacelle, which is due to mechanical noise from the generator and other components housed inside. This type of noise is not discussed in this paper.

Wind turbines produce aeroacoustic noise through airfoil self-noise, which is a result of the laminar and turbulent boundary layers passing over the TE of the blade, also known as trailing edge noise [4]. Small and large wind turbines produce broadband noise (“swishing sound”) when the flow past the TE of the blade is turbulent, this generally occurs when the Re is greater than $10^6$ [5] and is caused by the “turbulent boundary layer - trailing edge” (TBL-TE) mechanism [6]. Small wind turbines are specifically at risk for tonal noise because of the lower Re flow, which allows the “laminar boundary layer - vortex shedding” (LBL-VS) mechanism to create a persistent “whistling noise”. The LBL-VS mechanism can generally be found on airfoils operating with Re below $10^6$, and is caused by a combination of vortex shedding from the TE and flow instabilities generated by BL transition on the suction side of the blade [7]. These mechanisms are discussed in detail in the following section.

2.2. Low Reynolds Number Flow

The main challenge of analyzing low Re flow over an airfoil is predicting the natural BL transition process on the suction side of the airfoil, which often includes the formation of a laminar separation bubble (LSB). Small wind turbine blades often have a large portion of the blade covered by laminar or transitional flow [8] and are also susceptible to an LSB when the Re is less than $5 \times 10^5$ [3]. Since micro and mid-range turbines are likely to be fixed pitch systems, they have high AOAs at the cut in wind speed and the lowest AOAs occur at the rated wind speed [3]. While the natural transition process is heavily dependent on the blade geometry and the Re, a lower effective AOA will result in a later transition, making laminar and BL transition behaviour at the TE more common when the turbine is generating its maximum power. In terms of tonal acoustic behaviour, the LBL-VS mechanism only occurs when the flow at the TE is laminar or in the transition region, which is why tonal noise is a common issue in SWT blade design. For further analysis of the tonal noise generation, a closer look at the BL transition process and the formation of an LSB is necessary.

Figure 1 illustrates the flow dynamics of a blade segment with an LSB near the TE, and also shows the key mechanisms that create the LBL-VS tonal noise. The flow in the diagram is from left to right, with the suction side (top) of the airfoil experiencing the LSB and BL transition. First, the flow is laminar (location 1 in the diagram) until it reaches the point where the increasing pressure gradient makes the BL more susceptible to instabilities. This location is marked by the indifference Re (Re$_{ind}$), and begins the transition region of the BL (location 2 in the diagram)[9].

Within the transition region, three distinct behaviours happen in succession [9]. First, are the Tollmien-Schlicting (T-S) waves (location A in the diagram), which are small amplitude velocity fluctuations. The T-S waves experience exponential growth and roll up into Λ-structure vortices across the span of the blade segment (location B in the diagram). This behaviour, coupled with the adverse pressure gradient caused by the airfoil curvature, causes the laminar BL to separate and form the beginning of the LSB. Finally, Kelvin-Helmholtz (K-H) instabilities (location C in the diagram) cause mixing between the separated shear layers, reattaching the
LSB [10]. The BL behaviour has been uniform across the span until the introduction of the K-H instabilities, which cause spanwise differences. Once the LSB is reattached, the instabilities continue to develop, causing a fully turbulent BL (location 3 on the diagram). In the cases where tonal noise is an issue, the reattached BL needs to be in the late stages of the transition for the LBL-VS mechanism to occur.

![Figure 1. Boundary layer transition over a blade segment (blue), including LSB details (red) and LBL-TE noise mechanisms (green). Modified from [9] and [10].](image)

Figure 1 also describes the two separate mechanisms on the low Re airfoil that can create tonal aeroacoustic noise. The first mechanism is LBL-VS, as described by Brooks et al. [6]. A Kármán vortex street is formed when the flow from the pressure side (bottom) and suction side of the airfoil meet at the TE. This vortex shedding occurs at a given frequency and causes strong surface pressure fluctuations on the surface of the TE of the airfoil, which is then radiated outwards as noise. Since the LBL and transition region has consistent (or mostly consistent) spanwise behaviour, the alternating pressure occurs simultaneously across the entire span, generating the tonal noise. The second source of tonal noise is caused by the flow fluctuations of the K-H instabilities as they pass the TE. While the T-S waves occur at a low frequency and amplitude, as they develop into the K-H instabilities, the frequency and amplitude increase [10]. If the LSB reattachment location and the end of the transition region are close to the TE, these fluctuations of velocity and pressure are still present as the flow passes the suction side of the TE. If the BL has not fully transitioned to turbulence, these K-H instabilities can create tonal noise at a different frequency than the vortex shedding noise [11]. In order to accurately predict the aeroacoustic noise, all of these complex behaviours must be correctly simulated, which is why low Re CAA analysis currently requires a high computational cost.

2.3. Computational Fluid Dynamics

These types of low Re LSB simulations are not as frequently validated, especially on the type of cambered airfoils used on small wind turbines. This is largely due to the complexity as well as the fact that more focus tends to be put into higher Re cases due to aviation and large scale wind turbines. In general, the main challenge with CFD simulations of low Re flows is the balance between simulation accuracy and computational cost. This affects the simulation in two main ways: the flow model used, and the mesh size and density. Aeroacoustic prediction requires accurate transient data, including the small amplitude velocity fluctuations needed for LSB simulation and the pressure fluctuations on the TE that generate the tonal noise. The standard model for this level of accuracy is large eddy simulation (LES), which is the model used in this
paper. Another option not yet explored in this work is the unsteady Reynolds averaged Navier-Stokes (URANS) model, which is less computationally expensive but less accurate. Simulations conducted by Yuan et al. [10] on a cambered low Re airfoil with an LSB found that URANS was unable to simulate the natural transition without additional models, and that LES better captured the vortical structures in the transition process. In terms of the mesh size and density, a sufficient mesh density is required to achieve good element quality near the surface of the airfoil, reducing the amount of highly skewed cells. This quality is important for the prediction of the small scale BL behaviours present for low Re flow, which in turn impact the acoustic prediction. Computational power also limits the size of the simulation domain, which needs to have the inlet and outlet sufficiently offset from the airfoil surface to remove pressure effects from the boundaries. This also places a limit on the spanwise size of the domain, which needs to be wide enough to allow spanwise patterns to properly develop in the BL transition process.

For the LES model, a known issue is the accurate replication of turbulence conditions, since the model can be quite dissipative. This can create issues in the LSB simulation since the bubble length decreases with increasing turbulence, and if the turbulence is too low, the flow may never develop sufficient K-H instabilities to cause reattachment. This is shown in Figure 5(a), where the experimental pressure coefficient, $C_p$, is compared against those predicted by XFOIL [12] at varying Ncrit values (high Ncrit = low turbulence) [1]. For Ncrit of 2, 4, and 7 (high turbulence), there is a sharp drop in $C_p$ between $x/c = 0.8$ and the TE, indicating LSB reattachment, whereas an Ncrit $> 9$ (low turbulence) does not predict reattachment. While XFOIL can have some discrepancies in the exact separation and reattachment location, it illustrates the importance of correct inlet turbulence modeling for LSB and tonal noise prediction in low Re flows.

2.4. Computational Aeroacoustics

CAA is a fully analytical method of predicting the noise generated by an object in a flow. Fully analytical CAA methods are based on Lighthill’s analogy, which rearranged the Navier Stokes equations into the form of a wave equation [4]. Methods have been derived to solve this analogy directly, which is needed for complex acoustic behaviour that comes from compressibility effects and shock waves. However, for airfoil self-noise on small wind turbines, the source of the sound is considered to be “compact” which means that compressibility in the flow around the airfoil can be neglected in the acoustic analysis. Acoustically compact sources can be solved using the most simplified CAA model, which is Ffowcs-Williams and Hawkings (FW-H). This model uses transient pressure fluctuations on the surface of an object and propagates those to a chosen receiver location in the far-field [13]. For airfoil self-noise, the surface of the airfoil is selected as the source, and the receiver location is selected as the location of the observer/microphone relative to the airfoil.

The inputs for the FW-H model emphasize the importance of the transient data from the CFD simulation, since the only input for the acoustic model is the pressure behaviour on the surface of the airfoil. Also, for the FW-H analysis, the calculations are performed as a post-processing function on auto-save files of the surface pressure data history. For this reason, the bulk of the computation time is spent purely on the LES simulation of the low Re flow behaviour.

3. Methodology

3.1. Experimental Database

The experimental data for validation examined the flow and acoustic behaviours present on the SD 7037 airfoil which was specifically designed for low Re wind turbines [14]. Experiments consisted of a blade segment with a constant chord of 25.4 mm and span of 152.4 mm in a closed loop wind tunnel (152.4 mm square cross-section), and the simulated domains were set up to match these geometry and flow conditions. Particle Image Velocimetry (PIV) of the airfoil was conducted by Ghorbanishohrat [1], specifically focusing on the boundary layer transition process,
which serves as the validation for the simulated flow parameters. An aeroacoustic study was conducted by Tam [2] by placing a microphone in the lower wall of the tunnel directly below the airfoil. Both studies collected data at a Re of $4.3 \times 10^4$ at static AOAs and it was found that tonal noise occurs at low AOAs ($0^\circ$ to $5^\circ$).

### 3.2. Numerical Setup

The CFD model was set as LES with a dynamic Smagorinsky-Lilly subgrid scale model for an incompressible simulation. The flow was initialized with a RANS model ($k-\varepsilon$) to reduce LES convergence time. For the CAA model, FW-H was used with the surface of the airfoil selected as the source of the noise and the experimental microphone location was selected as the receiver. LES and FW-H models are built-in to ANSYS Fluent, therefore all simulations were performed using this software [15]. To decrease computing time, simulations were run using the high performance computer cluster Graham, which is a part of the SHARCNET network and the greater Compute Canada network [16][17]. Simulations were run for $0.081 s$ at $\Delta t = 1 \times 10^{-6} s$ to collect 2 mean flow residence times (MFRT) of data. The domain is a C-mesh with 20 chord boundary offsets (0.51m), and 7 million elements for the first version of the mesh “Case 1” (shown in Figure 2) and 1.4 million elements for the new version of the mesh “Case 2” (shown in Figure 3). The new mesh is modified to better capture tonal noise, by focusing extra elements at the leading edge (LE) and TE and including a cell expansion region downwind from the TE to improve mesh quality in the BL and wake. A third mesh was also created using the same element layout as Case 2, but with a total of 2.7 million elements, which is labelled as “Case 3”.

**Figure 2.** Case 1 C-Mesh with close up view of mesh quality around airfoil. **Figure 3.** Case 2 C-Mesh with close up view of mesh quality around airfoil.

### 3.3. Simulation Cases

In order to determine the most effective simulation setup for tone prediction, several simulations were run using the Case 1, 2 and 3 meshes. All simulations were conducted at $0^\circ$ AOA. These simulations examine key parameters that affect the accuracy of the BL prediction which in turn affect the predicted aeroacoustic noise. These factors were previously discussed in Section 2.3, and the corresponding simulation settings are summarized in Table 1. Case 2 serves as the base for all comparisons to show the differences in acoustic prediction caused by changes in mesh surface quality, mesh density, inlet turbulence and the spanwise boundary condition (BC).

As mentioned in the previous section, three versions of the mesh were used which have varying levels of mesh quality and density. The quality of the first layer of elements on the surface of
the airfoil were compared using the “orthogonal quality” metric in Fluent, which ranges from 0 (poor quality) to 1 (perfectly orthogonal). Case 1 was known to have low quality based on the skew of the elements near the LE (Figure 2) and has a minimum orthogonal quality of 0.5 and average of 0.91 on the suction side. Case 2 and 3 meshes were designed specifically to improve surface mesh quality, and has minimum orthogonal quality values of 0.73 and 0.75, respectively and averages of 0.95. The impact of mesh quality on the acoustic results is determined using the comparison of Case 1 with Case 2. Mesh density is compared using Case 3 and Case 2, which have the same quality, but Case 3 has 50% more elements.

Table 1. Simulation settings for Case 1, 2 and 3 meshes. - Bolded - entries indicate key parameter, with Case 2 as the base for all comparisons.

| Name    | Surface Quality | Mesh Density | Inlet Turbulence | Spanwise BC |
|---------|-----------------|--------------|------------------|-------------|
| Case 1  | - Low -         | High         | Yes              | Symmetry    |
| - Case 2 - |                | High         | Low              | Symmetry    |
| Case 2a | High            | Low          | - No -           | Symmetry    |
| Case 2b | High            | Low          | Yes              | - Periodic -|
| Case 3  | High            | - Medium -   | Yes              | Symmetry    |

All cases, except for Case 2a, have the same inlet turbulence model settings, and use the spectral synthesizer model in Fluent. The model inputs are turbulent intensity (I) and the length scale of the turbulence (l), which are set at $I = 1.23\%$ and $l = 6.7 \times 10^{-4}m$ to match the turbulence of the wind tunnel used to collect the experimental data [2]. Case 2 is compared with Case 2a, which has the turbulence model turned off to determine the effect of turbulence on the aeroacoustic noise prediction at low Re.

The final setting examined in this paper is the effect of the spanwise BC, which impacts the formation of spanwise patterns across the blade segment. The spanwise behaviour is important for the aeroacoustic prediction since it can change the BL transition process and affect the LSB reattachment dynamics. Spanwise differences begin to appear in the transition region when the separated shear layer experiences the K-H instabilities. The patterns within these instabilities can be amplified or dampened based on the type of spanwise BC, so the symmetry and periodic BCs are tested to determine their impact. The periodic boundary condition allows patterns to develop that have a wavelength longer than the total span of the simulated blade segment, where a symmetry boundary condition will damp out these patterns. It also is possible for the periodic BC to falsely impose patterns across the span, which could negatively impact the BL and aeroacoustic prediction. Case 2 and Case 2b compare the effects of the symmetry and periodic boundary conditions.

4. Results
All five simulation cases were able to successfully predict the average flow parameters when compared with the experimental PIV data at 1° AOA [1]. The averaged parameters include the average velocity fields, lift coefficient, drag coefficient and surface $C_p$. The $C_p$ comparison is shown in Figure 5(a), with Case 2 representing all Case 2 variations since they produced identical $C_p$ data. Given the small scale of the plot, all cases produced very similar $C_p$ data, and the smaller variations that occur near the TE will be discussed further in the following sections.

Differences between the simulations appear when examining the transient data since this reveals changes in the BL transition process, which in turn causes changes in the aeroacoustic noise prediction. A comparison of the Q-criterion is shown in Figure 4, where an iso-surface is generated at $1 \times 10^7 1/s^2$. Q-Criterion is frequently used in CFD simulations to identify
turbulent flow structures, and shows the instantaneous structures at a given moment in time in the simulation. In general, looking from the top left of the blade segment to the bottom right, the transition behaviours described in Figure 1 can be seen. At approximately 20% of the chord, T-S waves begin to appear, followed by the Λ-structures and the separation of the LSB at 65% of the chord (where the iso-surface breaks apart). This BL and LSB behaviour is consistent with surface oil flow visualization conducted at the same Re [1]. Closer to the TE, spanwise differences begin to appear, indicating K-H instabilities forming in the separated flow above the LSB. The TE is where the largest differences can be seen between the cases, with Case 1 and 3 being similar and Case 2, 2a and 2b showing similar behaviour. These differences will be discussed in the following sections, including the impact they have on the aeroacoustic prediction.

Figure 4. Q-Criterion surface at $1 \times 10^7 (1/s^2)$ for incompressible simulations of (a) Case 1 (b) Case 2 (c) Case 2a (d) Case 2b and (e) Case 3.

4.1. Mesh Quality
The effect of mesh quality on the surface of the blade segment is shown through the comparison of Case 1 and Case 2. The Q-criterion behaviour of Case 1 (Figure 4(a)) shows greater spanwise differences at the TE than Case 2 (Figure 4(b)). This indicates that the boundary layer in Case 1 has transitioned further towards turbulence than Case 2. Also, Case 1 does not show any T-S wave behaviour, which is attributed to the poor orthogonal quality at the LE. This must be disrupting the ability of the BL to develop the small scale velocity fluctuations of the T-S waves.

The acoustic results for the cases are shown in Figure 5(b) and 5(c), where both cases are able to predict a tone of approximately 90dB. Case 1 produces a tone that is exactly aligned with the 4.1kHz tone found in the experimental results. It also predicts the correct sound pressure level (SPL) for the broadband noise. However, the simulation was unable to predict the tone at 3.4kHz, which is not an important tone at 0° AOA but is the dominant tone at 1° AOA [2]. This inability to predict one of the two dominant tones was a main motivation for this parametric study for low Re tonal noise prediction.

Case 2 predicts a tone at 4.7kHz and has a lower broadband SPL prediction than was found experimentally. While this may seem like a poor prediction, the results of Case 2 are more reliable since it fully predicts all stages of the BL transition process. Predicting the low Re BL behaviour is crucial to eventually predicting the correct aeroacoustic tone. This is the reason that Case 2 is the base case for comparison with the simulation parameter changes in the other cases.

4.2. Mesh Density
Mesh density is increased between Case 2 and 3 while keeping the same mesh element distributions, as is done in a grid independence study. The Q-criterion data for Case 3 (Figure 4(e)) shows BL transition behaviour between what is seen in Case 1 and 2. Case 3 has small T-S
Figure 5. (a) Experimental pressure coefficient ($C_p$) at $1^\circ$ AOA [1] and simulated $C_p$ at $0^\circ$ AOA compared with $0^\circ$ AOA XFOIL calculations at Ncrit range of 2 to 9. (b) to (f) Sound pressure level (SPL) acoustic spectra for (b) Case 1 (c) Case 2 (d) Case 2a (e) Case 2b and (f) Case 3, compared with experimental data [2].
waves (seen very close to the blade segment surface) when compared to Case 2, and has similar TE spanwise patterns to Case 1. The resulting acoustic prediction in Figure 5(f) has the correct broadband SPL magnitude and predicts a tone at 2.5kHz with a second harmonic occurring at 5.1kHz. This comparison shows that an increased mesh density improves the accuracy of the broadband noise prediction, and also that a finer simulation mesh causes the tone frequency to change, in this case to a lower frequency. A full grid independence study would be able to determine the mesh density requirement for an accurate tone frequency prediction.

4.3. Inlet Turbulence
The effect of turbulence is gauged by the impact of no inlet turbulence (Case 2a) when compared with Case 2. The Q-criterion iso-surface for Case 2a is shown in Figure 4(c) and has nearly identical behaviour to Case 2. The same can be said for the acoustic spectra in Figure 5(d), with the exception of the 7.5kHz tone, which disappears when there is no inlet turbulence. When inlet turbulence is activated, the overall flow fluctuations generate small pressure fluctuations over the entire surface of the blade segment, which can account for the change in acoustic behaviour. The difference in inlet turbulence between Case 2 and 2a did not cause a drastic change in the LSB formation. However, if the turbulence was increased further, it is likely that there would be a greater impact as higher turbulence causes earlier reattachment of the LSB (Figure 5(a)).

4.4. Spanwise Boundary Condition
The final parameter tested is the use of the periodic boundary condition in Case 2b, which is compared to the symmetry boundary condition used in Case 2. As with Case 2a, the Q-criterion shown for Case 2b in Figure 4(d) is quite similar to the behaviour in Case 2. The differences are the spanwise inconsistencies in the T-S waves as well as consistent spanwise behaviour at the TE of the blade segment. This suggests that the periodic BC is changing the formation of spanwise patterns, and is delaying the formation of the K-H instabilities required for LSB reattachment.

The acoustic results for Case 2b are shown in Figure 5(e), and show the prediction of secondary tones around the main 4.7kHz tone. This is an indication that the periodic BC is causing additional patterns to form in the spanwise direction that are not found when using a symmetry boundary condition. For this airfoil profile and Re, no secondary tones were experimentally measured at static AOAs, meaning that the periodic BC is falsely imposing patterns that negatively impact the aeroacoustic prediction. However, this does not mean all geometries would have better results with symmetry as the spanwise BC.

5. Conclusions
The five cases presented in this paper highlight the challenges of predicting aeroacoustic noise for small wind turbine blades. The low Re flow experienced by the blades adds extra complexities to the CFD simulation, which can drastically impact the accuracy of the CAA prediction. The transient behaviour of the BL as it transitions from laminar to turbulent flow contains a number of sensitive flow structures that when combined with the curvature of the airfoil profile, cause a LSB to form. Proper simulation of the T-S waves, A-structures, K-H instabilities and the LSB is required to have the correct flow behaviour at the TE of the blade, which is where the aeroacoustic noise is generated. All simulation cases presented in this paper had the same averaged flow results, but small differences in the transient flow behaviour resulted in different acoustic spectra predictions. The cases were set up to specifically examine the effect of key simulation settings on the flow behaviour and its associated acoustic prediction.

It was determined that the quality of the mesh at the surface of the airfoil is crucial for prediction of the small scale fluctuations within T-S waves. This is especially important for the LE region of the airfoil, where the improvement of cell orthogonal quality between Case 1
and 2 resulted in the largest difference in behaviour of any of the cases. Increasing the mesh density (Case 3) was found to shorten the transition region of the blade segment, leading to more spanwise variations at the TE and an overall improvement in the prediction of broadband noise SPL. Changes in mesh density also caused a shift of the tone frequency, which requires a full grid independence study to determine the final converged tone frequency. Removing the inlet turbulence did not result in a large change with the only difference being the disappearance of a secondary high frequency tone. Between Case 2 and 2a, the change in turbulence was not large enough to change the BL transition or LSB size, which is possible with stronger inlet turbulence. The final parameter was the spanwise boundary condition (Case 2 and 2b), which showed that the periodic boundary condition delayed the BL transition and created additional patterns that added secondary tones around the main tone. Since this behaviour was not present in the experimental acoustic measurements, it was concluded that the symmetry boundary condition was better suited for this blade segment geometry.

The testing of these simulation parameters on a low Re airfoil profile designed specifically for small wind turbines provides insight into the challenges facing small wind turbine aeroacoustic design. Large scale wind turbines, aircraft and other common sources of aeroacoustic noise do not produce tonal noise through the LBL-VS mechanism that occurs on low Re blades. Future work using the FW-H CAA model is planned to test the impact of other simulation parameters on the accurate prediction of the low Re tonal noise. By determining the sensitivity of the aeroacoustic noise prediction to different combinations of simulation parameters, an optimized CFD and CAA simulation is possible. Further validation of these methods will allow accurate trailing-edge noise prediction for small wind turbines to assist in noise mitigation for future turbine designs.

References
[1] Ghorbanishohrat F 2019 Study of a low Re airfoil considering laminar separation bubbles in static and pitching motion Ph.D. thesis University of Waterloo
[2] Tam N 2017 An Aeroacoustic Study of Airfoil Self-Noise for Wind Turbine Applications Master's thesis University of Waterloo
[3] Wood D 2011 Small Wind Turbines (London: Springer-Verlag)
[4] Wagner S, Bareiss R and Guidata G 1996 Wind Turbine Noise (Berlin: Springer-Verlag Berlin Heidelberg)
[5] Oerlemans S 2011 Primary Noise Sources Wind Turbine Noise (Essex: Multi-Science Publishing Co. Ltd.) chap 2, pp 13–45
[6] Brooks T F, Pope S and Marcolini M A 1989 Airfoil Self-Noise and Prediction Tech. rep. URL http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19890016302.pdf
[7] Nash E C, Lawson M V and McAlpine A 1999 Journal of Fluid Mechanics 382 27–61
[8] Lou W and Hourmouziadis J 2000 Journal of Turbomachinery 122 634–643
[9] Schlichting H and Gersten K 2017 Boundary-Layer Theory 9th ed (Springer-Verlag Berlin Heidelberg)
[10] Yuan W, Khalid M, Windte J, Scholz U and Radespiel R 2005 An Investigation of Low-Reynolds-Number Flows past Airfoils 23rd AIAA Applied Aerodynamics Conference AIAA-2005-4607
[11] Yarusevych S, Sullivan P E and Kawal J G 2009 Journal of Fluid Mechanics 632 245–271
[12] Youngren H and Drela M 2000 XFoil 6.99 Tech. rep. Massachusetts Institute of Technology (MIT)
[13] Ffowcs Williams J and Hawking D 1969 Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences 264 321–342
[14] Selig M S, Lyon C A, Giguere P, Ninhom C P and Guglielmo J 1996 Summary of low-speed airfoil data, Vol. 2 (VA: SoarTech Publications)
[15] ANSYSWorkbench 2016 ANSYS Fluent (SAS IP Inc.)
[16] SHARCNET 2018 SHARCNET, Ontario’s network of high-performance computer clusters URL www.sharcnet.ca
[17] ComputeCanada 2018 Compute Canada, Advanced computing services in support of research URL www.computecanada.ca