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Airfoil Trailing Edge Noise Reduction Using a Boundary-Layer Bump

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Summary

This paper presents a new idea of reducing airfoil trailing edge noise using a small bump in the turbulent boundary layer. First, we develop and validate a new computational approach to predict airfoil trailing edge noise using steady RANS CFD, an empirical wall pressure spectrum model, and Howe's diffraction theory. This numerical approach enables fast and accurate predictions of trailing edge noise, which is used to study the noise reduction from the bump for various airfoil geometries and flow conditions at high Reynolds numbers. Three types of bumps, the suction-side bump, pressure-side bump, and both-side bumps, are studied. The results show that all types of bumps are able to reduce far-field noise up to 10 dB compared to clean airfoils, but their impacts are different in terms of the effective frequency range. Also, bumps with four different heights are compared with each other to investigate the effect of the height of bumps on noise reduction. It is demonstrated that a bump causes velocity deficit within the boundary layer near the wall. This velocity deficit results in reduced turbulence kinetic energy near the wall, which is responsible for trailing edge noise reduction. Overall, this paper demonstrates the potential of a boundary-layer bump in trailing edge noise reduction and sheds light on the physical mechanism of noise reduction with boundary-layer bumps.

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1. Introduction

Trailing edge noise is produced when turbulent flows within a boundary layer pass a sharp trailing edge. This noise is prominent in many applications, such as wind turbines [1], marine rotors [2], and high-lift devices [3].

In order to control trailing edge noise, various noise reduction techniques have been investigated, which can be divided into two categories: active noise control and passive noise control. The idea of the active noise control is to attenuate noise through small localized momentum input. Examples are trailing edge suction and blowing. Arnold *et al.* [4] designed a suction system for an industrial full-size wind turbine and found a total trailing edge noise reduction of 3.6 dB with a net enhancement of total rotor power of 4.75%. Additionally, Gerhard *et al.* [5] investigated trailing edge blowing for airfoil trailing edge noise reduction. It was found that a well-designed blowing jet on the airfoil suction side can significantly reduce the turbulence intensity and the surface pressure fluctuations near the trailing edge. As a consequence, trailing edge noise associated with a hump at 500 Hz could be reduced by 3 dB. Though the active noise control is adaptive to different flow conditions, it suffers from high energy expenditure.

Passive noise control mainly refers to add-on devices near a trailing edge, including trailing edge serrations [6], trailing edge brushes [7], and poroelastic trailing edges [8]. All those methods modify the physical trailing edge geometry such that its scattering efficiency is reduced, ultimately mitigating trailing edge noise.

Recently, a bio-inspired concept “finlet” was found to be a promising trailing edge noise reduction method [9, 10, 11, 12]. Clark *et al.* [10] conducted comprehensive wind tunnel experiments for various configurations of finlets, and up to 10 dB trailing edge noise reduction was observed for airfoils with finlets. In addition, Afshari *et al.* [11, 12] found finlets can significantly reduce the surface pressure fluctuations near the trailing edge by around 8 dB, lessen the spanwise coherence, and reduce the convection velocity of the turbulent structures. The above work demonstrates the potential of finlets in terms of trailing edge noise reduction. Instead of experiments, Bodling *et al.* [13, 14] conducted numerical simulations of airfoils with finlets using Large Eddy Simulation (LES). They showed that finlets can reduce trailing edge noise by 10 dB through changing the turbulence kinetic energy profile. However, their study was limited to low Reynolds numbers due to the expensive computation cost. These recent studies on the finlet have inspired us to perform this research.

Although the finlets demonstrated noise reduction at high frequencies, low-frequency noise was increased due

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to the small spacing between finlets [10, 11]. Low-frequency noise is important for far-field sound propagation such as wind turbine noise, where the noise propagates in long distances with less atmospheric attenuation. Therefore, the application of finlets to wind turbine blades might be limited. In addition, Clark [15] found that the pressure-side finlet increases the wall pressure spectrum, which has an adverse impact on noise reduction.

In order to overcome issues in the finlet and fully exploit its benefits, a new trailing edge noise reduction method is proposed in the current paper by using a 2-D bump within the boundary layer upstream of the trailing edge. The primary role of the bump is to change the turbulence characteristics before turbulent eddies pass by a sharp trailing edge. It is worthwhile to emphasize that the 2-D bump is unique and different from the 3-D finlet, since it does not have spacing in the spanwise direction or a channel flow between adjacent finlet walls. To the authors' best knowledge, no one has investigated a 2-D boundary-layer bump in terms of trailing edge noise reduction.

The goal of this paper is threefold: 1) to propose and validate a new, efficient numerical approach to predict airfoil trailing edge noise; 2) to investigate effects of the 2-D boundary-layer bump on the turbulent wall pressure spectrum and trailing edge noise for various configurations; and 3) to better understand the physical mechanism of noise reduction with 2-D bumps. In the proposed numerical approach, the wall pressure spectrum near the trailing edge and far-field acoustics are obtained using RANS CFD solutions, an empirical wall pressure spectrum model, and Howe's diffraction theory. The fast turnaround time of RANS CFD and an empirical wall pressure spectrum model enables us to study various bump configurations at high Reynolds number to investigate its physical mechanism of trailing edge noise reduction.

2. Numerical Approach

A numerical approach using RANS CFD, an empirical wall pressure spectrum (WPS) model, and an analytical acoustic model will be given in this section. RANS CFD provides boundary layer parameters for the WPS model, and then the acoustic model can predict far-field noise based on pressure fluctuations obtained from the WPS model.

2.1. RANS CFD

OpenFOAM 5.0 is used to carry out simulations. Considering operating conditions of investigated cases, the flow is assumed to be steady, incompressible, and Newtonian. Therefore, simpleFoam, a solver in OpenFOAM, is selected. If the boundary layer is tripped at a fixed position, $k-\omega SST$ is used as a turbulence model, and the transition is enforced by setting turbulent viscosity and turbulent kinetic energy in the region upstream of that point to be zero. On the other hand, if it is a free transition, $k-\omega SSTLM$ (a correlation-based model using local variables proposed by Langtry and Menter [16, 17]) is used.

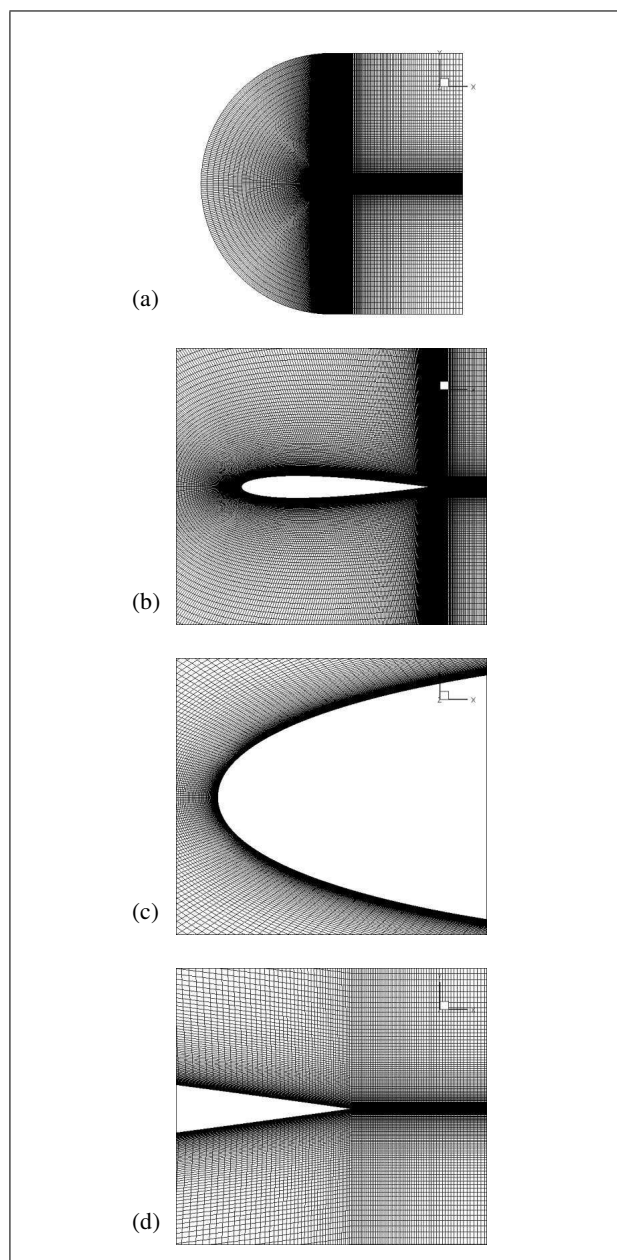


Figure 1. CFD mesh for a NACA0012 airfoil. (a) Mesh overview, (b) Mesh around the airfoil, (c) Mesh at the leading edge, (d) Mesh at the trailing edge.

Figure 1 shows a C-type mesh for a NACA0012 airfoil. The far-field is 15 chord length away from the airfoil as shown in Figure 1a. Note this airfoil geometry does not have a bump, and it is called a clean airfoil in this paper. Mesh around the airfoil can be seen in Figure 1b, and there are 460 points and 214 points in circumferential and normal directions of the airfoil, respectively. Points are clustered at the leading edge and the trailing edge in order to capture flow features. Close-up views at the leading edge and the trailing edge are given in Figures 1c and 1d. The total number of cells is around 200,000. In addition, y^+ is selected to be less than one. Once steady RANS CFD simulations are completed, the velocity profile, the pressure

coefficient, and the skin friction coefficient are obtained near the trailing edge.

2.2. Empirical Wall Pressure Spectrum Model

A recently developed empirical wall pressure spectrum by Lee [18] is used to predict the wall pressure spectrum near the trailing edge, which is written as

$$\frac{\Phi(\omega)U_e}{\tau^2\delta^*} = \frac{\max(a, (0.25\beta_c - 0.52)a)(\omega\delta^*/U_e)^2}{[4.76(\omega\delta^*/U_e)^{0.75} + d^*]^e + [8.8R_T^{-0.57}(\omega\delta^*/U_e)]^{h^*}}, \quad (1)$$

where ω is the angular frequency, $\beta_c = (\theta/\tau)(dp/dx)$, $a = 2.82\Delta^2(6.13\Delta^{-0.75} + d)^e[4.2(\Pi/\Delta) + 1]$, $\Delta = \delta/\delta^*$, $\Pi = 0.8(\beta_c + 0.5)^{3/4}$, $R_T = (\delta/U_e)/(v/u_\tau^2)$, $d = 4.76(1.4/\Delta)^{0.75}[0.375e - 1]$, and $e = 3.7 + 1.5\beta_c$. Parameter δ is the boundary layer thickness, δ^* is the boundary layer displacement thickness, θ is the boundary layer momentum thickness, dp/dx is the pressure gradient in the streamwise direction, v is the kinematic viscosity, U_e is the edge velocity, u_τ is the friction velocity, and τ is the maximum shear stress when the flow separates or the wall shear stress when the flow is attached. When β_c is negative, the absolute value is used. This indicates that Equation (1) is used for favorable pressure gradient flows as well, which was well validated for numerous cases [18]. Parameters h^* and d^* are defined as

$$h^* = \min(3, (0.139 + 3.1043\beta_c)) + 7 \quad (2)$$

and

$$\text{if } (\beta_c < 0.5), \text{ then } d^* = \max(1.0, 1.5d). \quad (3)$$

This wall pressure spectrum model was well validated for numerous flat plate and airfoil flows [19].

2.3. Aeroacoustics Model

Trailing edge noise is obtained using Howe's diffraction model [20] for low Mach number and an observer perpendicular to the trailing edge:

$$S(\omega) = \frac{1}{4} \left(\frac{L}{\pi^2 R^2} \right) \left(\frac{M_{ac}}{1 - M_{ac}} \right) \Lambda_3(\omega) \Phi(\omega), \quad (4)$$

where $S(\omega)$ is the acoustic spectrum, $M_{ac} = U_c/c_0$ is the convective Mach number, R is the observer distance, L is the spanwise length, and Λ_3 is the spanwise length scale. Parameter $\Phi(\omega)$ is the wall pressure spectrum calculated from Equation (1). The convective velocity is assumed to be

$$U_c = 0.7U_\infty, \quad (5)$$

and the spanwise length scale Λ_3 is from the Corcos' model [21], where the value of constant b is suggested by Kamruzzaman [22].

$$\Lambda_3 = \frac{U_c}{b\omega}, \quad b = 1.0. \quad (6)$$

Table I. Clean airfoil simulation matrix [25].

No.	airfoil	c, m	$U_\infty, m/s$	Re	AoA
1	NACA0012	0.4	53.0	1.5×10^6	0°
2	NACA0012	0.4	54.8	1.51×10^6	4°
3	NACA0012	0.4	53.0	1.5×10^6	6°
4	NACA0012	0.4	37.7	1.0×10^6	0°
5	DU96-W-180	0.6	60.0	1.13×10^6	4°

Cautions should be taken when using the Corcos' model [21] for 2-D bumps. It will be shown in the following sections that 2-D bumps are able to lift up turbulent eddies, resulting in a greater spanwise length scale. The authors believe the Corcos' model implicitly or partially captures the increase in the spanwise length scale when turbulent eddies are lifted up from the airfoil surface. Note that small-scale eddies close to the wall generate high-frequency wall pressure spectrum, while large-scale eddies away from the wall generates low-frequency wall pressure spectrum [23, 24]. For example, as the eddies move away from the wall, the eddy size is increased and the frequency corresponding to the eddy is reduced. As the frequency is reduced, according to Equation (6), the spanwise length scale and the power spectrum density is increased. However, the validity and accuracy of using the Corcos' model to the 2-D bump was not fully justified.

Sound pressure level (SPL) is computed as below

$$SPL(f) = 10 \log_{10} \left[\frac{2\pi S(\omega)df}{P_{ref}^2} \right], \quad (7)$$

where $P_{ref} = 2 \cdot 10^{-5}$ Pa and $df = 1$ Hz.

The combination of RANS CFD, an empirical WPS model, and an analytical acoustic model enables us to obtain numerous simulation results in a relatively short time. Therefore, various factors such as angle of attack (AOA), velocity, and Reynolds number can be considered with different bump configurations.

2.3.1. Validation

In this section, the proposed numerical approach is validated against experimental data for acoustics. Five cases in Benchmark Problems for Airframe Noise Computations (BANC) [25] are chosen as base cases; the flow conditions of these cases are summarized in Table I.

Figure 2 shows one-third octave band sound pressure level (SPL) for all five cases. The observer distance is 1 m perpendicular to the trailing edge. Error bars indicate ± 3 dB uncertainty in the experiments. It is shown that predicted far-field noise matches well with the measurement, though the model underpredicts noise in BANC case 1 and BANC case 4 at high frequencies. For all cases, the maximum noise level, the peak frequency, and the general shape of noise are well captured in the predictions.

This numerical approach will be applied to study 2-D bumps in the following sections. Unfortunately, there are neither experiments nor high-fidelity simulations available for the validation of the numerical approach for 2-D

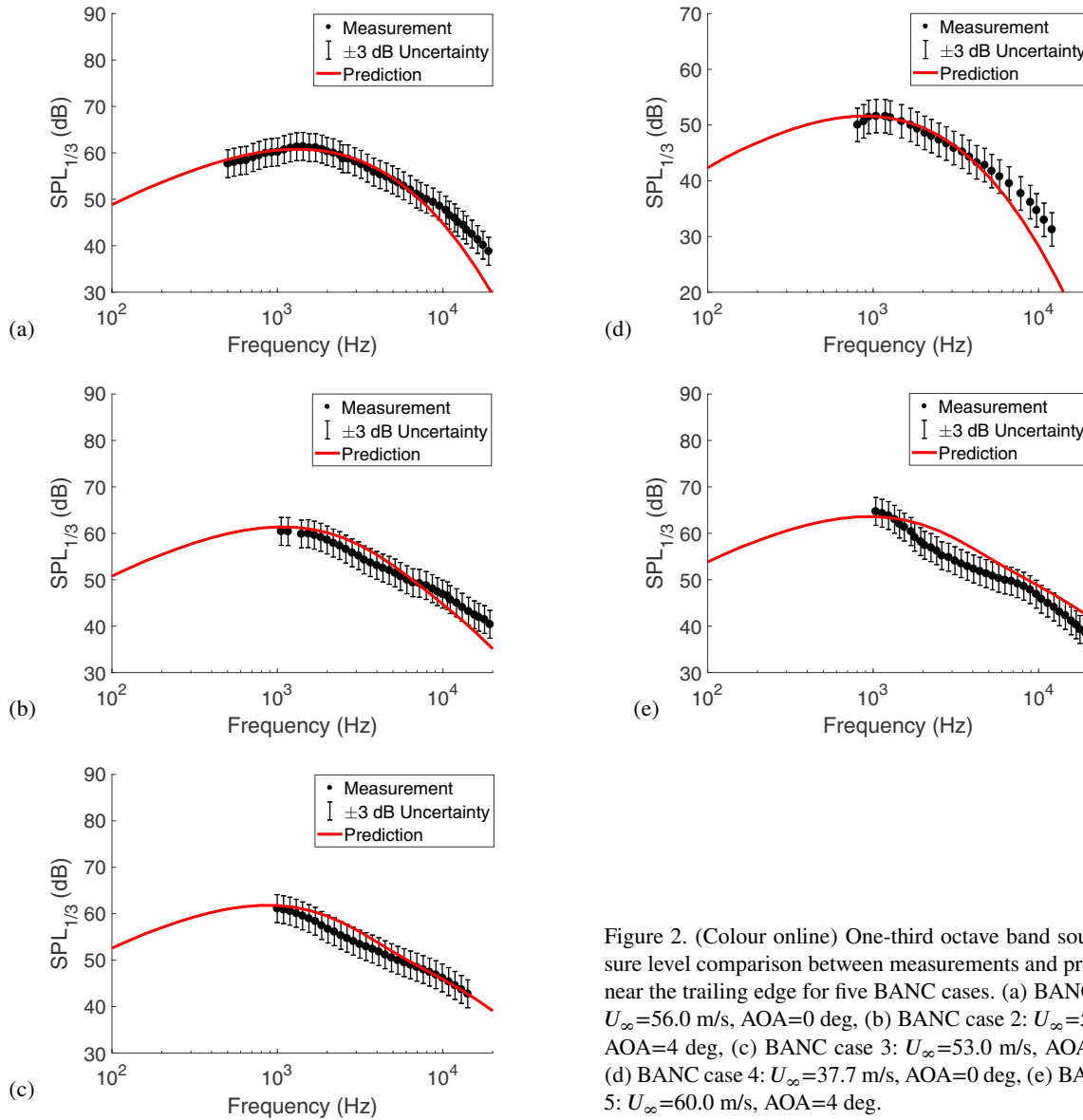


Figure 2. (Colour online) One-third octave band sound pressure level comparison between measurements and predictions near the trailing edge for five BANC cases. (a) BANC case 1: $U_{\infty}=56.0$ m/s, $AOA=0$ deg, (b) BANC case 2: $U_{\infty}=54.8$ m/s, $AOA=4$ deg, (c) BANC case 3: $U_{\infty}=53.0$ m/s, $AOA=6$ deg, (d) BANC case 4: $U_{\infty}=37.7$ m/s, $AOA=0$ deg, (e) BANC case 5: $U_{\infty}=60.0$ m/s, $AOA=4$ deg.

bumps. Given that the maximum height of 2-D bumps is less than 1% of the airfoil chord length and there is no flow separation, it is thought that the numerical approach is still valid for our study of 2-D bumps.

3. 2-D Bump Study

Since the proposed numerical approach was validated against experimental data for acoustics, it is used to assess noise reduction with 2-D boundary-layer bumps in this section.

3.1. Bump Parametric Model

Parametric models are necessary to generate various configurations for the bump. A bump's shape is assumed to follow a turbulent boundary layer profile. An approximation [26] of a turbulent boundary layer thickness is

$$\delta = \frac{0.37x}{Re_x^{1/5}} \quad (8)$$

where x is the downstream distance from the start of a boundary layer and $Re_x = (\rho V x) / \mu$.

With Re_x , Equation (8) can be written

$$\delta = \frac{0.37x^{4/5}v^{1/5}}{V^{1/5}} \quad (9)$$

Equation (9) can be generalized as

$$\delta = Cx^{\alpha} \quad (10)$$

where C and α are modifiable parameters in a computer-aided design (CAD) model.

There are five primary geometrical parameters to generate a bump, $xA = XA/c$, C , α , h/c , and $l_{\text{Horizontal}} = L_{\text{Horizontal}}/c$, where XA is the absolute horizontal coordinate of point A, xA is the relative horizontal coordinate of point A with respect to chord length c , h is the height of a bump, $L_{\text{Horizontal}}$ is the projection length of the bump

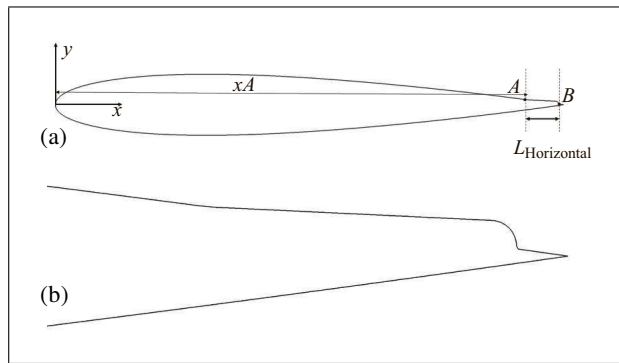


Figure 3. Schematic of a bump on an airfoil. (a) An airfoil with a trailing edge bump. (b) Bump zoom-in view.

Table II. Bump parameters summary.

Airfoil	NACA0012	DU96-W-180
xA	0.93	0.93
$l_{\text{Horizontal}}$	0.06	0.06
α	0.6	0.61
C	0.0012	0.002
h/c	0.0067	0.005

along the horizontal axis, and $l_{\text{Horizontal}}$ is the ratio between $L_{\text{Horizontal}}$ and c . Note that the profile of a bump grows as Equation (10) until the specified height is reached, and then the height is kept the same downstream. In addition, the rear part of a bump is rounded to avoid a sharp corner which might be a potential noise source.

A schematic of a bump is depicted in Figure 3a, and a zoom-in view of a trailing edge bump is also provided in Figure 3b. It should be noted that this bump ends upstream of the trailing edge in the 2-D configuration to ensure the change of turbulence characteristics in the boundary layer is in front of the trailing edge.

3.2. Acoustics Results

Effects of the bump on aeroacoustics can be studied by applying a bump to clean airfoils in the five BANC cases to investigate corresponding differences in far-field noise. It is important to test the bump for different airfoil geometries and flow conditions to verify the effectiveness of the bump for noise reduction in various cases. The five cases represent different airfoil geometries (NACA 0012 and DU96-W-180), different incoming velocities, and different angles of attack. Since our numerical approach is based on steady RANS CFD and an empirical WPS model, it is possible to simulate multiple cases in a relatively short time. Results provided in this section are able to give insights into physics of noise reduction with 2-D bumps.

Geometrical parameters of the bumps applied on NACA0012 and DU96-W-180 respectively are shown as below in Table II.

Note that these shapes do not necessarily represent the best geometries in terms of trailing edge noise reduction.

The best geometry can be found through the optimization, which is beyond the scope of this paper.

Figure 4 shows one-third octave band SPL for three different bump configurations in all BANC cases, where bumps are applied on the suction side only (SS bump), or on the pressure side only (PS bump), or on both sides (BS bumps). The observer distance is 1 m perpendicular to the trailing edge.

Several observations are summarized below:

1. All three configurations, i.e. the SS bump, the PS bump, and BS bumps, are able to reduce far-field noise up to 10 dB at certain frequencies.
2. At zero AOA, with a symmetrical airfoil (BANC case 1 and case 4), the PS bump and the SS bump tend to be equivalent in terms of the noise reduction as expected.
3. Impacts of the PS bump and the SS bump are different if the flow field is unsymmetrical, either because of the unsymmetrical airfoil (BANC case 5) or because of non-zero AOAs (BANC case 2, case 3, and case 5).
4. The SS bump reduces low and middle frequency noise in all cases, which is expected since the low and middle frequency noise is mainly generated from the suction side where the boundary layer thickness is thick.
5. The PS bump reduces high-frequency noise in non-zero AOA cases (BANC case 2, case 3, and case 5), which is expected since the pressure side, where the boundary layer thickness is thin, is the main contributor to high-frequency noise.
6. BS bumps can further reduce noise compared with the other two configurations. Specifically, it can further reduce noise at any frequency when AOA is zero; on the other hand, when AOA is non-zero, it increases low-frequency noise while effectively decreasing middle and high frequency noise compared with the SS and PS bumps.

It should be noted that these observations are different from the 3-D finlet study [15, 14]. For example, in the 3-D finlet study, noise reduction only occurs at high frequencies, and there is a noise increase at low frequencies. In addition, the pressure-side finlet increases the wall pressure spectrum at all frequencies. On the other hand, a 2-D PS bump reduces the wall pressure spectrum and noise at all frequencies. The detailed physical mechanism of all these observations will be explained later. Therefore, it is demonstrated that 2-D bumps perform better than 3-D finlets in terms of trailing edge noise reduction.

3.3. Wall Pressure Spectrum Sensitivity Study

As described in the numerical approach, the wall pressure spectrum at one point near the trailing edge is used to predict trailing edge noise. It is important to check the sensitivity of the noise predictions to this wall pressure spectrum measuring point to ensure the robustness of the predictions. The goal of this subsection is to investigate whether acoustic results are sensitive to the location of the measuring point. Sensitivity studies have been conducted for the SS bump, the PS bump, and the BS bumps for all

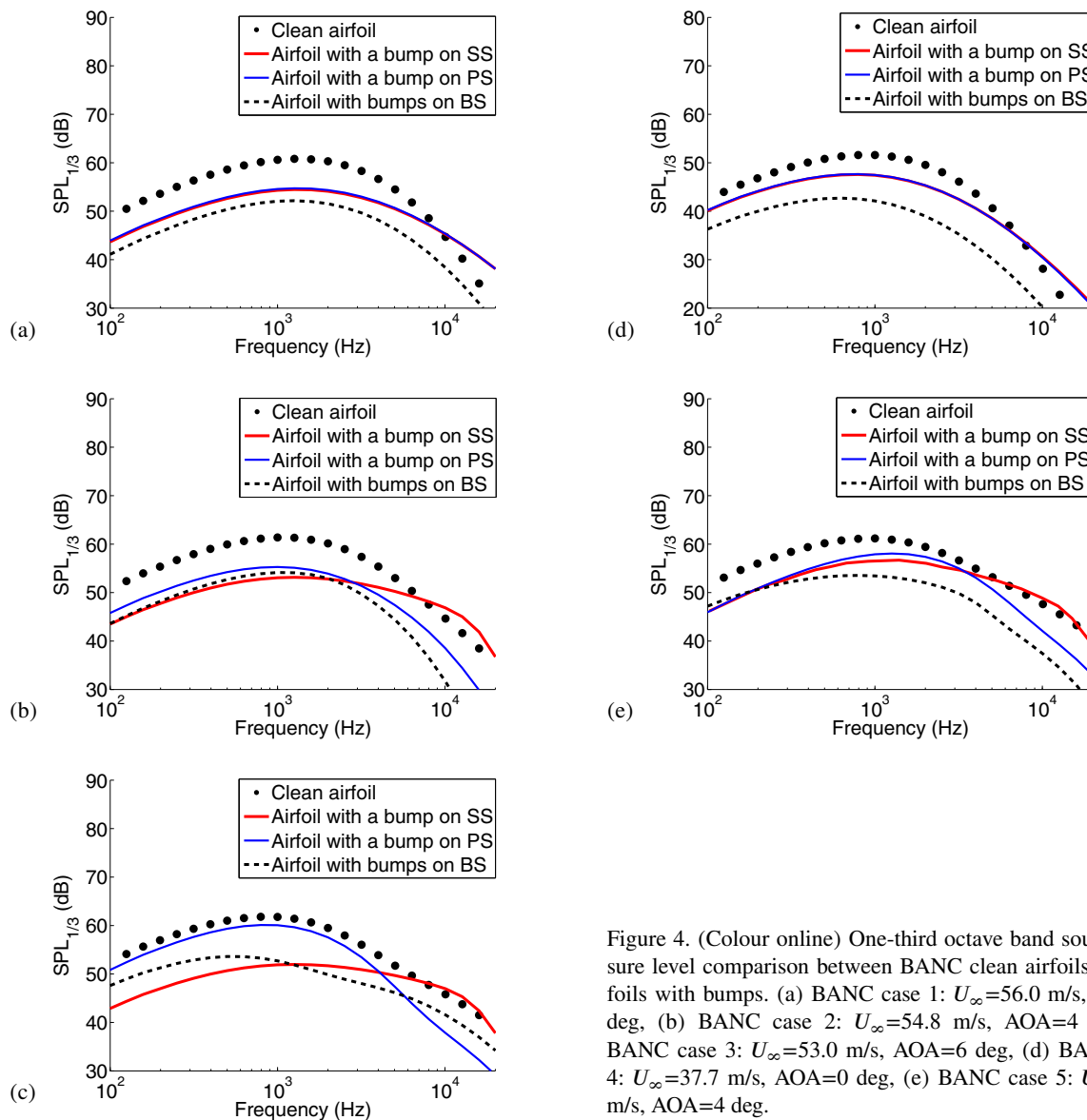


Figure 4. (Colour online) One-third octave band sound pressure level comparison between BANC clean airfoils and airfoils with bumps. (a) BANC case 1: $U_\infty=56.0$ m/s, AOA=0 deg, (b) BANC case 2: $U_\infty=54.8$ m/s, AOA=4 deg, (c) BANC case 3: $U_\infty=53.0$ m/s, AOA=6 deg, (d) BANC case 4: $U_\infty=37.7$ m/s, AOA=0 deg, (e) BANC case 5: $U_\infty=60.0$ m/s, AOA=4 deg.

BANC cases; however, for the sake of brevity, only results of BANC case 1 with SS and PS bumps will be shown.

Figure 5 shows sensitivity study results where the WPS measuring point varies from $x/c = 0.99$ to $x/c = 0.995$. It is shown that far-field noise is insensitive to the location of the WPS measuring point. This sensitivity study demonstrates the robustness of the predictive method for airfoil trailing edge noise with 2-D bumps.

A sensitivity study was performed for every case. Additionally, the range of the insensitive position is slightly different for each case. Table III shows the wall pressure spectrum measuring points that were used for all cases.

3.4. Bump Height Study

Height is one of the most important parameters for the bump design, and it is included in a bump CAD model. Before reaching the given value of height, the bump profile grows as Equation (10).

Table III. The WPS measuring point summary.

Case	SS bump	PS bump	BS bump
1	0.992	0.992	0.991
2	0.992	0.992	0.991
3	0.992	0.995	0.991
4	0.993	0.992	0.991
5	0.992	0.992	0.992

Four heights of bumps have been studied, specifically 0.001 m, 0.002 m, 0.003 m, and 0.004 m. All bumps in Figures 4 and 5 correspond to 0.002 m. Instead of absolute values, the heights of bumps are shown in terms of the boundary layer thickness of the corresponding clean airfoil in each BANC case in Figure 6. In this study, only the SS bump is considered.

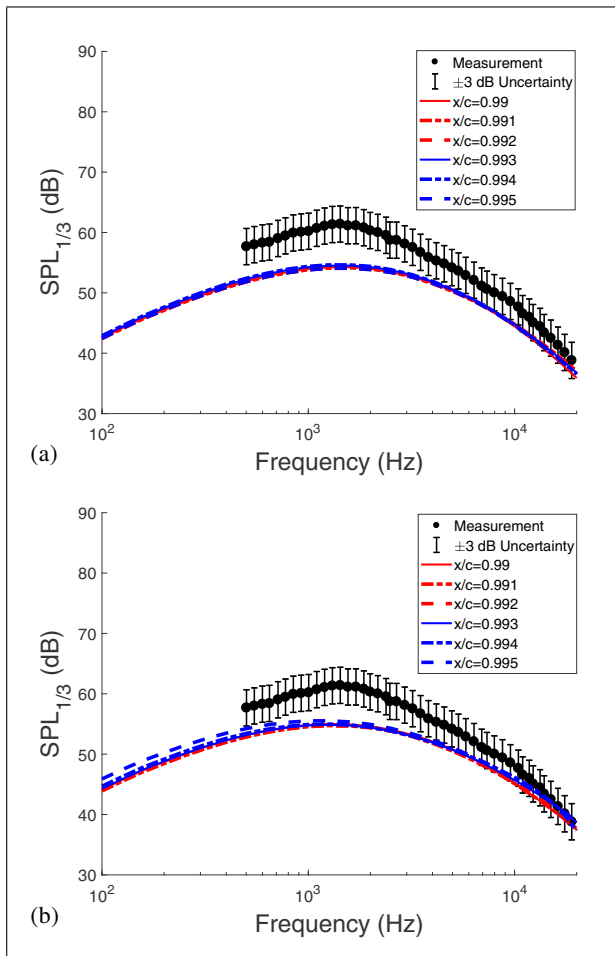


Figure 5. (Colour online) Wall pressure spectrum measuring point sensitivity study of two types of bumps for BANC case 1. (a) Suction-side bump, (b) Pressure-side bump.

From Figures 6a and 6d it is found that for a symmetrical flow field (symmetrical airfoil with zero AOA), the effectiveness of the bump with different heights are quite similar at low and middle frequencies, while a reduced-height bump is found to be better in reducing high-frequency noise. For BANC case 2, case 3, and case 5, a reduced-height bump performs better at high frequencies, whereas a high bump is more effective at low and middle frequencies. It is worthwhile to note that the observed behaviors are different from 3-D finlets in terms of the effect of height, where a taller finlet is capable of reducing middle and high frequency noise while increasing low-frequency noise compared to a reduced-height finlet [14]. It is also important to note that a very high bump might generate the bluntness vortex shedding noise.

Based on the above analyses, there is a trade-off between low-frequency noise and high-frequency noise reductions. An optimal height can be obtained for a specific application.

3.5. Aerodynamic Impacts

Aerodynamic impacts of the bump are studied in this section. The goal of applying the bump is to reduce trailing

Table IV. Lift-over-drag ratio comparison between the clean airfoil and three types of bumps.

No.	clean	SS	PS	BS	difference (%)
2	40.4	34.5	42.9	28.1	-14.4, +6.3, -30.5
3	52.9	47.4	47.0	40.2	-10.5, -11.2, -24.0
5	50.4	47.9	44.0	43.5	-4.9, -12.6, -13.6

Table V. Lift coefficient comparison between the clean airfoil and three types of bumps.

No.	clean	SS	PS	BS	difference (%)
1	3.1e-7	-0.063	0.063	-0.0088	NA, NA, NA
2	0.43	0.38	0.50	0.42	-11.2, +17.3, -1.6
3	0.64	0.60	0.64	0.62	-6.0, +0.63, -1.9
4	1.1e-6	-0.062	0.062	-0.0021	NA, NA, NA
5	0.69	0.66	0.70	0.70	-4.2, +2.2, +1.6

Table VI. Drag coefficient comparison between the clean airfoil and three types of bumps.

No.	clean	SS	PS	BS	difference (%)
1	0.0097	0.010	0.010	0.012	+7.3, +7.3, +19.7
2	0.011	0.011	0.013	0.015	+3.8, +10.4, +41.5
3	0.012	0.013	0.014	0.016	+5.0, +13.3, +29.2
4	0.0097	0.011	0.011	-0.012	+15.6, +15.6, +20.7
5	0.014	0.014	0.016	0.016	+0.74, +16.9, +17.6

edge noise while maintaining a similar aerodynamic performance of a clean airfoil. Comparisons of the lift-to-drag ratio, the lift coefficient, and the drag coefficient between airfoils with and without bumps are shown in Tables IV, V, and VI, respectively. In the table, 'clean' means the clean airfoil without a bump, 'SS' means a SS bump, 'PS' means a PS bump, and BS represents BS bumps. The 'difference' is the difference relative to the clean airfoil in percentage. Here, the height of bumps is 0.002 m. Note that in Table IV only results of non-zero AOA cases are given. Also, the percentage increase or decrease relative to clean airfoils is provided in the tables. There are a few Not Available (NA) in Table V, because the calculation would give infinity for those symmetrical cases.

The followings are observed from the tables:

1. Compared with clean airfoils, SS bumps reduce C_L by up to 11.2%, PS bumps increase C_L by up to 17.3%, while C_L of BS bumps lies between the values of the other two configurations.
2. All three types of bumps increase C_D compared with clean airfoils, and BS bumps have the largest C_D due to the largest exposed area.
3. In general, all bumps tend to reduce L/D by up to 30.5% compared with clean airfoils. It is interesting to find that the pressure-side bump increases L/D by 6% for case 2, which is due to a significant increase in the lift coefficient (17.3%). This increase in lift with the PS bump might be related to the change of the circulation,

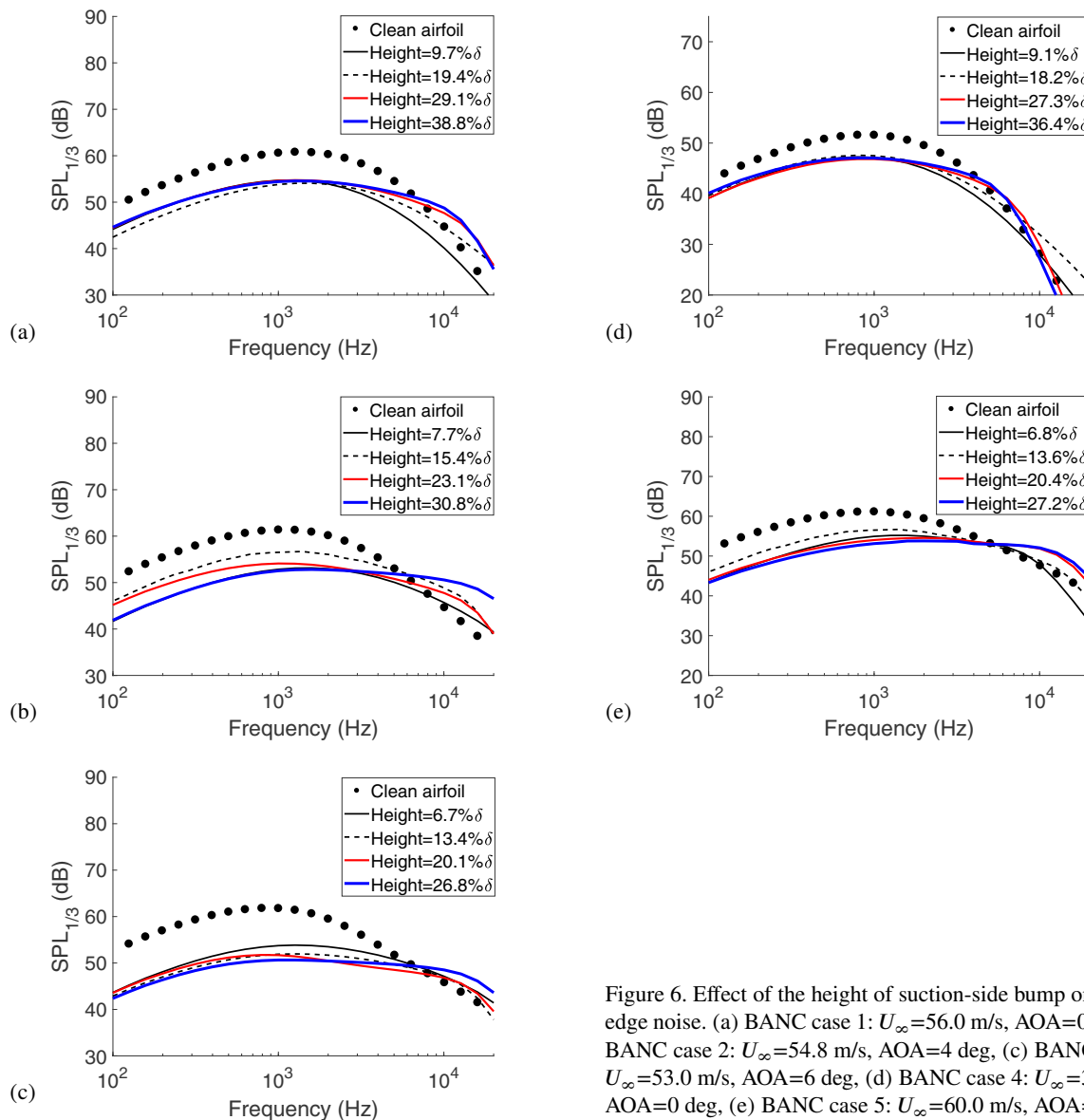


Figure 6. Effect of the height of suction-side bump on trailing edge noise. (a) BANC case 1: $U_\infty=56.0$ m/s, AOA=0 deg, (b) BANC case 2: $U_\infty=54.8$ m/s, AOA=4 deg, (c) BANC case 3: $U_\infty=53.0$ m/s, AOA=6 deg, (d) BANC case 4: $U_\infty=37.7$ m/s, AOA=0 deg, (e) BANC case 5: $U_\infty=60.0$ m/s, AOA=4 deg.

which is similar to the circulation control with a Gurney flap [27] placed on the pressure side.

4. SS bumps can give relatively lower C_D than the other two bumps, while PS bumps can give relatively higher C_L than the other two bumps.

Additionally, effects of 2-D bumps on $C_{L,max}$ are investigated and results are shown in Table VII. Flow conditions are consistent with BANC case 3 except that AOA is increased by 0.5 degrees consecutively to find $C_{L,max}$ and the corresponding stall angle. It is found that 2-D bumps have negligible effects on $C_{L,max}$, but the stall occurs 0.5 degrees earlier than the clean airfoil.

Obviously, there is a penalty on the aerodynamic efficiency by applying a bump. It is important to investigate whether a bump is able to reduce trailing edge noise while maintaining the same L/D of a clean airfoil. Figure 7 shows the trailing edge noise reduction capability of bumps for case 3 with AOA of 6 degrees. The L/D of

Table VII. $C_{L,max}$ and the stall angle comparisons between the clean airfoil and three types of bumps.

Case	$C_{L,max}$	stall angle (deg)
clean airfoil	1.488	17.5
SS bump	1.487	17.0
PS bump	1.493	17.0
BS bump	1.491	17.0

a bump airfoil is kept the same as a clean airfoil through increasing AOA by about 1 or 2 degrees. It is found the bump is still able to reduce trailing edge noise without losing aerodynamic efficiency or L/D. This result demonstrates the benefits of the bump for real-world applications. For example, low-noise wind turbine blades with the bump could have higher twist angles by only 1 or 2 degrees near the tip region compared to the baseline blades. This alter-

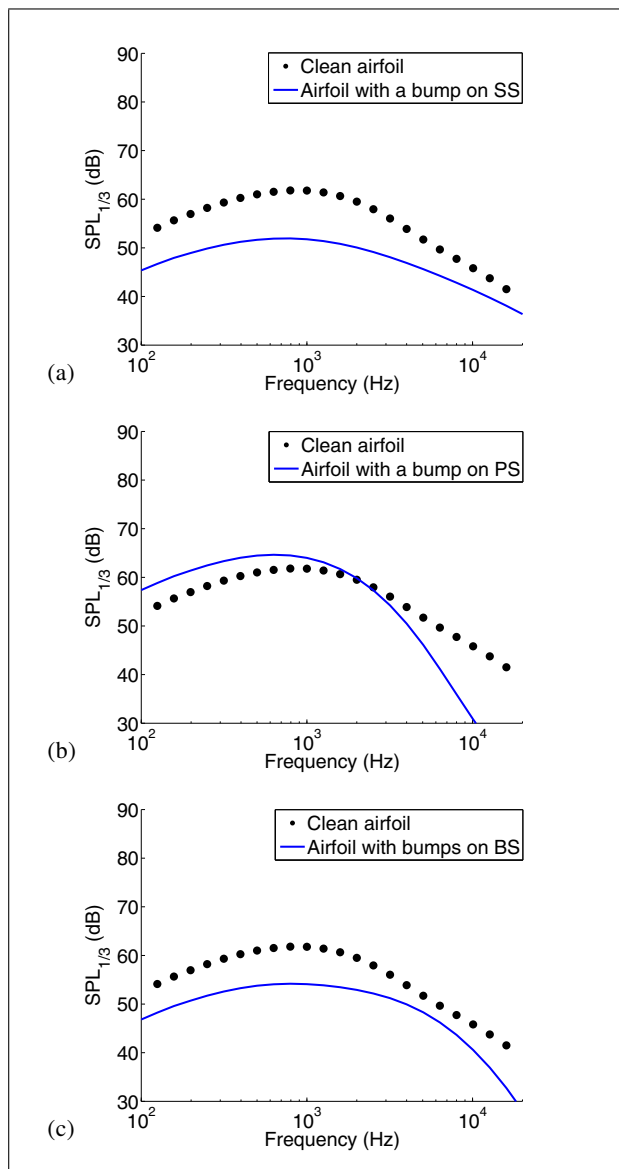


Figure 7. One-third octave band sound pressure level comparison between BANC clean airfoils and airfoils with bumps with the same L/D. (a) BANC case 3: a SS bump, (b) BANC case 3: a PS bump, (c) BANC case 3: BS bumps.

ation would provide the same power output with a significant reduction in noise.

3.6. Physical Mechanism of Noise Reduction

Results shown so far have demonstrated the potential of a boundary-layer bump in trailing edge noise reduction. This section serves to propose a physical mechanism of the bump by investigating flow field variable profiles within the boundary layer behind the bump.

Among all flow variables, turbulence kinetic energy (TKE) is one of the most important parameters since it directly represents the source of trailing edge noise. Also, streamwise velocity is another important variable that gives insights into the flow physics, such as flow acceleration, deceleration, or separation. Figures 8, 9, 10, and

11 show TKE profiles and the streamwise velocity profiles on both the suction side (SS) and the pressure side (PS).

Velocity deficits (lower velocity compared to the clean airfoil) are observed for the SS bump and BS bumps in the streamwise velocity profiles on the suction side near the wall. On the other hand, the streamwise velocity profiles of the PS bump are almost the same as those of clean airfoils. Velocity deficits indicate the flow is less active near the wall, which results in a reduction in the TKE profile which will be shown.

In the TKE profiles on the suction side, it is shown that TKE of the SS bump and BS bumps is reduced near the wall, while that of the PS bump is close to clean airfoils. The significantly reduced TKE near the wall is likely to reduce wall pressure fluctuations, which reduces trailing edge noise. This phenomenon was also shown in the LES study [13, 14] of the 3-D finlet. It is also found that this phenomenon occurs in all cases with different angles of attack and different airfoil geometries.

A physical mechanism of noise reduction with 2-D boundary-layer bumps is proposed here based on above discussions: the presence of the bump retards the flow downstream, causing velocity deficits or even recirculations near the wall. This results in reduced TKE near the wall, hence wall pressure fluctuations are reduced as well. Consequently, trailing edge noise is reduced. It should be noted that there have been several attempts to understand the physical mechanism with finlets [15, 28, 14], where the spacing in the spanwise direction plays a very important role through the friction in the channel and the modification of the spanwise correlation length scale. Therefore, a 2-D bump, which does not have the spacing, should be distinguished from 3-D finlets since their physical mechanisms are different, though two treatments do share some similarities especially in velocity and TKE profiles.

4. Conclusions

This paper presents a novel idea of airfoil trailing edge noise reduction using 2-D boundary-layer bumps. A numerical approach to predict airfoil trailing edge noise using steady RANS CFD, an empirical wall pressure spectrum model, and an analytical acoustic model, was proposed and validated for five BANC cases against the experimental data. This numerical approach enables fast and accurate predictions of trailing edge noise, which was used to study the noise reduction with the bump for various airfoil geometries and flow conditions at high Reynolds numbers. It was shown that predicted noise levels agree quite well with the measurements for clean airfoils.

Various aspects of 2-D bumps were studied, including bump parametric model definition, acoustic assessment of three types of bumps (the suction-side bump, the pressure-side bump, and both-side bumps), a numerical sensitivity study, a bump height study, and aerodynamic impacts. The following conclusions are highlighted based on the detailed analyses in this paper:

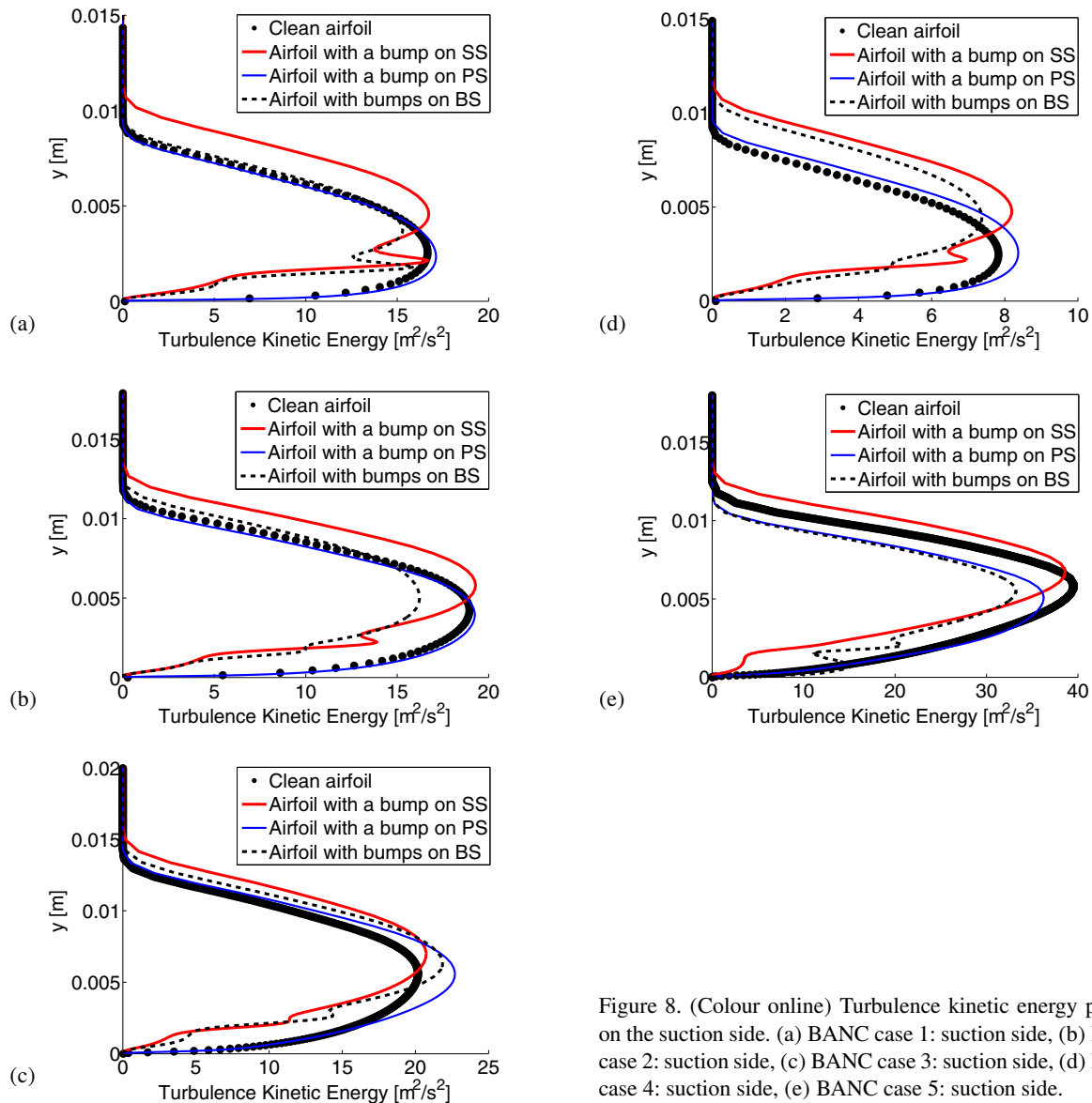


Figure 8. (Colour online) Turbulence kinetic energy profiles on the suction side. (a) BANC case 1: suction side, (b) BANC case 2: suction side, (c) BANC case 3: suction side, (d) BANC case 4: suction side, (e) BANC case 5: suction side.

1. Developed an efficient and accurate numerical approach to predict trailing edge noise and validated it against the measurement data for clean airfoils.
2. Proposed and investigated a new trailing edge noise reduction method termed 2-D boundary-layer bump.
3. Both the PS bump and the SS bump are able to reduce far-field noise up to 10 dB. However, the PS bump tends to reduce high-frequency noise, while the SS bump reduces the low and middle frequency noise.
4. BS bumps can further reduce far-field noise by reducing TKE near the wall on both sides.
5. Far-field noise is independent of the wall pressure spectrum measuring point near the trailing edge. This demonstrates the robustness of airfoil trailing edge noise predictions with a bump.
6. A high bump is more effective in noise reduction at low and middle frequencies when AOA is not zero, while a reduced-height bump is better at high-frequency noise

reduction in all cases. This might be due to how the high bump affects an upper region in the boundary layer, which is responsible for low frequency noise; and the reduced-height bump influences more on a lower region in the boundary layer, which is responsible for high frequency noise.

7. All three types of bumps increase C_D and reduce L/D compared with clean airfoils. However, noise reduction as much as 10 dB is still evident for the same L/D values.

Synthesizing obtained results, a physical mechanism is proposed: the presence of the bump retards the flow downstream, causing velocity deficits or even recirculations near the wall. This results in reduced TKE near the wall, hence wall pressure fluctuations are reduced as well. Consequently, trailing edge noise is reduced. Attention should be paid to the difference between 2-D bumps and 3-D finlets. Compared to 3-D finlets, the 2-D pressure-side bump

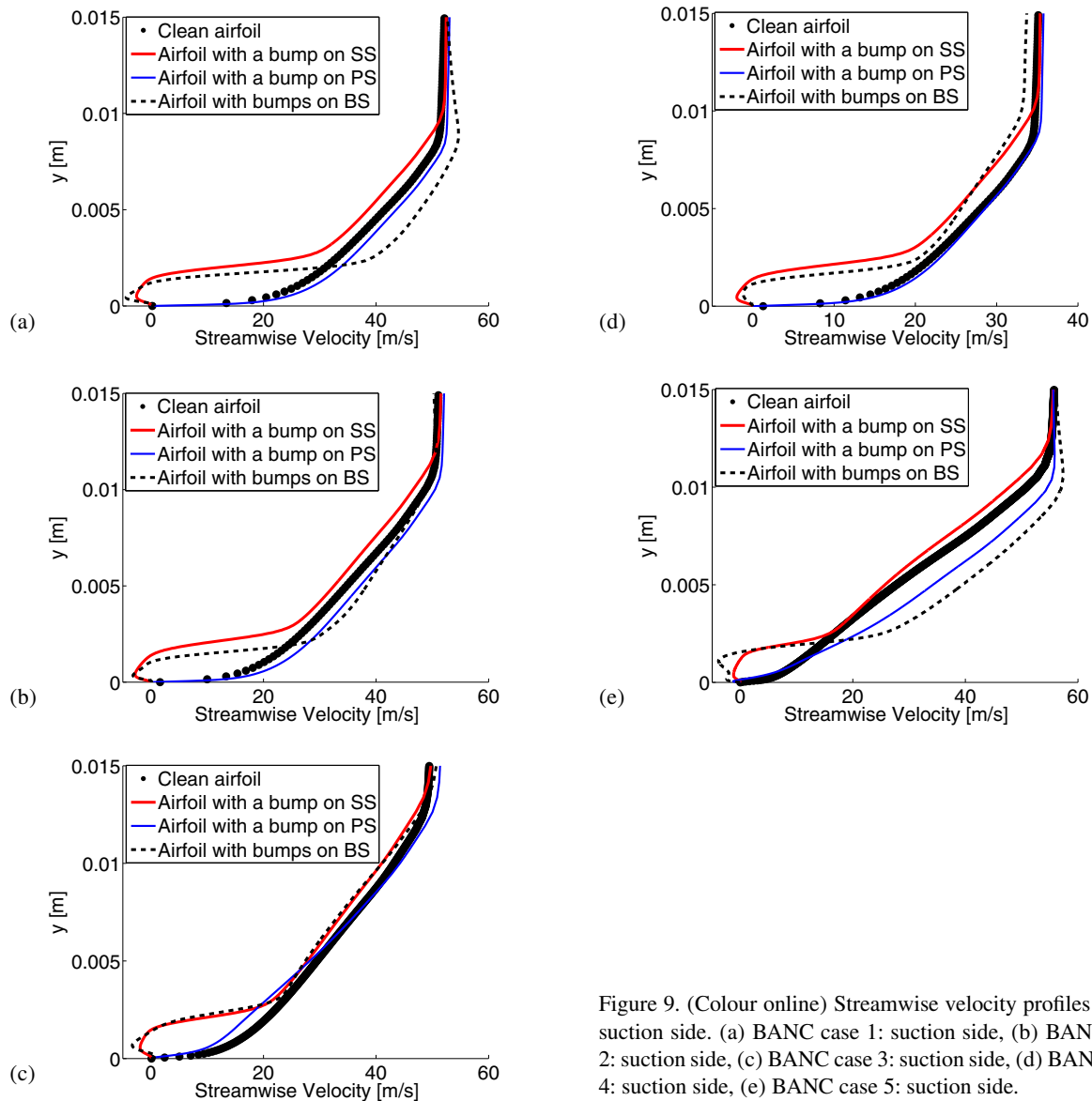


Figure 9. (Colour online) Streamwise velocity profiles on the suction side. (a) BANC case 1: suction side, (b) BANC case 2: suction side, (c) BANC case 3: suction side, (d) BANC case 4: suction side, (e) BANC case 5: suction side.

is still able to induce velocity deficits on the pressure side, therefore reducing the wall pressure spectrum and trailing edge noise. Contrary to 3-D finlets, noise reduction is apparent at all frequencies for 2-D bumps.

In order to fully exploit the benefits of a 2-D bump, the trailing edge bluntness vortex shedding noise should be investigated. If the bluntness noise becomes important, additional flow control methods, such as blowing or suction, could be separately considered to mitigate this noise. In addition, the application of high-fidelity simulations, such as LES for a 2-D bump, is suggested to verify the phenomena observed with low-fidelity simulations.

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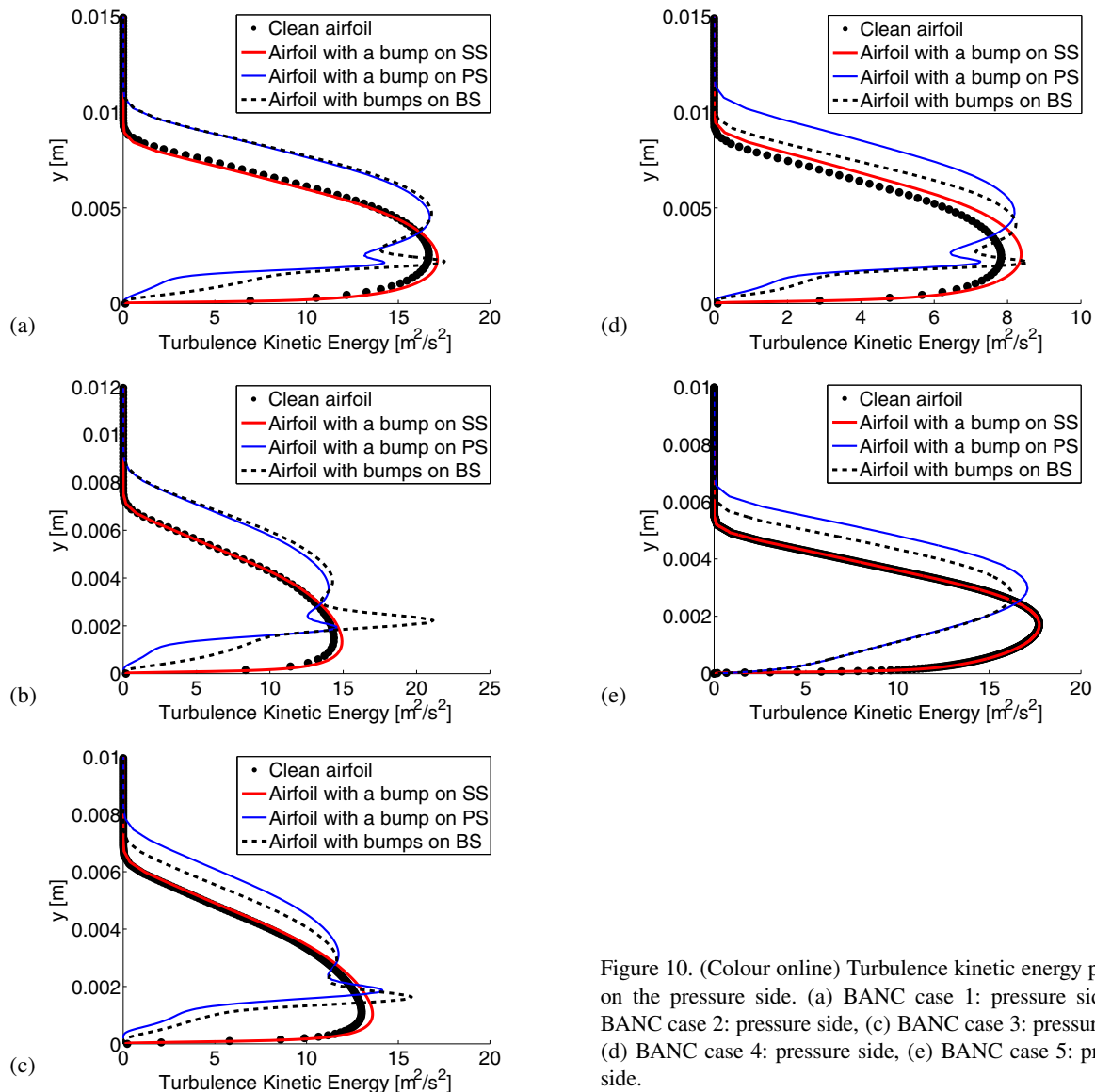


Figure 10. (Colour online) Turbulence kinetic energy profiles on the pressure side. (a) BANC case 1: pressure side, (b) BANC case 2: pressure side, (c) BANC case 3: pressure side, (d) BANC case 4: pressure side, (e) BANC case 5: pressure side.

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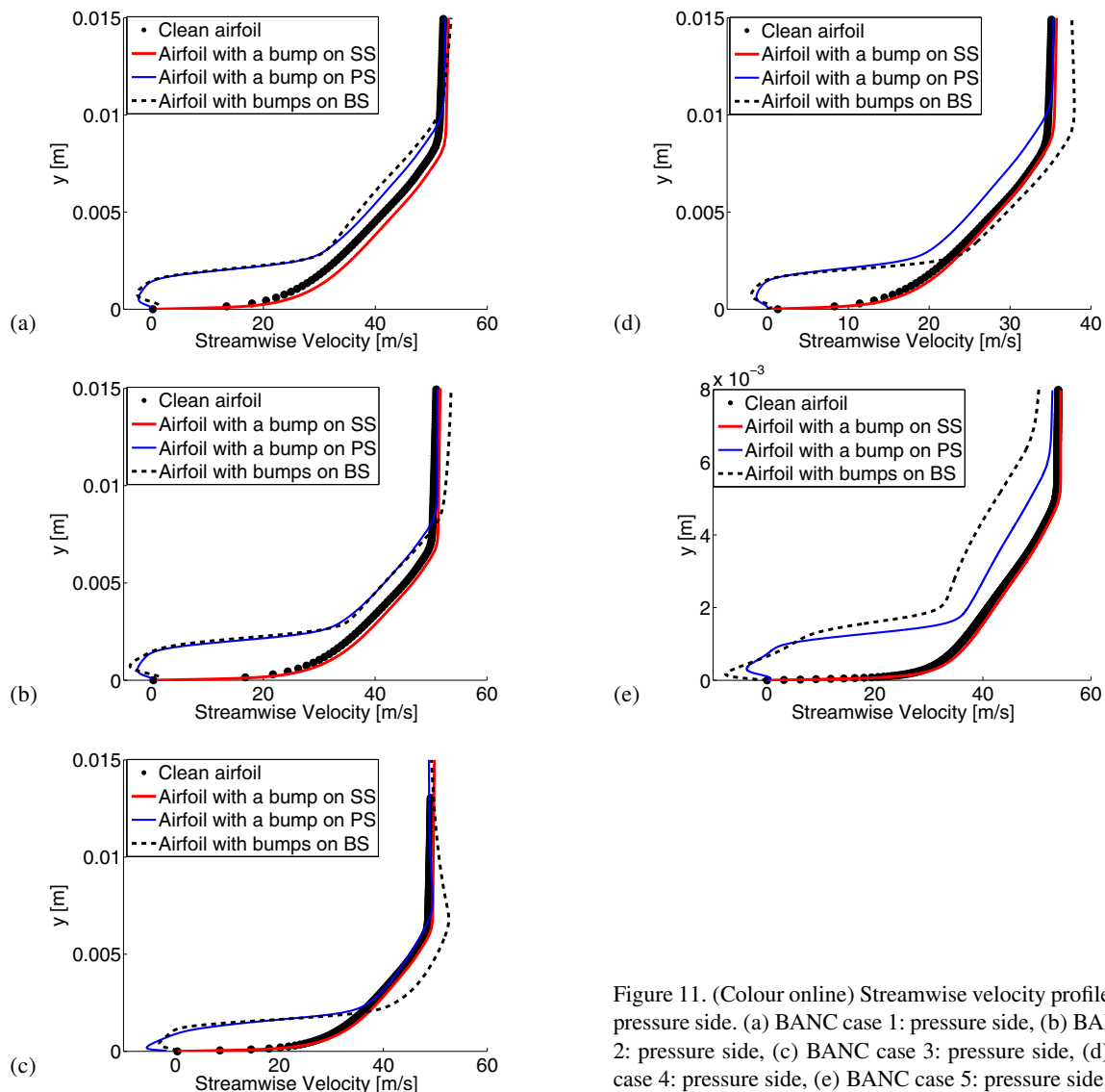


Figure 11. (Colour online) Streamwise velocity profiles on the pressure side. (a) BANC case 1: pressure side, (b) BANC case 2: pressure side, (c) BANC case 3: pressure side, (d) BANC case 4: pressure side, (e) BANC case 5: pressure side.

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