

## Control of Flow Separation over an Aerofoil by External Acoustic Excitation at a High Reynolds Number

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The effectiveness of acoustic excitation as a means of flow control at high Reynolds number turbulent flows is investigated numerically by using Improved Delayed Detached Eddy Simulations. Previous studies on low Reynolds number laminar flows have shown that acoustic excitation can substantially suppress flow separation for specific effective frequency and amplitude ranges. However, the effect of acoustic excitation on higher Reynolds number turbulent flow separation has not yet been explored due to limitations on appropriate fidelity computational methods or experimental facility constraints. Therefore, this paper addresses this research gap. A NACA (National Advisory Committee for Aeronautics) 0015 aerofoil profile at 1 million Reynolds number based on the aerofoil chord length is used for the investigations. Acoustic excitation is applied to the baseline flow field in the form of transient boundary conditions at the computational domain inlet. A parametric study revealed that the effective sound frequency range shows a Gaussian distribution around the frequency of the dominant disturbances in the baseline flow. A maximum of  $\sim 43\%$  increase in lift-to-drag ratio is observed for the most effective excitation frequency  $F^+ = 1.0$  at a constant excitation amplitude of  $A_m = 1.8\%$ . The effect of excitation amplitude follows an asymptotic trend with a maximum effective excitation amplitude above which the gains are not significant. A fully reattached flow is observed for the highest excitation level considered ( $A_m = 10\%$ ), that results in  $\sim 120\%$  rise in aerofoil lift-to-drag coefficient. Overall, the findings of the current work demonstrate the higher Reynolds number effectiveness of acoustic excitation on separated turbulent flows, thereby paving the way for application in realistic flow scenarios observed in aircraft and gas turbine engine flow fields.

### NOMENCLATURE

|            |   |                                                                                 |
|------------|---|---------------------------------------------------------------------------------|
| $\alpha$   | = | angle of attack                                                                 |
| $A_m$      | = | acoustic excitation amplitude, in percentage of $U_\infty$                      |
| $c$        | = | chord length                                                                    |
| $C_D, C_L$ | = | drag and lift coefficients                                                      |
| $C_p, C_f$ | = | pressure and skin friction coefficients                                         |
| $\Delta t$ | = | numerical time step                                                             |
| $E(k)$     | = | Turbulent kinetic energy                                                        |
| $f_0$      | = | fundamental frequency of the most amplified disturbances within the shear layer |
| $f_{exc}$  | = | acoustic excitation frequency                                                   |
| $F^+$      | = | reduced frequency, $f_{exc}/f_0$                                                |
| $k$        | = | wave number                                                                     |
| $\nu$      | = | kinematic viscosity of air                                                      |
| $P$        | = | pressure                                                                        |
| $Re_c$     | = | Reynolds number based on chord length, $U_\infty c/\nu$                         |
| $St$       | = | Strouhal number, $f c/U_\infty$                                                 |
| $\tau$     | = | $t(U_\infty/c)$ , convective time                                               |
| $U_\infty$ | = | freestream velocity magnitude                                                   |
| $\bar{U}$  | = | mean streamwise velocity magnitude                                              |
| DES        | = | Detached Eddy Simulation                                                        |
| IDDES      | = | Improved Delayed Detached Eddy Simulation                                       |
| rmse       | = | root-mean-square error                                                          |

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## I. INTRODUCTION

The onset of flow separation in fluid engineering devices is often a dividing line between peak performance and sudden deterioration, as evidenced by well known examples such as the wing providing maximum lift before stall, or turbomachinery blades operating at maximum loading before adverse pressure gradient effects begin to dominate. Flow separation, after it occurs, is usually associated with a degradation in aerodynamic performance and efficiency, alongside structural concerns in some cases such as transonic regimes<sup>1–3</sup>. Therefore, a delay or reduction in flow separation can help not only recover aerodynamic performance, but also ensure stable peak performance to improve the efficiency of the system or a vehicle. Such control over the onset and occurrence of flow separation has been achieved by active methods: boundary layer suction and blowing<sup>4</sup> and synthetic jet actuators<sup>5</sup>, and passive methods: roughness enhancing materials<sup>6</sup> and vortex generators<sup>7</sup>. These methods are classified based on the method of energy addition to the system.

Beside these classical flow control techniques, acoustic excitation is a promising alternative technique that takes advantage of the instabilities present in a separated flow field to suppress the flow separation and improve the aerodynamic performance. Acoustic excitation can be applied in the form of either internal or external excitation, depending on the location of the sound source. In external acoustic excitation, a sound source is located away from the geometry of interest, while in internal excitation, the sound source is located inside the boundary layer, usually on or underneath a surface of the geometry<sup>8</sup>. In this study, the control effectiveness of acoustic excitation is investigated as there is no geometric packaging constraints. The focus is on the exploration of the effects of sound wave frequency, amplitude, and the freestream turbulence intensity.

It has been demonstrated by several studies that acoustic excitation can suppress flow separation and improve aerodynamic performance for low Reynolds number laminar flows when applied at an effective excitation frequency and amplitude<sup>9–15</sup>. Zaman and McKinzie<sup>10</sup> and Hsiao et al.<sup>16</sup> observed that acoustic excitation is most effective at near-stall angle-of-attacks when applied at the frequency of the most amplified disturbances in the shear layer. The instability frequency of the shear layer is locked into the excitation frequency of sound waves such that transition to turbulence in the separated shear layer is promoted, resulting in advancement of reattachment location, shifting of separation location downstream, and hence a reduced separation length, as reported by<sup>13,17</sup>. Acoustic excitation amplitude, on the other hand, has a more intricate effect on aerofoil performance. An increase in excitation amplitude is accompanied by an increase in lift and a reduction in drag when applied above a minimum effective amplitude threshold. As the rapid transition to turbulence is promoted with increasing excitation amplitude, flow becomes more resistant to separation with a delay on the onset of separation. Moreover, there is a maximum excitation amplitude beyond which the effect of amplitude increment does not contribute to performance improvement any further<sup>18</sup>.

A vast majority of research on the ability of sound waves to influence separated flows focuses on the experimental investigation of the control of laminar flow separations encountered at low Reynolds numbers. In an experimental environment, acoustic excitation is usually implemented by means of subwoofers and loudspeakers<sup>13</sup>. Although parametric studies can be carried out, the equipments may have limitations on the available sound amplitude range for a specific frequency range<sup>19</sup> that requires careful design/selection of the sound source. These limitations encouraged researchers to investigate the effectiveness of acoustic excitation computationally. Traditionally, computational approaches for studying acoustic excitation have been challenging because of the difficulties associated with the resolution of instabilities that are closely associated with turbulent flow structures. Consequently, little to no attention is paid to the control of separated turbulent flows at high Reynolds numbers, which are representative of aircraft wing or engine turbomachinery operating conditions. Therefore, this study is designed to fill the gap in the application of acoustic excitation to separated turbulent flows using scale-resolving high fidelity computational simulations.

The aim of this paper is to extend our previous research<sup>20,21</sup> on the numerical investigation of acoustic excitation effects on a flow over a NACA0015 aerofoil profile at  $\alpha = 11^\circ$ , which is a near-stall angle of attack. This paper investigates the flow physics in acoustically excited flow in a greater detail to explore the physical mechanism behind the effectiveness of acoustic excitation. This study focuses on the investigation of the effectiveness of acoustic excitation on controlling flow separation

at a chord-based Reynolds number of 1 million, while all previous studies<sup>9–15</sup> were done only up to  $Re = 10^5$ . A computational approach that utilizes Improved Delayed Detached Eddy Simulation (IDDES) is developed, validated and employed. Being a hybrid RANS/LES method, IDDES provides reasonable accuracy with an affordable computational cost. The investigations include IDDES method validation for the problem of interest and a parametric study on the effects of acoustic excitation frequency and amplitude for the identification of the effective excitation parameter ranges. The demonstration of the effects of acoustic excitation on realistic operating conditions, representative of high Reynolds numbers, as described in this work holds the potential for application in gas turbine compressor and turbine aerofoils, amongst several other possible areas.

## II. METHODOLOGY

Highly unsteady behaviour of separated flows and resolution of sound-flow interactions require the use of scale resolving turbulence models. The main advantage of scale resolving methods over (U)RANS models is the resolution of all or a portion of turbulent spectrum depending on the method and the resolution requirements. Improved Delayed Detached Eddy Simulation (IDDES), a hybrid Reynolds-averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES) method that uses RANS inside the boundary layer and LES elsewhere, is used. This method provides the necessary accuracy at an affordable computational cost. The run time for a single IDDES simulation for a grid composed of approximately five million cells is around 130 hours for 40,000 iterations with 11 sub-iterations per physical time step on 192 cores.

### A. Improved Delayed Detached Eddy Simulation (IDDES)

Improved Delayed Detached Eddy Simulation (IDDES) is a hybrid RANS/LES method that aims at combining the strengths of RANS and LES models to provide a sufficiently accurate and computationally efficient model. IDDES approach is superior to RANS models in capturing flow separation and unsteady flow characteristics with a significantly lower computational cost compared to an LES<sup>22</sup>. The accuracy of IDDES model is sacrificed due to B/L modelling and blending between RANS and LES models that imposes the main challenges. IDDES is an improved version of DES that resolves the known issues of modelled stress depletion and log-layer mismatch encountered in a classical DES<sup>23</sup>. This is accomplished by a new definition of subgrid length scale and a use of a shielding function to prevent activation of LES inside the B/L as proposed by Shur<sup>23</sup> and Menter<sup>24</sup>. The definition of subgrid length scale in this proposal depends on both grid spacing and wall distance, unlike other hybrid RANS/LES methods such as the DDES model, which uses a length scale dependent only on the grid spacing.

IDDES model is based on two-equation  $k - \omega$  SST, with the following turbulent kinetic energy,  $k$ , and eddy dissipation,  $\omega$ , equations:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = \tau_{ij} \frac{\partial u_i}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ (\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right] - C_\mu \rho \omega k l_{IDDES} \quad (1)$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} = \frac{\gamma}{\nu_t} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[ (\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_1) \frac{\rho \sigma_{\omega 2}}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \quad (2)$$

where  $\rho$  is density,  $k$  is turbulent kinetic energy (TKE),  $\omega$  is specific dissipation,  $x_i$  represents spatial coordinates,  $t$  is time,  $\mu$  is laminar viscosity,  $\mu_t$  is turbulent eddy viscosity and  $l_{IDDES}$  is IDDES length scale given as;

$$l_{IDDES} = \tilde{f}_d(1 + f_e)l_{RANS} + (1 - \tilde{f}_d)l_{LES} \quad (3)$$

$$l_{RANS} = \frac{\sqrt{k}}{C_\mu k}, \quad l_{LES} = C_{DES} \Delta \quad (4)$$

$$C_{DES} = C_{DES1} F_1 + C_{DES2} (1 - F_1)$$

where  $l_{IDDES}$ ,  $l_{RANS}$  and  $l_{LES}$  are IDDES, RANS and LES length scales, respectively.  $C_{DES1} = 0.78$  and  $C_{DES2} = 0.61$  are model constants and  $F_1$  is a blending function.

The LES length scale is given by:

$$\Delta = \min \{C_\omega \max[d_\omega, h_{max}], h_{max}\} \quad (5)$$

where  $h_{max}$  is the cell maximum edge length and  $d_\omega$  is the distance from the cell to the wall.  $\tilde{f}_d$  in Equation 3 is an empirical blending function computed as:

$$\begin{aligned} \tilde{f}_d &= \max \{(1 - f_{dt}), f_b\} \\ f_{dt} &= 1 - \tanh[(C_{dt1} \cdot r_{dt})^{C_{dt2}}] \\ r_{dt} &= \frac{V_t}{\kappa^2 d_\omega^2 \sqrt{0.5(S^2 \Omega^2)}} \\ f_b &= \min \{2\exp(-9\alpha^2), 1.0\} \\ \alpha &= 0.25 - d_\omega/h_{max} \end{aligned} \quad (6)$$

where  $\kappa$  is Karman constant,  $S$  is strain rate tensor magnitude and  $\Omega$  is vorticity tensor magnitude. Further detail can be found in Gritskevich et al.<sup>25</sup> and Menter<sup>26</sup>.

## B. Computational Approach and Grid Independence Study

A NACA0015 aerofoil operating at  $Re_c = 1.0 \times 10^6$  based on chord length,  $c = 0.35m$ , and  $\alpha = 11^\circ$  is used as the baseline model for the validation of the numerical approach. The aerodynamic characteristics of this aerofoil are investigated in detail by Siau<sup>27</sup> in their experimental study. The freestream turbulence intensity is  $TI = 5\%$ . Numerical computations are carried out on a commercial software, ANSYS-Fluent, which utilizes a cell-centred finite volume flow solver. A fully implicit, pressure-based solution scheme is utilized. Second-order numerical spatial discretization is used for pressure, momentum, and energy, while Green-Gauss Node-Based spatial discretization is used for gradients and derivatives. A second-order implicit Newtonian dual-time stepping method is used for the transient formulations with 15 pseudo sub-iterations per time advancement for solution of the mean flow and turbulent quantities.  $k - \omega$  SST based RANS computations are used as a precursor to the transient  $k - \omega$  SST IDDES model. A computational domain with a size of  $L_C \times L_N \times L_Z = 20c \times 10c \times 0.2c$ , where  $c$  is the chord length, is used as shown in Figure 1 with corresponding boundary conditions. Velocity is used at the inlet boundary, pressure at the outlet, and periodicity is applied to the side boundaries. A sensitivity study is carried out on the effect of spanwise domain width for  $0.2c$ ,  $0.3c$ , and  $0.5c$ . It revealed that the spanwise width of the computational domain has no major effect on the results with a maximum deviation of 5%. Therefore, a spanwise width of  $0.2c$  is used for computational efficiency. Finally, the aerofoil wall is a no-slip boundary condition (BC).

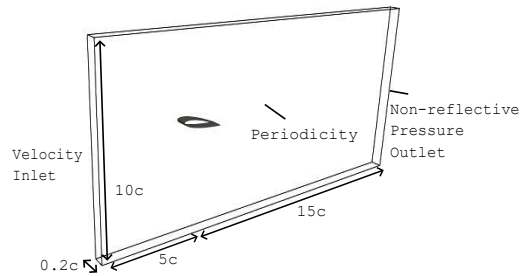


FIG. 1. Computational domain with boundary conditions.

The structured mesh generated in accordance with IDDES requirements is shown in Figure 2. There are 251 nodes on the aerofoil and 46 nodes in the spanwise direction. The wall spacing satisfies  $y^+ \leq 1$ . The total cell number of the grid is  $\sim 6$  million.

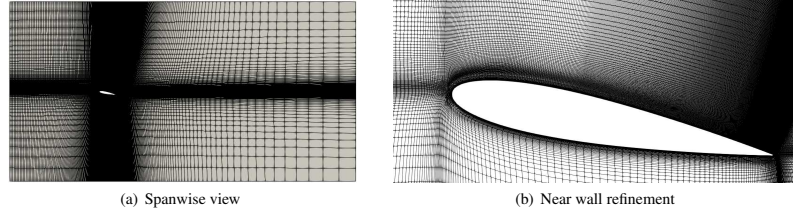


FIG. 2. Computational domain; a) spanwise view and b) near wall refinement. (Reproduced from Coskun et al., AIAA Aviation Forum 2022<sup>20</sup>)

Initial computational grids are generated to model the flow around a NACA0015 aerofoil profile with the RANS grid generation practices. The wall-normal resolution of  $y^+ \leq 1$  is satisfied for all the grids with 32 layers in the boundary layer and a stretching ratio of  $\Delta_{n+1}/\Delta_n = 1.1$  with a cell size  $\Delta s/c \approx 0.01$  in all three directions in the focus region. Thereafter, the cell size in the focus region shown in Figure 2 is halved twice to refine the grid resolution in this region to generate three different grid resolutions. The number of total cells in the computational domain is  $\sim 6$  million,  $\sim 9.6$  million, and  $\sim 13$  million, as shown in Table I.

|        | $y^+$ | # of layers in B/L | Cell size in focus region $[\Delta s/c]$ | Total grid size $(\times 10^6)$ | Onset of separation $(x/c)$ |
|--------|-------|--------------------|------------------------------------------|---------------------------------|-----------------------------|
| Grid 1 | 1     | 32                 | 0.01                                     | 6                               | 0.41                        |
| Grid 2 | 1     | 32                 | 0.005                                    | 9.6                             | 0.47                        |
| Grid 3 | 1     | 32                 | 0.0025                                   | 13                              | 0.56                        |

TABLE I. Grid convergence parameters for NACA0015 aerofoil.

The end results are evaluated in terms of the prediction of time- and span-averaged pressure coefficient distributions over the aerofoil compared to the experimental data<sup>27</sup> in Figure 3. All three grids under consideration provide reasonably well prediction of the aerofoil  $C_p$  distribution. However, Grid 3 provides the most accurate prediction of the onset of flow separation at  $x/c = 0.56$  compared to experimental value of  $x/c \approx 0.6$ . The accurate prediction of flow separation characteristics is of crucial importance in flow control studies. Therefore, Grid 3 is used in acoustic excitation studies for the low-speed, low-Re flow over the aerofoil.

A computational time step independence study revealed that a non-dimensional time step size of  $\Delta t^* = \Delta x_{min}/2U_\infty$  ( $\Delta t = 10^{-5}s$ ) provides the adequate temporal resolution without being influenced by time-stepping numerics. The preliminary acoustic excitation frequency is determined by the modal frequencies of the uncontrolled baseline flow. Therefore, spectral parameters such as frequency resolution, sampling rate, and Nyquist frequency also put a requirement on the computational time step size for accurate prediction of the spectral content of the flow field through a Fast Fourier Transform (FFT) analysis of transient data. The required frequency resolution is given by:

$$\Delta f = \frac{1}{\Delta t N} \quad (7)$$

where  $\Delta f$  is the frequency resolution,  $\Delta t$  is the time step size and  $N$  is the number of samples. Transient simulations are run for 20 flow-through times for the initial transient and further 20 flow-through times for data sampling that provides a frequency resolution of  $\Delta f = 2Hz$ , which is sufficient to provide the required accuracy for the purposes of the current work.

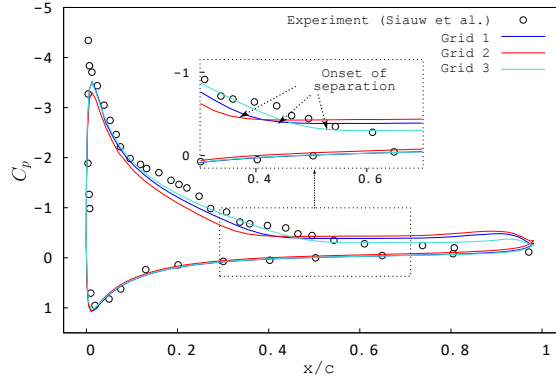


FIG. 3. Comparison of pressure coefficient over aerofoil for different grids.

### C. Acoustic Excitation Modelling

The finite bounds of a computational domain may introduce spurious wave reflections that impose non-physical disturbances on the flow, reducing the level of accuracy<sup>28</sup>. The static pressure outlet boundary condition used here, as shown in Figure 1 is highly reflective<sup>29</sup> and it can introduce non-physical reflections of sound waves to interact with the separated flow, and produce non-physical results. Therefore, a non-reflective boundary condition (NRBC) is used to remedy spurious reflections from the downstream boundary back into the computational domain. NRBC used here is based on characteristic wave reflections derived from Euler equations<sup>30</sup> to ensure the transfer of sound waves out of the domain.

Monochromatic planar sound waves are generated in the computational domain by means of transient velocity inlet boundary conditions to impose acoustic disturbances on instantaneous freestream variables, as shown in Figure 4. The transient velocity inlet boundary condition used is defined by:

$$U = U_{\infty} \left[ 1 + A_m e^{i(kx_i - \omega t)} \right] \quad (8)$$

where  $A_m$  is excitation amplitude in percentage of  $U_{\infty}$ ,  $k = \sqrt{k_x^2 + k_y^2 + k_z^2} = \omega/c_0$  is the wave number of planar waves and  $\omega = 2\pi f_{exc}$  is the circular frequency,  $f_{exc}$  is excitation frequency and  $c_0$  is the speed of sound.

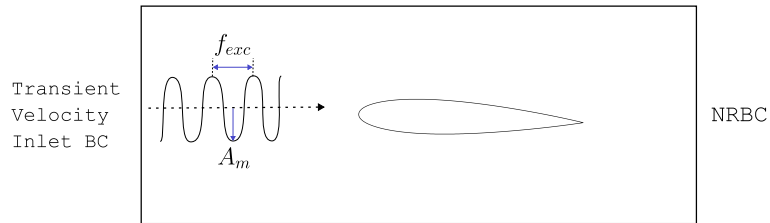


FIG. 4. Schematic of acoustic waves implementation into the computational domain.

The frequency of the sound waves for acoustic excitation of the separated flow is determined based on the uncontrolled flow turbulent kinetic energy spectra at the different transient data monitoring locations shown in Figure 5. These are located along the centre line of the separated shear layer in the uncontrolled flow. The red-shaded region in Figure 5 is where the flow separation takes place in the uncontrolled flow, identified by  $u \leq 0$ . The outer boundary of the flow separation region is highlighted by the blue line shown over which the streamwise velocity is zero. Station 1 is inside the attached boundary layer at  $x/c = 0.5$ , while station 2 is located at the onset of flow separation. These two stations are critical in understanding the development of the instability mechanism within the shear layer that eventually results in the transition to turbulence and shear layer breakdown. Stations 3, 4 & 5 are located at the boundary of the separation region, particularly at the centre line of the shear layer.

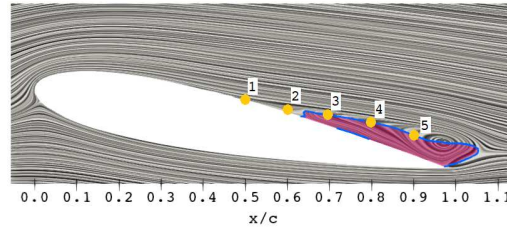


FIG. 5. Transient data monitoring locations.

The streamwise evolution of turbulent kinetic energy spectra shown in Figure 6 reveals distinct frequency peaks at  $F^+ = 1$  and  $F^+ = 2$  for the monitor locations within the shear layer over the aerofoil. The peak at  $F^+ = 1$  is the shear layer fundamental frequency, as it is more dominant in terms of its magnitude and hence the turbulent kinetic energy content. The concentration of turbulent kinetic energy at the distinct frequencies identifies the shear layer roll-up and demonstrates the vortex coherence. With the breakdown of the shear layer during transition at  $x/c \approx 0.8$ , the turbulence spectra at  $x/c \geq 0.8$  display turbulent flow characteristics that are associated with Kolmogorov's power law for the inertial subrange in the turbulence spectrum. These fundamental frequencies in the uncontrolled flow frequency spectra are used as the preliminary frequencies for acoustic excitation.

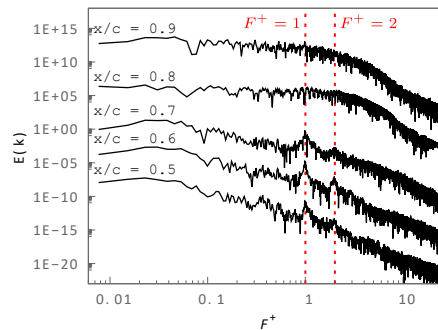


FIG. 6. Streamwise evolution of turbulent kinetic energy spectra for the uncontrolled flow at monitor locations. The amplitude of each successive spectrum is increased by four orders of magnitude for clarity.

### III. RESULTS AND DISCUSSION

The effects of acoustic excitation on turbulent flow separation over an aerofoil are discussed in the current work in terms of:

- A parametric study is carried out to identify the effective excitation frequencies. A range of sound frequencies between  $0.5 \leq F^+ \leq 2.0$  is investigated at a constant excitation amplitude. Normalized frequency,  $F^+ = f_{exc}/f_{natural}$ , is defined as the ratio of excitation frequency to the natural frequency of the uncontrolled flow. The corresponding Strouhal numbers are  $1.53 \leq St \leq 6.125$ . A detailed flow field analysis is provided for understanding the effect of acoustic excitation on flow separation characteristics.
- Upon obtaining the effective frequency range, a parametric study is conducted for excitation amplitude effect between  $1\% \leq A_m \leq 10\%$ . The corresponding lowest and the highest sound wave amplitudes are 135dB and 154dB, respectively. Relatively higher excitation amplitudes (i.e.,  $A_m = 10\%$ ) are included for illustration of the sound wave amplitude effects.
- Although the focus of the current work is on turbulent flows, the effectiveness of acoustic excitation at lower turbulent intensities are also explored to provide a more comprehensive understanding of the acoustic excitation effects.

#### A. The Effect of Excitation Frequency

One of the main parameters on the effectiveness of acoustic excitation is the excitation frequency. According to the findings of Zaman and McKinzie<sup>10</sup> and Hsiao et al.<sup>16</sup>, acoustic excitation is most effective in low Reynolds number flows when applied with the frequency of the most amplified disturbances in the uncontrolled flow shear layer for near-stall angles of attack. Therefore, the effect of excitation frequency on the baseline flow field is investigated in this section at a constant excitation amplitude  $A_m = 1.8\% U_\infty$ , which is chosen as the initial sound wave amplitude based on the literature<sup>8,11,18</sup>.

The dominant frequency in the uncontrolled flow shown in Figure 6 corresponds to  $F^+ = 1.0$ . For the investigation of the effect of sound wave frequency on the effectiveness of acoustic excitation, a frequency range between  $0.5 \leq F^+ \leq 2.0$  is explored. This frequency range includes the lower and higher harmonics of the dominant frequency in the uncontrolled flow as well as the second modal frequency, i.e.,  $F^+ = 2.0$ .

##### 1. Effect of Excitation Frequency on Flow Field

The effect of acoustic excitation on flow separation characteristics is demonstrated in Figure 7 in terms of the extent of separation shown by streamlines over the aerofoil and contours of velocity magnitude normalised by the freestream velocity magnitude. The aerofoil experiences a significant amount of flow separation over the suction surface. With the application of acoustic excitation at  $F^+ = 0.5$ , the effect of excitation is negligible as the extent of flow separation remains unchanged. With increase of acoustic excitation frequency, the sound excitation effect becomes perceptible at  $F^+ = 0.75$  with a 39% narrower separation width compared to the uncontrolled flow. Excitation with the natural frequency of the uncontrolled flow field, i.e.,  $F^+ = 1.0$ , results in a reduction in flow separation that the extent of separation shrinks to a 70% smaller area accompanied with local flow reattachment aft of the aerofoil. The effect of acoustic excitation becomes smaller with further increase in excitation frequency to  $F^+ = 1.5$  and  $F^+ = 2.0$  compared to the natural frequency excitation, although there is still a 29% reduction in flow separation for excitation with  $F^+ = 1.5$ . The highest frequency considered,  $F^+ = 2.0$  has a less pronounced effect with a 15% reduction in the separated flow area.

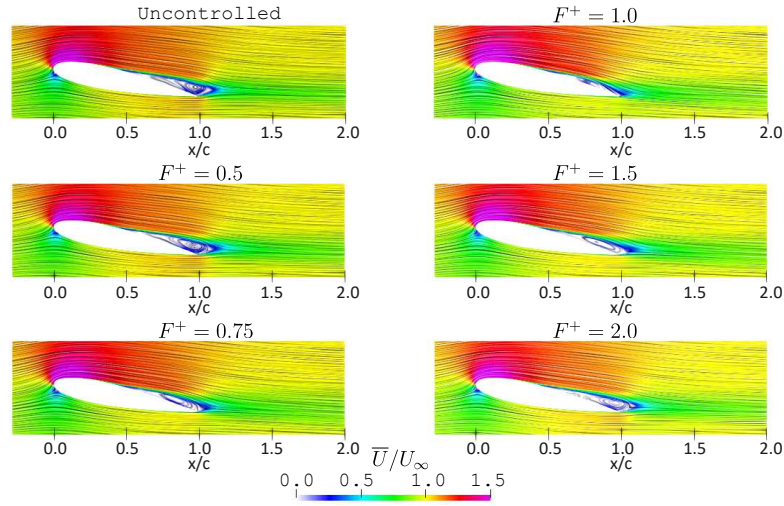


FIG. 7. Streamlines over the aerofoil coloured by mean velocity magnitude.

Boundary layer mean and root-mean-square error (rmse) velocity profiles are shown to demonstrate the effect of acoustic excitation in Figure 8 for four different streamwise stations at  $x/c = 0.6, 0.7, 0.8$  and  $0.9$ . At  $x/c = 0.6$ , which is just after the onset of separation in the uncontrolled flow, local wall-normal extent of the flow separation is slightly reduced for only  $F^+ = 1.0$  excitation with an increased near-wall turbulent intensity shown by rmse velocity profile. At  $x/c = 0.7$ , excitations with  $F^+ = 0.75$  and  $F^+ = 1.5$  frequencies also reduce the wall-normal extent of flow separation although the effect of excitation with  $F^+ = 1.0$  is more pronounced as the near-wall peak turbulent intensity is increased by 68% compared to the uncontrolled flow. The acoustic excitation effect becomes gradually more pronounced for further downstream stations for the effective frequency range,  $F^+ = 0.75, 1.0$  and  $1.5$ , such that nearly full reattachment of flow is observed at  $x/c = 0.9$  for the natural frequency excitation case with a reduction in wall-normal flow separation extent shown by enhancements in mean velocity profiles, which reaches to 51% reduction in the width of separated flow region with respect to the uncontrolled flow. The improvements on near-wall rmse velocity profiles, on the other hand, provide energy and momentum transfer to separated flow at the aft of aerofoil, thus promoting reduction in the extent of separation and almost reattachment of flow as in  $F^+ = 1.0$ .

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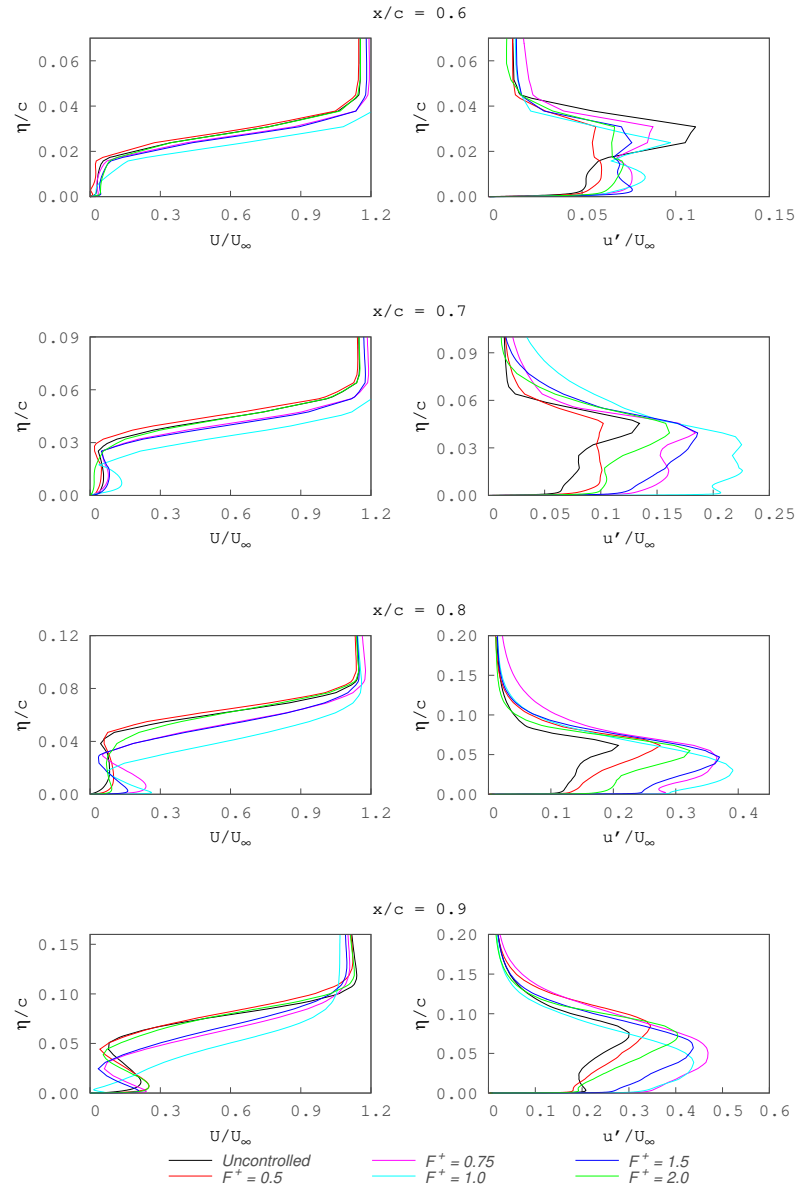


FIG. 8. Boundary layer mean (left) and rmse (right) velocity profiles.

The effect of acoustic excitation frequency is also assessed in terms of the wake velocity profiles at  $x/c = 2.0$  as illustrated in Figure 9. It is observed that the momentum deficit is reduced for  $F^+ = 0.75$  and  $1.0$  with an accompanied reduction in the width of wake. Acoustic excitation frequencies  $F^+ = 0.75$  and  $1.0$  reduce the wake loss by 30.3% and 56.6%, respectively. It should be noted that excitation with  $F^+ = 1.5$  has an imperceptible effect on the wake profile. The results also suggest that there is a reduction in wake turbulent intensities with acoustic excitation.

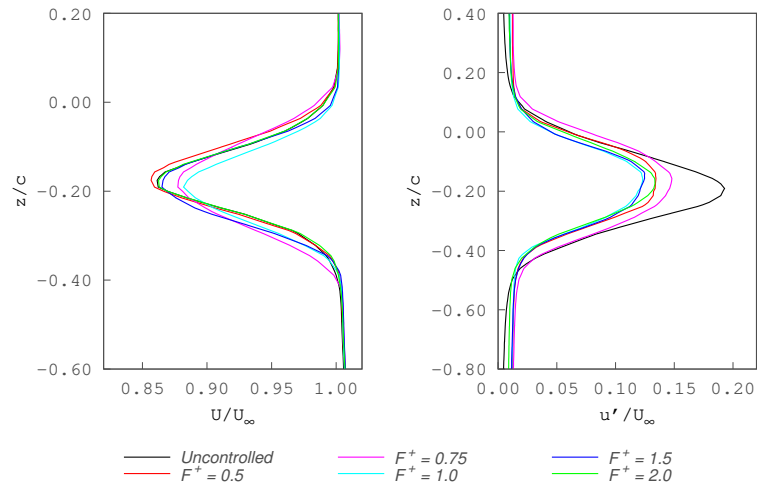


FIG. 9. Wake mean (left) and rmse (right) velocity profiles at  $x/c = 2.0$ .

## 2. Excitation Frequency and Separated Flow Interactions

The physical mechanism behind the effectiveness of acoustic excitation is investigated in terms of nondimensionalised instantaneous spanwise vorticity contours and iso-surfaces of Q-criterion, as illustrated in Figure 10 and Figure 11, respectively. Acoustic excitation reorganizes the separated shear layer breakdown in such a way that more coherent vortical structures are shed from the shear layer as identified by the magnitude of vorticity. For effective excitation frequencies such as  $F^+ = 1.0$ , the separated shear layer moves closer to the aerofoil suction surface compared to the uncontrolled flow. As a result, a narrower vortex street is generated and smaller scale and more coherent vortices are shed downstream. Being closer to the aerofoil surface, these vortical structures with improved coherence enhance turbulent mixing and hence, energy transfer across the shear layer. Therefore, the wall-normal extent of flow separation is reduced with local reattachments in some cases. Although excitation with  $F^+ = 0.5$  and  $F^+ = 2.0$  affects the shear layer roll up characteristics, the effect is not profound to result in a considerable change in the location of shear layer. In other words, excitation with these frequencies promotes earlier vortex breakdown of the shear layer compared to the uncontrolled flow, but the shear layer is not moved closer to the aerofoil surface. This results in shed vortices being unable to provide sufficient energy transfer to separated flow region that separation characteristics remain unchanged. Conversely, excitation with  $F^+ = 0.75$  and  $F^+ = 1.5$  results in relocation of shear layer closer to the aerofoil whilst the vortex coherence is substantially reinforced. Consequently, the momentum transfer is improved across the shear layer that results in a diminished separation region, supporting the velocity profile improvements at the outer zones of separated flow shown in Figure 8.

Acoustic excitation with the most unstable frequency, i.e.,  $F^+ = 1.0$ , provides the highest improvement in vortex shedding characteristics amongst the frequencies considered. Excitation at this frequency results in highest vortex coherence and the closest shear layer placement in the vicinity of aerofoil. This promotes increased energy transfer to the separated flow in the near-wall region starting from the immediate vicinity of the separation onset as seen in an increase in rmse velocity profiles at  $x/c = 0.6$  shown in Figure 8. The effect becomes more substantial further downstream with vortex breakdown at  $x/c \approx 0.7$  with a significantly increased turbulent intensity within the separated flow. With transfer of more energy to the separated flow towards the aft of the aerofoil, the extent of the flow separation is considerably reduced with a nearly attached flow in the vicinity of the trailing edge region.

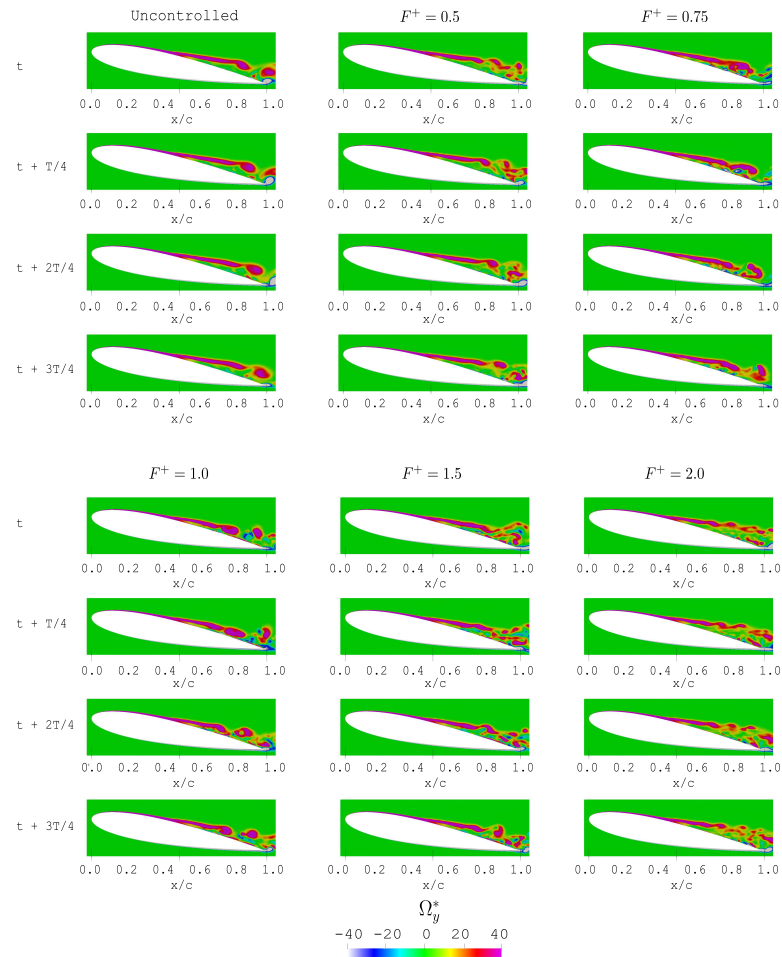


FIG. 10. Nondimensional spanwise vorticity distributions.

The Q-criterion is used in visualization of the vortical structures in the flow field in Figure 11. In the uncontrolled flow, the break down of separated shear layer takes place around the trailing edge region that results in lack of coherence in vortical structures in the separated flow and large vortices are shed in the wake of aerofoil. With emerging of acoustic excitation at  $F^+ = 0.5$ , an earlier shear layer break down with a meagre rise in vortex coherence is observed. However, the excited flow is still not transferring sufficient energy to separated flow regions as the separation characteristics show no major change. With excitation frequency  $F^+ = 0.75$ , advancement of the shear layer break down and enhancement on the vortex coherence is observed. For excitation at  $F^+ = 1.0$ , the location of transition within the separated shear layer advances further upstream and moves closer to the aerofoil wall and a substantial increase in vortex coherence is generated that increases the momentum transfer across the shear layer to the separated flow. The effectiveness of acoustic excitation becomes smaller with further increase in excitation frequency and eventually has negligible effect for  $F^+ = 2.0$  with a reduced vortex coherence and delayed transition and break down of the shear layer compared to excitation at  $F^+ = 1.0$ .

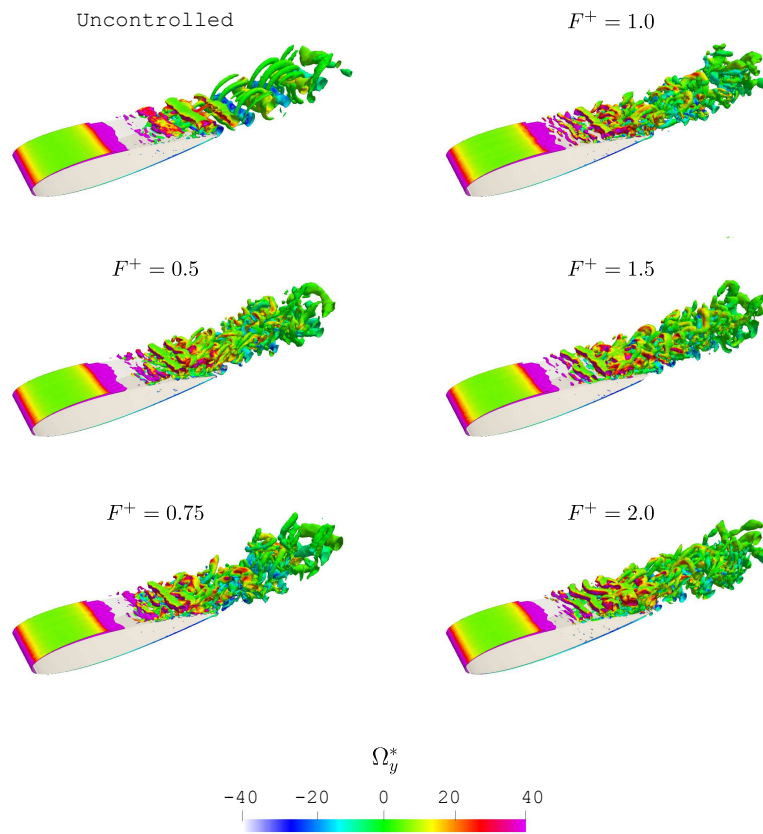


FIG. 11. The Q-criterion at  $Q = 10^5$  coloured by normalised mean velocity magnitude.

The comparison of the turbulent kinetic energy spectra at streamwise locations shown in Figure 5 and a monitor location at  $x/c = 2.0$  is illustrated in Figure 12. In the controlled flow, the natural frequencies in the separated shear layer correspond to  $F^+ = 1.0$  and  $F^+ = 2.0$  as illustrated in Figure 6. The implication of acoustic excitation throughout the monitor stations under investigation is to lock the excitation frequency onto the instability frequencies in the separated shear layer for the effective acoustic excitation frequencies. This promotes acceleration of the growth of natural instabilities, consequently resulting in an earlier transition in the separated shear layer. Therefore, energy cascade is improved and more coherent structures are generated, which improves the momentum transfer across the shear layer.

Sound waves with a frequency corresponding to  $F^+ = 0.5$  are unable to excite the instability mechanisms in the uncontrolled flow as the modal frequencies and the corresponding energy content show no major change in the turbulent kinetic energy spectra throughout the separated flow region. Excitation with frequencies  $F^+ \geq 0.75$  results in a better defined peak at the frequency of excitation with a higher energy content in the spectra for the stations at  $x/c = 0.5$  and further downstream. The results suggest that the most effective excitation frequency corresponds to the natural dominant frequency,  $F^+ = 1.0$ , of the separated shear layer in the uncontrolled flow. The instability mechanism in the flow is excited by sound waves at this frequency that results in a substantial energization of the instability mechanisms in the separated flow that eventually results in an earlier breakdown of the shear layer. As a result, more coherent structures are generated at the excitation frequency as well as its harmonic frequencies. As the flow reattaches at  $x/c \approx 0.7$ , the modal frequencies in the spectra disappear for further downstream stations including the wake. Furthermore, harmonic frequencies are generated in the excited flow that indicates generation of smaller scale vortices with an increased coherence. This is attributed to the breakdown of large scale structures into smaller length scale structures in the flow as demonstrated by the flow field analyses in Figure 10 & 11. The implication of concentration of the dominant frequency peaks at the frequency of the acoustic excitation is that acoustic excitation successfully locks the instabilities in the flow onto the excitation frequency.

Although the sound wave frequency at  $F^+ = 2.0$  excites the instability mechanism in the uncontrolled flow upstream of the onset of flow separation at  $x/c = 0.5$ , its effect in the turbulent kinetic energy spectra is suppressed by the mean flow at further downstream stations for  $x/c \geq 0.6$ . This results in a limited effectiveness of acoustic excitation for this frequency. Therefore, excitation with this frequency has negligible effect in the flow field although it is one of the modal frequencies in the uncontrolled flow turbulent kinetic energy spectra.

In conclusion, the most dominant frequency in the uncontrolled flow turbulent spectrum is the most effective acoustic excitation frequency. Although the frequencies in between the most dominant frequency and its lower and higher harmonics provide an improvement in the flow separation characteristics, the dominant frequency results in the highest control over the separated flow.

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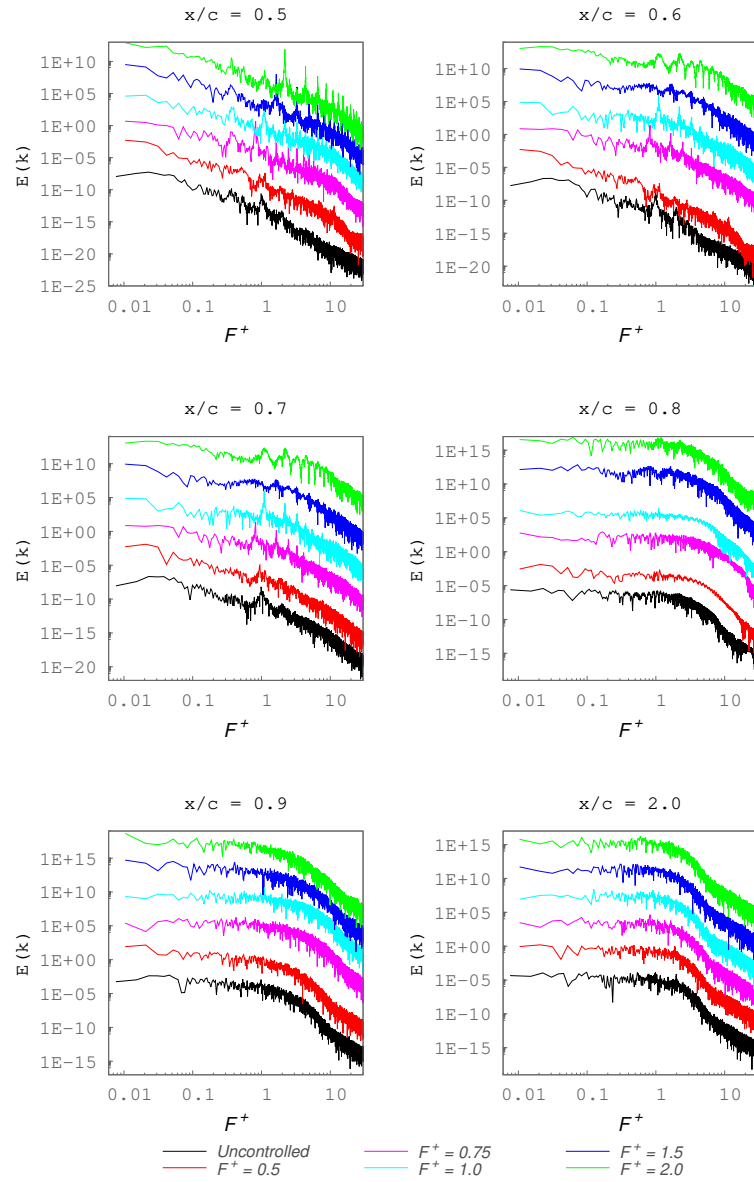


FIG. 12. Turbulent kinetic energy spectra with respect to excitation frequency. The amplitude of each successive spectrum is stepped by four orders of magnitude for clarity.

Reynolds shear stress (RSS) is a measure of turbulent mixing that results in momentum transfer to the near-wall regions. This energizes the low momentum flow in these regions in wall-bounded flows. RSS normalized by the freestream velocity,  $-\overline{u'v'}/U_\infty^2$ , is shown in Figure 13. In the uncontrolled flow, the break down of the separated shear layer takes place aft of the aerofoil that increases the RSS in this region. With acoustic excitation, the break down of the shear layer shifts upstream as outlined earlier due to amplification of the instabilities by acoustic excitation. Therefore, an increase in Reynolds shear stress is observed further upstream when the flow is excited. Although the turbulent mixing is increased for  $F^+ = 0.5$ , momentum transfer to near-wall region is insufficient because of the shear layer break down taking place away from the aerofoil surface. For excitation with  $F^+ = 0.75$  and  $F^+ = 1.5$ , there is a significant rise in RSS in near-wall regions aft of the aerofoil due to increased turbulent fluctuations due to the break down of the shear layer. This results in improved momentum transfer to near-wall separated flow region, reducing the extent of flow separation. For the excitation frequency  $F^+ = 1.0$ , shear layer breaks down closer to the wall than any other excitation frequency considered, resulting in a significantly lower spreading region that substantially improves the momentum transfer. The lower turbulent mixing in this case indicated by a lower peak value of RSS is due to the wall damping as the shear layer is located in the immediate vicinity of the aerofoil surface. Excitation frequency  $F^+ = 2.0$ , on the other hand, is unable to provide sufficient momentum transfer because of the shear layer break down taking place away from the wall although there is a considerable rise in turbulent mixing compared to the uncontrolled flow.

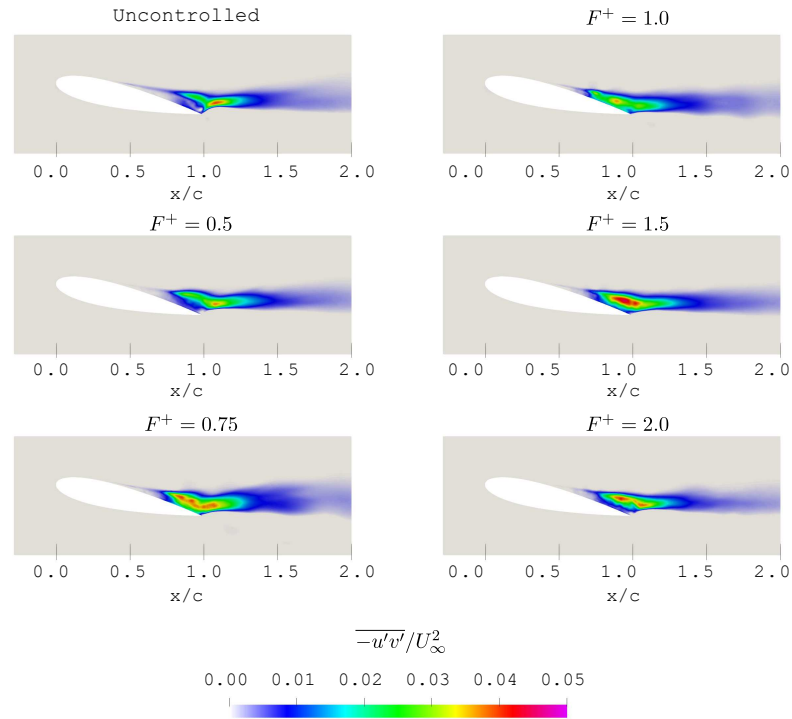


FIG. 13. Reynolds shear stress comparisons.

### 3. The Effect of Excitation Frequency on Aerofoil Aerodynamic Performance

The overall effect of acoustic excitation on aerofoil performance is quantified in terms of the locations of flow separation (S), transition (T) and reattachment (R), if existent, in the flow field as shown in Table II. These locations are determined from time-averaged pressure coefficient,  $C_p$ , and skin friction coefficient,  $C_f$ , as illustrated in Figure 14. The point of separation is identified by a nearly constant pressure region whereas the transition location is at where a sudden increase in pressure occurs as transition takes place over a region instead of a single point. Lastly, reattachment location is identified by the location where skin friction coefficient starts to recover. In the baseline flow, the separated flow does not reattach over the aerofoil as the shear layer break down takes place near the trailing edge of the aerofoil. With acoustic excitation emerging, the onset of separation is slightly delayed downstream, whereas the location of transition shifts upstream resulting in reattachment of the separated flow, forming a separation bubble over the aerofoil suction surface. The most effective excitation is observed at  $F^+ = 1.0$  where the onset of separation is moved downstream by  $\Delta x/c \approx 0.07$  and the location of transition is shifted upstream by  $\Delta x/c \approx 0.13$ . The flow reattachment is also observed at  $x/c = 0.703$ . This results in a reduction in the separation bubble length to  $\Delta x/c \approx 0.102$  compared to baseline flow that is exposed to flow separation for  $\Delta x/c \approx 0.45$ .

| $[x/c]$          | Uncontrolled | $F^+ = 0.5$ | $F^+ = 0.75$ | $F^+ = 1$ | $F^+ = 1.5$ | $F^+ = 2$ |
|------------------|--------------|-------------|--------------|-----------|-------------|-----------|
| Separation (S)   | 0.546        | 0.566       | 0.573        | 0.601     | 0.550       | 0.570     |
| Transition (T)   | 0.743        | 0.696       | 0.649        | 0.605     | 0.664       | 0.640     |
| Reattachment (R) | —            | —           | 0.742        | 0.703     | 0.720       | —         |

TABLE II. Effect of excitation frequency on aerofoil suction surface separation, transition and reattachment points.

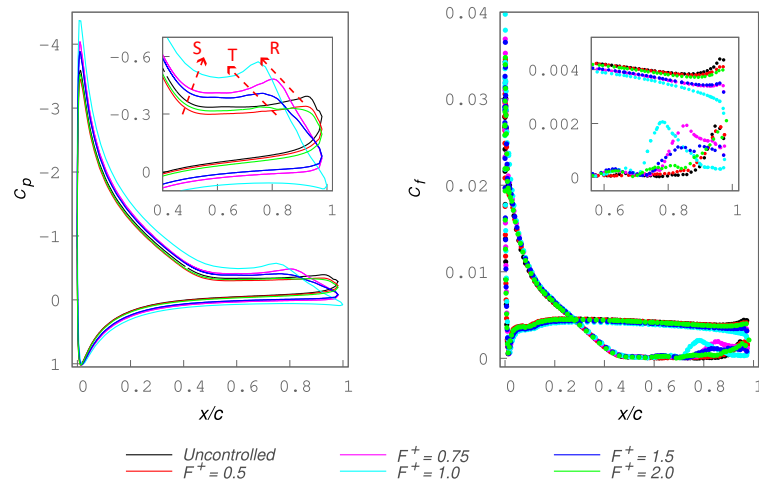


FIG. 14. Time- and span-averaged  $C_p$  and  $C_f$  distributions with excitation frequency.

The aerodynamic performance of the aerofoil is enhanced by acoustic excitation with regard to change in  $\Delta C_L/C_D$  in a Gaussian-like distribution with excitation frequency that centres at the natural frequency of the uncontrolled flow with an accompanied increase by  $\sim 43\%$ . Excitation with frequencies corresponding to  $F^+ = 0.75$  and  $F^+ = 1.5$  provides nearly 15% improvement in aerodynamic performance whilst excitation with lower and higher harmonic frequencies of the natural frequency, i.e.,  $F^+ = 0.5$  and  $F^+ = 2.0$ , has a negligible effect. The reduction in the size of separation region with acoustic excitation consistently improves the lift generated by the aerofoil with a reduction in aerofoil drag. The levels of improvement can reach up to 30% increase in lift coefficient whilst 10% reduction in drag coefficient for  $F^+ = 1.0$  as demonstrated in Figure 15. These observations are in agreement with the previous flow field analyses as described in the previous section.

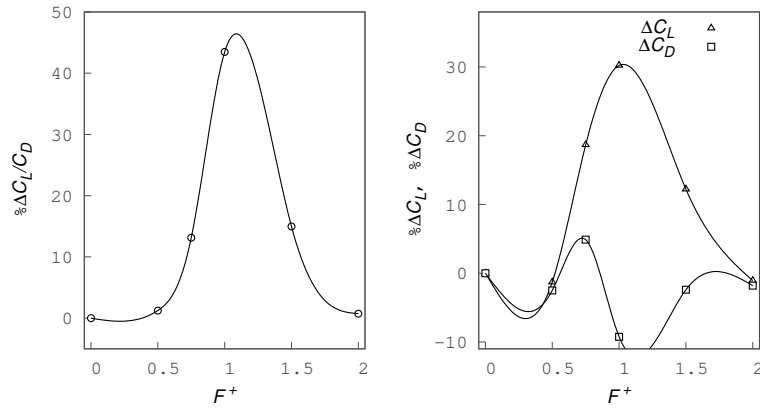


FIG. 15. Percentage change in  $C_L/C_D$  (left),  $C_L$  and  $C_D$  (right) with respect to  $F^+$ .

The time-histories of  $C_L$  and  $C_D$  for the uncontrolled flow and acoustically excited flow are shown in Figure 16 for the most effective sound wave frequency, i.e.,  $F^+ = 1.0$ . The transient data illustrate amplified fluctuations in both  $C_L$  and  $C_D$  at the frequency of excitation. An initial period of 20 convective times is disregarded in the results for the elimination of the initial transient in the numerical simulations. After the removal of the initial transients, ensemble averaging is used in the transient data to calculate the time-averaged values of aerofoil lift and drag coefficients. The effect of acoustic excitation on the aerofoil lift and drag coefficients converges to  $C_L = 1.155$  and  $C_D = 0.0488$  after the initial transient in the numerical simulation, which implies a rise in  $C_L$  by 30% and a reduction in  $C_D$  by 10% compared to the uncontrolled flow.

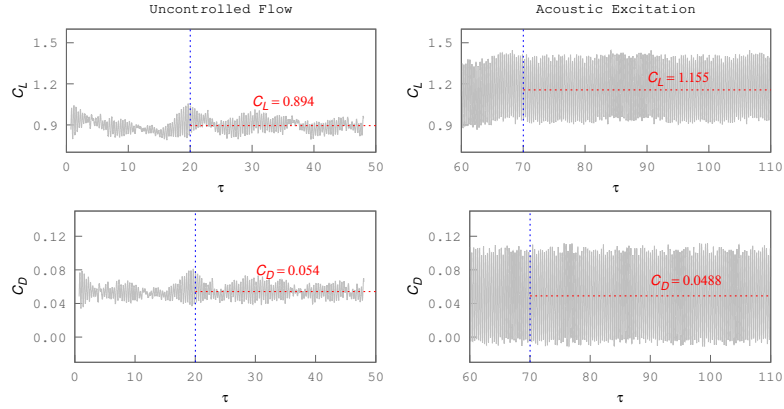


FIG. 16.  $C_L$  and  $C_D$  time histories with and without acoustic excitation at  $A_m = 1.8\%$  and  $F^+ = 1.0$ .

Boundary layer analyses are carried out in terms of displacement thickness,  $\delta^*$ , and shape factor,  $H$  for the effect of acoustic excitation in B/L on the aerofoil suction surface as shown in Figure 17. The displacement thickness defines the physical distance through which external inviscid flow is displaced in the presence of viscous B/L<sup>31</sup>, given by:

$$\delta^* = \int_0^\eta \left(1 - \frac{\rho u}{\rho_e u_e}\right) d\eta \quad \delta \leq \eta \rightarrow \infty \quad (9)$$

where  $\eta$  represents the wall-normal direction and  $\rho_e$  and  $u_e$  are air density and velocity at the edge of the boundary layer, respectively. The upper limit for the wall-normal distance goes to infinity because of the boundary layer hypothesis, which implies the outer edge of the B/L.

Momentum thickness,  $\theta$ , is a measure of the distance by which the geometry needs to be replaced in the wall-normal direction in an inviscid flow to compensate for the missing momentum due to the presence of B/L<sup>31</sup>. Momentum thickness is given by:

$$\theta = \int_0^\eta \frac{\rho u}{\rho_e u_e} \left(1 - \frac{u}{u_e}\right) d\eta \quad \delta \leq \eta \rightarrow \infty \quad (10)$$

The B/L shape factor,  $H$ , is the ratio of displacement thickness to momentum thickness<sup>32</sup>:

$$H = \frac{\delta^*}{\theta} \quad (11)$$

The shape factor is considered to be an indicator of the state of the boundary layer<sup>33,34</sup>. A strong adverse pressure gradient in the uncontrolled flow results in a rise in the shape factor, in agreement with the findings by Vaquero et al.<sup>33</sup>. The reason behind this is the B/L thickening due to an adverse pressure gradient, as illustrated by the significant rise in displacement thickness in Figure 17 downstream of the onset of flow separation. Acoustic excitation results in a substantially reduced displacement thickness because of the suppression of the extent of flow separation. As a result of the decrease in the adverse pressure gradient due to separation suppression and, hence, displacement thickness, the shape factor is also dramatically reduced. The level of suppression in flow separation is better illustrated in comparison of the shape factor in the presence of acoustic excitation to the theoretical value of the shape factor,  $H = 2.59$ , for the laminar flat plate boundary layer<sup>35,36</sup>.

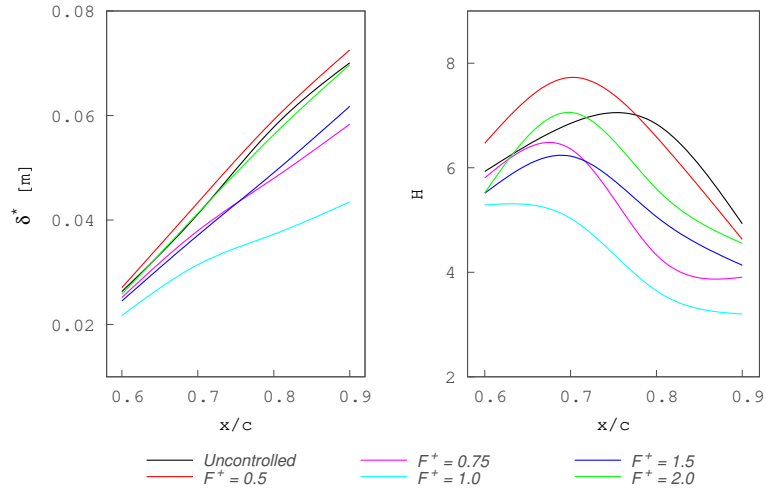


FIG. 17. Displacement thickness,  $\delta^*$ , (left) and shape factor,  $H$ , (right) with excitation frequency.

Overall, the results indicate that acoustic excitation can significantly improve the aerodynamic performance when the flow is excited with sound wave frequencies in  $0.75 \leq F^+ \leq 1.5$ , the most effective excitation frequency corresponding to the natural frequency of the shear layer in the uncontrolled flow. The physical mechanism behind this is that sound waves amplify the inherent instabilities in the uncontrolled flow that eventually results in an earlier transition in the separated shear layer, resulting in an earlier roll-up and breakdown of the shear layer. Earlier breakdown of the shear layer implies vortex coherence in the vicinity of the aerofoil surface, which improves the momentum transfer across the separated shear layer into the separated flow regions to control the flow separation.

#### B. The Effect of Excitation Amplitude

It has been observed in previous research<sup>13,21,37</sup> that the excitation amplitude is the other major parameter for the effectiveness of acoustic excitation alongside the frequency. Therefore, with establishment of the optimum excitation frequency, the effect of excitation amplitude on flow separation is investigated in this section. The amplitude of excitation,  $A_m$ , is quantified as a fraction of the freestream velocity at the upstream boundary of the computational domain, i.e.,  $A_m \sim u/U_\infty$  %. A parametric study is conducted on excitation amplitude in the range  $1.0\% (135dB) \leq A_m \leq 10.0\% (154dB)$ . The upper excitation amplitude boundary is above the amplitude limits that can be provided by a subwoofer in an experimental environment to define the boundaries of effective amplitude range for acoustic excitation.

### 1. Effect of Excitation Amplitude on Flow Field

The effect of excitation amplitude on the flow around the aerofoil is demonstrated in Figure 18 by streamlines superimposed on mean velocity magnitude contours. The excitation frequency is fixed at  $F^+ = 1.0$ . The results indicate that the extent of flow separation over the suction surface is significantly reduced even with the lowest excitation amplitude  $A_m = 1.0\%$ . This is because of the change in the transition mechanism in the separated shear layer by acoustic excitation such that earlier transition is promoted, which results in an intermittent boundary layer reattachment and generates a separation bubble over the aerofoil. Increasing excitation amplitude promotes reduction in the separation bubble size. At a certain excitation amplitude, the separation bubble size is minimised and further increase in amplitude results in no major effect in the flow field, which is  $A_m = 5\%$  in this case.

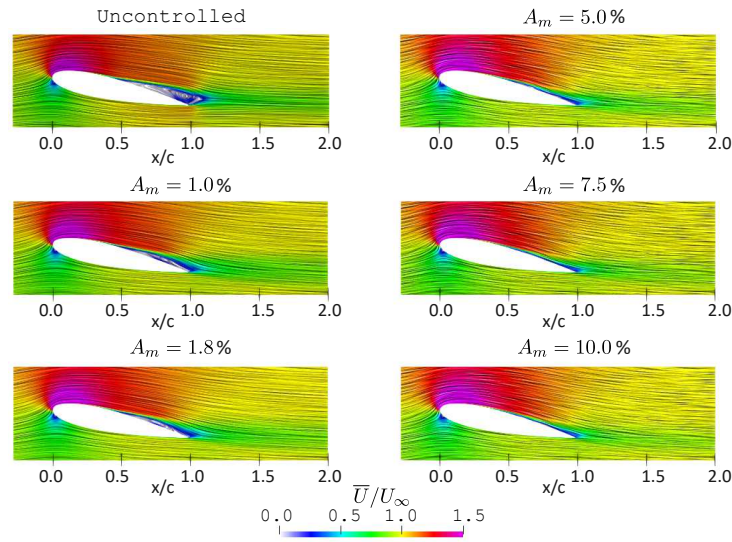


FIG. 18. Streamlines over the aerofoil coloured by mean velocity magnitude.

Mean and rmse boundary layer and wake velocity profiles are compared in Figure 19 and 20, respectively, with respect to the excitation amplitude. From the station just after the onset of flow separation,  $x/c = 0.6$ , the effect of sound excitation starts to appear as the vertical extent of separated flow profile reduces with excitation. The change in the flow field due to excitation amplitudes  $A_m = 1.0\%$  and  $1.8\%$  is such that there is a reduction in the vertical extent of the flow separation for all the stations shown in Figure 18, with a growing effect downstream. The effectiveness of excitation increases significantly with a rise in sound amplitudes. The effect of acoustic excitation becomes more pronounced for further downstream stations over the suction surface such that the excited flow displays a nearly attached velocity profile for  $x/c = 0.7$  and the flow is fully attached at  $x/c = 0.8$  and  $0.9$  for the excitation amplitudes  $A_m \geq 5.0\%$ . The improvement in the flow field is not as pronounced for amplitudes  $A_m \geq 5.0\%$ . There is a negligible change in the flow with further increase in the amplitude.

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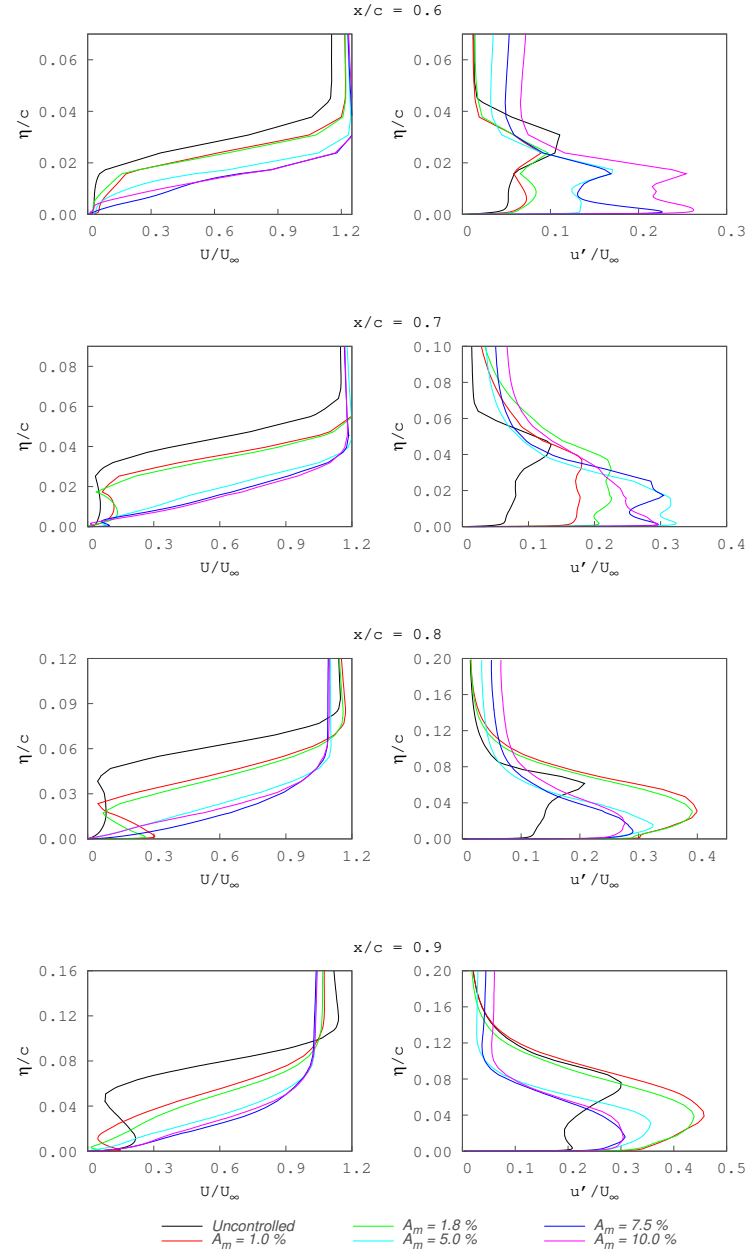


FIG. 19. Boundary layer mean and rms velocity profiles with respect to excitation amplitude at  $F^+ = 1.0$ .

The comparison of the wake velocity profiles at  $x/c = 2.0$  reveals an enhanced momentum deficit with increasing sound amplitude compared to the uncontrolled flow as illustrated in Figure 20. A nearly 4% enhancement on the peak velocity deficit is obtained for  $A_m = 5.0\%$ .

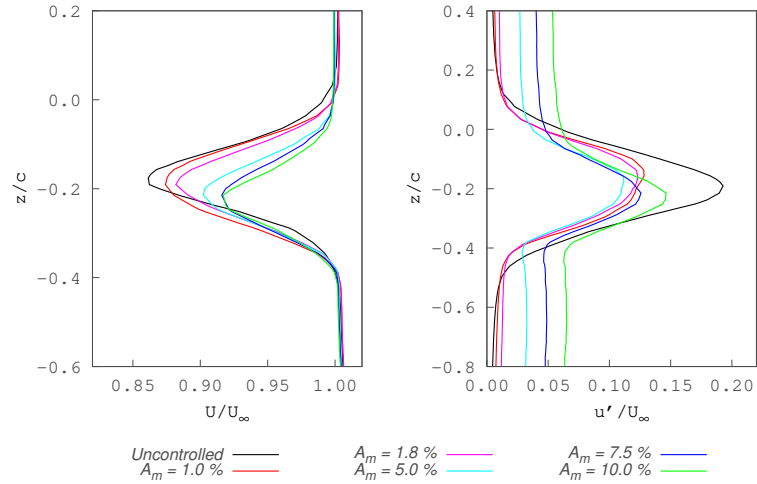


FIG. 20. Wake mean and rms velocity profiles at  $x/c = 2.0$ .

## 2. Excitation Amplitude and Separated Flow Interactions

A quantitative comparison of the excitation amplitude effect is carried out for the changes in separation, transition and reattachment locations as given in Table III. The results indicate that the onset of flow separation shifts downstream over the aerofoil with increasing excitation amplitude with emerging sound waves at  $A_m = 1.0\%$ . A flow reattachment is also observed at  $x/c \sim 0.775$  that results in generation of a separation bubble. Increasing excitation amplitude moves the reattachment location upstream over the suction surface, shortening the separation bubble size. For the excitation amplitude  $A_m = 10.0\%$ , the separated shear layer reattaches at  $x/c \sim 0.636$ , a 15% chord length shift upstream compared to  $A_m = 1.0\%$  excitation as seen in  $C_p$  and  $C_f$  distributions in Figure 21.

| $[x/c]$              | Uncontrolled | $A_m = 1\%$ | $A_m = 1.8\%$ | $A_m = 5\%$ | $A_m = 7.5\%$ | $A_m = 10\%$ |
|----------------------|--------------|-------------|---------------|-------------|---------------|--------------|
| Separation ( $S$ )   | 0.546        | 0.556       | 0.573         | 0.599       | 0.600         | 0.594        |
| Transition ( $T$ )   | 0.743        | 0.635       | 0.605         | 0.605       | 0.604         | 0.603        |
| Reattachment ( $R$ ) | —            | 0.775       | 0.703         | 0.693       | 0.606         | 0.636        |

TABLE III. Effect of excitation amplitude on the flow separation, transition and reattachment locations.

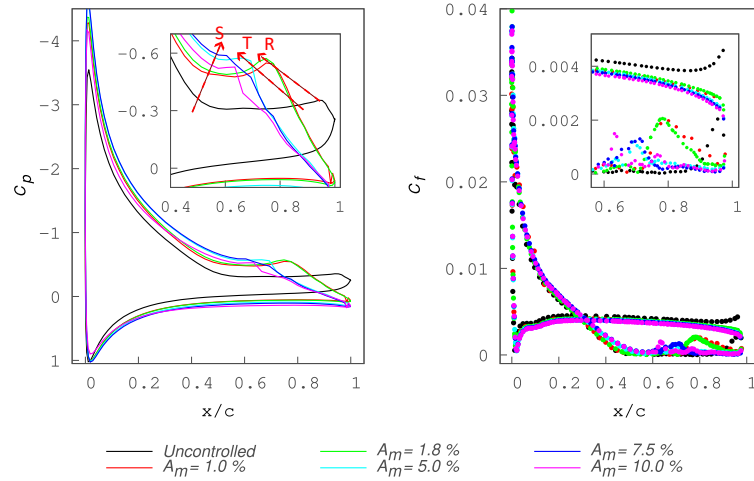


FIG. 21. Time- and span-averaged  $C_p$  and  $C_f$  distributions.

### 3. Effect of Excitation Amplitude on Aerofoil Performance

Aerofoil  $C_L/C_D$  is compared in the presence of acoustic excitation in this section for quantification of the overall effect of excitation amplitude on the aerofoil aerodynamic performance. The results display an asymptotical increase in aerofoil  $C_L/C_D$  with amplitude increase as shown in Figure 22. The reduction in flow separation with excitation decreases aerofoil drag more than 20% for excitation amplitudes  $A_m \geq 5\%$  while increasing the lift coefficient dramatically up to  $\Delta C_L = 40\%$ . This eventually rises  $C_L/C_D$  nearly 120% because of the significant suppression of the flow separation with acoustic excitation.

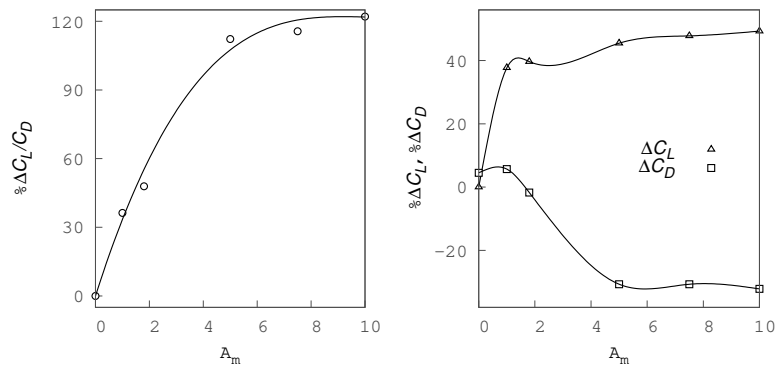


FIG. 22. Percentage change in  $C_L/C_D$  (left),  $C_L$  and  $C_D$  (right) with respect to  $A_m$ .

The effect of sound wave amplitude on the effectiveness of acoustic excitation is to accelerate the amplification of the instabilities with increasing sound amplitude at an effective excitation frequency. The results indicate there is a maximum effective sound amplitude beyond which the effectiveness of acoustic excitation does not improve further with the sound amplitude. This is because the flow is nearly fully attached that increasing the sound amplitude does not improve the flow field any further.

### C. The Effect of Freestream Turbulence Intensity

The current angle of attack of the aerofoil under investigation is in the transition-to-stall region where the flow separation, shear layer and aerofoil wake are the most susceptible to freestream turbulence intensity ( $TI$ )<sup>38</sup>. As the focus of the current work is the investigation of acoustic excitation effects on turbulent flow separation, a range of freestream turbulent intensity levels are explored for the effectiveness of acoustic excitation. A freestream turbulence intensity of  $TI = 5\%$  is utilised up to now. In this section, a further investigation on the effect of freestream turbulence intensity level on the effectiveness of acoustic excitation is explored for three levels of turbulence intensity at  $TI = 5\%$ ,  $3\%$  and  $0.5\%$ .

#### 1. Effect of Turbulence Intensity on Excited Flow Field

As the chord-based Reynolds number for the flow over the aerofoil is relatively high, the inertial forces in air flow are dominant to viscous forces and the flow can be classified as a turbulent flow due to this high  $Re_c$ , irrespective of the freestream turbulence. Therefore, the extent of the flow separation has minimal differences in the uncontrolled flow for the freestream turbulence levels compared, as illustrated in Figure 23. This is in agreement with the previous findings by Ameri et al.<sup>39</sup>. The effect of acoustic excitation is compared for the three turbulence levels at a constant excitation frequency,  $F^+ = 1.0$ , and amplitude,  $A_m = 5\%$ , which were obtained as the most effective acoustic excitation frequency and amplitude in previous sections for the flow under investigation. Acoustically excited flows, on the contrary to uncontrolled flow, show a strong dependence on freestream turbulence intensity. The results suggest that the effectiveness of acoustic excitation on suppression of the flow separation increases with the freestream turbulence intensity. Acoustic excitation successfully reduces the flow separation for low freestream turbulence levels, i.e.,  $TI = 0.5\%$  and  $3\%$ , whilst the separation over the aerofoil is almost completely suppressed for  $TI = 5\%$ . Therefore, acoustic excitation can be used as a means of flow control for high turbulence intensity flows such as internal flows.

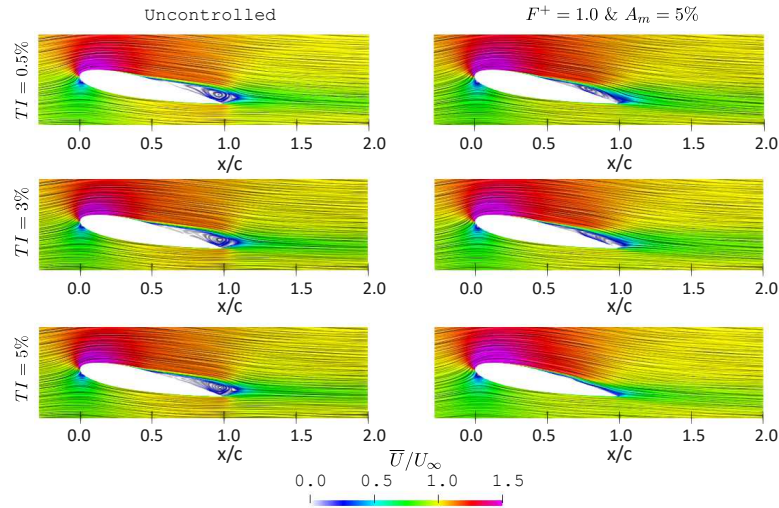


FIG. 23. Streamlines over the aerofoil coloured by mean velocity magnitude.

## 2. Aerofoil Performance with Acoustic Excitation and Turbulence Intensity

The overall effect of freestream turbulence levels on the effectiveness of acoustic excitation is quantified in terms of the aerofoil aerodynamic performance in  $C_L/C_D$ ,  $C_L$  and  $C_D$  as illustrated in Figure 24. Although the highest improvement on the aerofoil performance is obtained for  $TI = 5\%$ , the lower turbulence levels,  $TI = 0.5\%$  and  $3\%$ , also provide considerable improvement on the aerodynamic performance of the aerofoil such that a nearly 30% rise in aerofoil  $C_L/C_D$  for  $A_m = 5\%$  sound amplitude is obtained for both  $TI = 3\%$  and  $TI = 0.5\%$ . The main reason underneath being the rise in  $C_L$  as there is little to no change in  $C_D$ . However, the control authority of acoustic excitation on flow separation suppression is more dramatic for the highest turbulence level utilised. The separated shear layer is eminently susceptible to acoustic excitation that the lowest excitation amplitude considered,  $A_m = 1.0\%$  can provide an extensive rise in aerofoil performance. Therefore, the results indicate that acoustic excitation can improve flow separation characteristics at high Reynolds number turbulent flows.

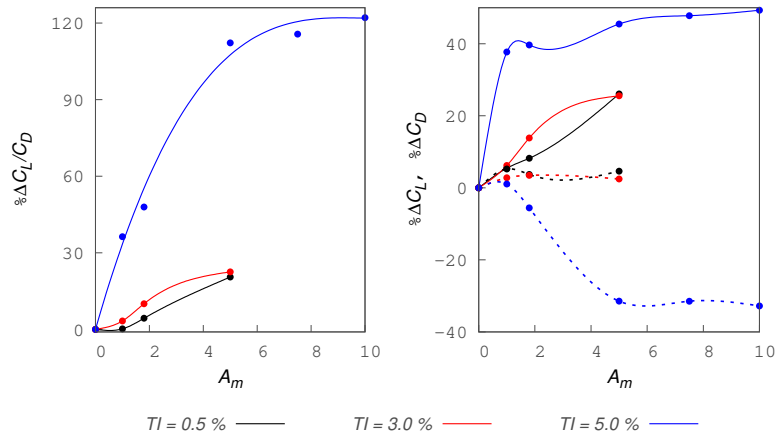


FIG. 24. Percentage change in  $C_L/C_D$  (left),  $C_L$  and  $C_D$  (right; solid lines for  $C_L$  and dashed lines for  $C_D$ ) with respect to  $A_m$ .

#### IV. CONCLUSIONS

The focus of this study is the investigation of acoustic excitation as a flow control technique for turbulent separated flow over a NACA0015 aerofoil at a high Reynolds number. The study is carried out numerically with the use of Improved Delayed Detached Eddy Simulations. The developed methodology in this work provides crucial insight into the effectiveness of acoustic excitation at high-Re separated flows, which could not be investigated before. The control parameters under investigation for acoustic excitation are the excitation frequency, sound wave amplitude, and freestream turbulence intensity. The effects of these parameters on flow separation over the aerofoil are as follows:

- A range of effective acoustic excitation frequencies is explored. The optimum excitation frequency corresponds to the frequency of the most amplified disturbances in the uncontrolled flow. It was observed that the separated shear layer moves closer to the aerofoil surface with acoustic excitation, enhancing the momentum transfer to separated flow regions. Acoustic excitation shifts the location of the flow separation downstream, while the transition in the separated shear layer takes place earlier that may result in intermittent flow reattachment, generating a separation bubble. Consequent to these manipulations of the flow mechanisms, the aerofoil performance is improved by up to  $\sim 43\%$  in  $C_L/C_D$  at a constant excitation amplitude of  $A_m = 1.8\%$ .
- A strong dependence of the effectiveness of acoustic excitation on the excitation amplitude is observed. A maximum effective excitation amplitude was also observed, beyond which little to no further improvement is gained. The most effective excitation amplitude corresponds to  $A_m = 5\%$  that results in  $\Delta C_L/C_D \approx 120\%$  compared to the uncontrolled flow.
- Freestream turbulence intensity plays a critical role in the effectiveness of acoustic excitation. A considerable improvement in excitation effectiveness with freestream turbulence intensity was obtained. The results suggested that acoustic excitation is most effective at the highest freestream turbulence level, although flow separation is also reduced at lower turbulence levels.

Overall, it was shown in this work that acoustic excitation can control the flow separation for high Reynolds number turbulent flows when applied under an effective range of excitation parameters and operating conditions. One of the potential impacts of this research is the control of flow separation over wings at near-stall operations. The potential implications of this are a delay in the stall angle of attack while increasing the aerodynamic efficiency substantially.

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#### DATA AVAILABILITY

The data that support the findings of this study are available within the article. Additional data that support the findings of this study are available from the corresponding author upon reasonable request.

#### REFERENCES

- <sup>1</sup>P. K. Chang, *Separation of Flow*, 1st ed. (Pergamon Press, 1970).
- <sup>2</sup>R. L. Simpson, "A review of some phenomena in turbulent flow separation," *Journal of Fluids Engineering, Transactions of the ASME* **103**, 520–533 (1981).
- <sup>3</sup>D. Greenblatt and I. J. Wygnanski, "Control of flow separation by periodic excitation," *Progress in Aerospace Sciences* **36**, 487–545 (2000).
- <sup>4</sup>L. Huang, P. G. Huang, R. P. LeBeau, and T. Hauser, "Numerical study of blowing and suction control mechanism on NACA0012 airfoil," *Journal of Aircraft* **41**, 1005–1013 (2004).
- <sup>5</sup>D. You and P. Moin, "Active control of flow separation over an airfoil using synthetic jets," *Journal of Fluids and Structures* **24**, 1349–1357 (2008).
- <sup>6</sup>P. Servini, F. T. Smith, and A. P. Rothmayer, "The impact of static and dynamic roughness elements on flow separation," *Journal of Fluid Mechanics* **830**, 35–62 (2017).
- <sup>7</sup>V. Von Stillfried, S. Wallint, and A. V. Johansson, "An improved passive vortex generator model for flow separation control," 5th Flow Control Conference, 1–14 (2010).
- <sup>8</sup>F. G. Collins and J. Zelenyevitz, "Influence of sound upon separated flow over wings," *AIAA Journal* **13**, 408–410 (1975).
- <sup>9</sup>K. B. M. Q. Zaman, "Effect of acoustic excitation on stalled flows over an airfoil," *AIAA Journal* **30**, 1492–1499 (1992).
- <sup>10</sup>K. B. M. Q. Zaman and D. J. McKinzie, "Control of laminar separation over airfoils by acoustic excitation," *AIAA Journal* **29**, 1075–1083 (1991).
- <sup>11</sup>K. B. M. Q. Zaman, A. Bar-Sever, and S. M. Mangalam, "Effect of acoustic excitation on the flow over a low-re airfoil," *Journal of Fluid Mechanics* **182**, 127–148 (1987).
- <sup>12</sup>M. Nishioka, M. Asai, and S. Yoshida, "Control of flow separation by acoustic excitation," *AIAA Journal* **28**, 1909–1915 (1990).
- <sup>13</sup>S. Yarusevych, P. E. Sullivan, and J. G. Kawall, "Effect of acoustic excitation amplitude on airfoil boundary layer and wake development," *AIAA Journal* **45**, 760–771 (2007).
- <sup>14</sup>S. Yarusevych, P. E. Sullivan, and J. G. Kawall, "Airfoil boundary layer separation and control at low Reynolds numbers," *Experiments in Fluids* **38**, 545–547 (2005).
- <sup>15</sup>S. Yarusevych, J. G. Kawall, and P. E. Sullivan, "Airfoil performance at low Reynolds numbers in the presence of periodic disturbances," *Journal of Fluids Engineering* **128**, 587–595 (2006).
- <sup>16</sup>F. B. Hsiao, J. J. Jih, and R. N. Shyu, "The effect of acoustics on flow passing a high-aoa airfoil," *Journal of Sound and Vibration* **199**, 177–178 (1997).
- <sup>17</sup>B. H. Carmichael, "Low Reynolds number airfoil survey," Tech. Rep. (NASA CR No. 165803, Vol. 1, Nov. 1981).
- <sup>18</sup>K. K. Ahuja and R. H. Burrin, "Control of flow separation by sound," *AIAA* **84-2298** (1984), <https://doi.org/10.2514/6.1984-2298>.
- <sup>19</sup>A. I. Krikunova, A. D. Cheshko, and R. Khaddour, "Vortex zone dynamics in premixed flame under complex gravity and acoustic impact," *Physics of Fluids* **35**, 053614 (2023), [https://pubs.aip.org/aip/pof/article-pdf/doi/10.1063/5.0150239/17643037/053614\\_1\\_5.0150239.pdf](https://pubs.aip.org/aip/pof/article-pdf/doi/10.1063/5.0150239/17643037/053614_1_5.0150239.pdf).
- <sup>20</sup>S. Coskun, V. Pachidis, I. Ubulom, and M. Bacic, "Improved delayed detached eddy simulations applied to a naca0015 aerofoil subject to acoustic excitation," in *AIAA AVIATION 2022 Forum*, <https://arc.aiaa.org/doi/pdf/10.2514/6.2022-3237>.

- <sup>21</sup>S. Coskun, D. J. Rajendran, V. Pachidis, and M. Bacic, "Effect of acoustic excitation amplitude on flow separation over NACA0015 aerofoil for near-stall angle-of-attacks," in *AIAA AVIATION 2023 Forum*, <https://arc.aiaa.org/doi/pdf/10.2514/6.2023-3282>.
- <sup>22</sup>N. M. Khalifa, A. Rezaei, and H. E. Taha, "On computational simulations of dynamic stall and its three-dimensional nature," *Physics of Fluids* **35**, 105143 (2023), [https://pubs.aip.org/aip/pof/article-pdf/doi/10.1063/5.0170251/18179282/105143\\_1\\_5.0170251.pdf](https://pubs.aip.org/aip/pof/article-pdf/doi/10.1063/5.0170251/18179282/105143_1_5.0170251.pdf).
- <sup>23</sup>M. L. Shur, P. R. Spalart, M. K. Strelets, and A. K. Travin, "A hybrid RANS-LES approach with delayed-DES and wall-modelled LES capabilities," *International Journal of Heat and Fluid Flow* **29**, 1638–1649 (2008).
- <sup>24</sup>F. R. Menter and M. Kuntz, "Adaptation of Eddy-Viscosity Turbulence Models to Unsteady Separated Flow Behind Vehicles," (Springer, Berlin Heidelberg New York (2004), Monterey, USA, 2002) pp. 339–352.
- <sup>25</sup>M. S. Gritskevich, A. V. Garbaruk, J. Schütze, and F. R. Menter, "Development of DDES and IDDES formulations for the  $k-\omega$  shear stress transport model," *Flow, Turbulence and Combustion* **88**, 431–449 (2012).
- <sup>26</sup>F. R. Menter, "Two-equation eddy-viscosity turbulence models for engineering applications," *AIAA Journal* **32**, 1598–1605 (1994).
- <sup>27</sup>W. L. Siau, *Transient process of separation and attachment over a NACA 0015 airfoil controlled by fluidic vortex generators*, Ph.D. thesis, University of Poitiers, France (2008).
- <sup>28</sup>S. Eriksson and J. Nordstrom, "Exact Non-reflecting Boundary Conditions Revisited: Well-Posedness and Stability," *Foundations of Computational Mathematics* **17**, 957–986 (2017).
- <sup>29</sup>K. Zaabar, *Non-reflective Boundary Conditions for Prediction of Acoustic Tones in Non-uniform Mean Flow for Ducted Flows*, Ph.D. thesis, University of Southampton, United Kingdom (2022).
- <sup>30</sup>ANSYS, "Fluent 19.1 theory guide," Tech. Rep. (ANSYS, Inc., 2018).
- <sup>31</sup>J. D. Anderson, *Fundamentals of Aerodynamics*, 5th ed. (Mc Graw Hill, 2011).
- <sup>32</sup>F. M. White, *Viscous Fluid Flow*, 3rd ed. (Mc Graw Hill, 2006).
- <sup>33</sup>J. Vaquero, N. Renard, and S. Deck, "Effects of upstream perturbations on the solution of the laminar and fully turbulent boundary layer equations with pressure gradients," *Physics of Fluids* **31** (2019), 10.1063/1.5125496.
- <sup>34</sup>J. P. Monty, Z. Harun, and I. Marusic, "A parametric study of adverse pressure gradient turbulent boundary layers," *International Journal of Heat and Fluid Flow* **32**, 575–585 (2011).
- <sup>35</sup>H. Blasius, "Grenzschichten in flüssigkeiten mit kleiner reibung," *Z. Math. Physik*, Bd. 56, 1–37 (1908).
- <sup>36</sup>H. Schlichting, *Boundary-Layer Theory* (Springer, 2017).
- <sup>37</sup>A. V. Boiko, G. R. Grek, A. V. Dovgal, and V. V. Kozlov, "Transition to turbulence in separation bubbles," in *The Origin of Turbulence in Near Wall Flows* (Springer-Verlag, Berlin, 2002) 1st ed., pp. 167–197.
- <sup>38</sup>R. Mishra, I. Neunaber, E. Guilmineau, and C. Braud, "Wind tunnel study: Is turbulent intensity a good candidate to help in bypassing low Reynolds number effects on 2d blade sections?" *Journal of Physics: Conference Series* **2265** (2022), 10.1088/1742-6596/2265/2/022095.
- <sup>39</sup>A. Ameri, S. A. Attia, G. J. Van Fossen, and P. E. Poinssat, "High reynolds number and turbulence effects on turbine heat transfer," *Journal of Propulsion and Power* **10**, 868–875 (1994).



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## **Control of flow separation over an aerofoil by external acoustic excitation at a high Reynolds number**

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