The Effect of Surface Roughness on Laminar Separated Boundary Layers

Roughness effects on a laminar separation bubble, formed on a flat plate boundary layer due to a strong adverse pressure gradient similar to those encountered on the suction side of typical low-pressure turbine blades, are studied by direct numerical simulation. The discrete roughness elements that have a uniform height in the spanwise direction and ones that have a height that is a function of the spanwise coordinate are modeled using the immersed boundary method. The location and the size of the roughness element are varied in order to study the effects on boundary development and turbulent transition; it was found that the size of the separation bubble can be controlled by positioning the roughness element away from the separation bubble. Roughnesses that have a height that varies in a periodic manner in the spanwise direction have a great influence on the separation bubble. The separation point is moved downstream due to the accelerated flow in the openings in the roughness element, which also prevents the formation of the recirculation region after the roughness element. The reattachment point is moved upstream, while the height of the separation bubble is reduced. These numerical experiments indicate that laminar separation and turbulent transition are mainly affected by the type, height, and location of the roughness element. Finally, a comparison between the individual influence of wakes and roughness on the separation is made. It is found that the transition of the separated boundary layer with wakes occurs at almost the same streamwise location as that induced by the three-dimensional roughness element.

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Introduction

A laminar separation bubble is normally formed when low Reynolds number laminar boundary layers are subjected to strong adverse pressure gradients (APGs) as in low pressure turbines (LPTs). Control of the laminar separation has long been a point of interest. Generally, laminar separation bubbles are controlled by the airfoil design. If that is not successful, steady or unsteady forcing is explored. The latter is accomplished either by time periodic wall-blowing and suction (see, e.g., Ref. [1]) or with incoming wakes (see, e.g., Refs. [2–5]). The former control method is related to the positioning of certain elements on the surface of the turbine blade. These elements either cause a transition to turbulence which prevents laminar separation from occurring or perturbs the bubble in order to transition earlier and accelerate reattachment (see, e.g., Refs. [6–9]). In both cases, profile losses are reduced. However, it should be noted that this seems to be true only for LPTs at low Reynolds numbers and low freestream turbulence [6,10].

In the case of steady forcing, three main principles are applicable; namely, to place rather large elements on the surface which are two-dimensional in the spanwise direction, to put smaller three-dimensional elements on the surface, or to increase the overall roughness finish of the turbine blade [11]. The two-dimensional elements normally induce separation of the flow upstream of the unforced separation point, which is highly unstable and will cause the flow to transition to turbulence [12], thus preventing separation. The three-dimensional elements are positioned on the turbine blade periodically in the spanwise direction. The periodicity is chosen to be the most unstable spanwise perturbation of the separation bubble. This perturbation will not cause a transition to turbulence upstream of the separation point, but will cause the separation bubble to transition faster [13]. An overall increase in the roughness of the turbine blade will have much the same effect in terms of accelerating transition as the two former methods, depending on the average height of the roughness [11].

It is known that the growth rates of the perturbations caused by incoming wakes or, in general, time periodic forcing is higher than the growth rates of the three-dimensional steady perturbations [13] when the optimum perturbation parameters are chosen. However, a better understanding of steady forcing is necessary for various reasons. First, turbine blades do not stay smooth over their service life and, due to various reasons, become rough [6]. Second, it is necessary to gain a better understanding of how steady forcing aids in reducing the extension of the separation bubble. It would be especially interesting to try and obtain an equilibrium between successfully controlling the separation bubble, while not introducing turbulence upstream of the separation point. From a more physical point of view, we are interested in comparing the influence of wakes with the influence of roughness on the separation bubble.

Apart from the work done on turbine configurations, a large amount of basic research and research in other areas has also been undertaken to better understand the control and instability of separation bubbles (see, e.g., Refs. [12,14]). Research related to the influence that 3D spanwise perturbations have on the separation bubble can be found in Refs. [15–17]. In the latter studies, the perturbations are imposed using a constant blowing with a certain periodic spanwise variation. Therefore, only the influence on the separation of the spanwise periodicity is being studied but not the possible effects of the no-slip boundary conditions at the roughness elements. We would like to contribute to filling the gap between the basic research and the applied turbine research by determining the effect of surface roughness on the boundary layer development on low-pressure turbine blade type flows and, if so, to further understand the physical mechanisms involved.

This paper is organized as follows: after describing the numerical setup we discuss the results of various direct numerical simulations. The first section gives the results for an element that is

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two-dimensional in the spanwise direction. This section is divided into two parts. First, the influence of the roughness height is discussed and, in the second part, the location of the roughness element is discussed. The second section discusses the results for a roughness element having a height that changes periodically in the spanwise direction. The last part compares the various results with each other and the results for incoming wakes as obtained in Ref. [4]. The paper ends with our conclusions.

**Numerical Experiments**

The model that we are using in this study is a flat plate with a streamwise pressure distribution similar to those encountered on the suction side of turbine blades. The unforced base flow was chosen to match the experiment in Ref. [9], in which a flat plate was set in a convergent-divergent wind tunnel designed to reproduce the same pressure gradient as on the suction side of a T106C ultra-high-lift LP turbine blade. Our simulations match the APG part of that experiment, including the Reynolds number and the inflow conditions, which were found to be very close to a laminar Hiemenz profile. The curvature effects are not important in this part of the blade, which is typically flat [5]. For example, Ref. [9] also includes experiments on a real T106C cascade and mentions that the length of the separation bubble agrees in both cases, although the separation itself is slightly delayed on the plate.

The Reynolds number at the inlet of the simulation, based on the inflow momentum thickness $\theta_0 = 0.268 \text{ mm}$ and on the free-stream velocity $U_{ref} = 6.3 \text{ m/s}$, is $Re_{\theta_0} \approx 110$, which is low enough to be in the realm of expensive direct numerical simulations.

The code uses a fractional step method on a staggered grid, with third-order Runge–Kutta time-integration, fourth-order compact spatial discretization for the convective and viscous terms, and second-order discretization for the pressure in the directions perpendicular to the span, which is spectral. The viscous and second-order-accurate for the velocities, but with an almost-spectral resolution of the derivatives. The unforced simulation is described in Refs. [18,19], including resolution studies, a full discussion of the numerical scheme, and a comparison with the available experimental data.

Table 1 shows the parameters used for the various simulations presented here. The simulation domain $(L_x \times L_y \times L_z)/\theta_0 = 1640 \times 468 \times 774$ is discretized in $N_x \times N_y \times N_z = 1539 \times 301 \times 768$ collocation points, which, in Fig. 1, is shown to result in grid cells of the order of the Kolmogorov length scale. The only location where the dimension of the grid cells is relatively large in comparison with this length scale is around the reattachment and only extremely close to the wall. Two other resolutions were used, namely, $N_x \times N_y \times N_z = 1539 \times 301 \times 384$ for various cases (see Table 1) and $N_x \times N_y \times N_z = 513 \times 301 \times 192$ for one case ($\#3d6c$). It is obvious from Fig. 1 that the grid in these latter two cases is coarse relative to the Kolmogorov scales. However, Fig. 2 shows that the numerical errors due to the coarser grid on the first order statistics is small. These coarse grid simulations are therefore considered to be sufficient for the purpose of this study.

![Fig. 1 From top to bottom, these figures show $\Delta xH_{\alpha}$, $\Delta yH_{\alpha}$, and $\Delta zH_{\alpha}$ for $\#3d/f$. The solid line indicates the zero contour of the streamwise velocity.](image1)

![Fig. 2 Difference between the shape factor obtained using $1537 \times 301 \times 768$ points $H_{\theta_0}$ ($\#3d/f$) and $H_{\theta_0}$ ($\#3d/f$), discretized with $1537 \times 301 \times 384$ points and between $H_{\theta_0}$ and $H_{\theta_0}$ ($\#3d6c$) discretized with $513 \times 301 \times 192$ points. The solid line indicates $\Delta H = |H_{\theta_0} - H_{\theta_0}| / H_{\theta_0}$ and the dashed line indicates $\Delta H = |H_{\theta_0} - H_{\theta_0}| / H_{\theta_0}$.](image2)
and differentiation schemes, but is complicated when compact finite difference schemes are used. Both roughnesses that have a uniform height in the spanwise direction and roughnesses with a periodic z dependent height variation are simulated. The former will be denoted as 2D roughness and the latter as 3D roughness. Steady three-dimensional perturbations are explicitly added at the inflow for transition to occur in the cases where no roughness or a 2D roughness is imposed. Statistics are formed by averaging in the spanwise direction and time.

The conditions at the separation points presented in Table 1 lie within the range of values observed in previous studies. According to Ref. [25], the pressure gradient parameter $K_s$ has a value of $-0.082$ at the separation point. This value is in close agreement with the smooth case. For almost all cases, excluding the high roughness cases $R_2d_1$ and $R_2d_3$, the value of the pressure gradient parameter at the separation point is consistent with prior studies; Curle and Skan [26] found $-0.171 < \Lambda_s < -0.068$ for the onset of separation.

Results

In this section, three-dimensional simulations will be discussed. First, the results for roughness elements that are uniform in the spanwise direction are shown. Both the influence of the roughness locations along with their height will be scrutinized. The second part of this section will discuss the influence of a roughness with a periodic spanwise variation of its height for two different wave numbers.

Effect of Roughness Height. The height of the roughness element directly affects the boundary layer development by introducing high disturbance levels after the roughness element. In order to study the effect of the roughness height on the separated region, two-dimensional straight step elements with two different heights are investigated. The height of the roughness elements are $h_i/\theta_0 = 0.7$ and 1.8 for cases $2d_1$ and $2d_1h$, respectively. For both cases, the roughness is located close to the inflow $x_i/\theta_0 = 35$.

Figure 3 shows the effect of the roughness height on the instantaneous streamwise velocity. The differences between the smooth and rough cases are quite large. The small roughness element generates laminar-like vortices that transition to turbulence. After reattachment, streaks develop, as shown in Fig. 3(d), which are not seen in the smooth case. The development of the shear layer after the short roughness element is clear. For the high roughness element large vortices form due to instability of the shear layer, formed in between the negative velocity in the recirculation region and the positive free-stream velocity. Figure 4 shows the streamwise velocity fluctuation distribution along the flat plate. The time-averaged separated region is also indicated in the same

![Fig. 3 Effect of roughness on the instantaneous streamwise velocity. (a),(c), and (e) A longitudinal plane $z/\theta_0 = 200$. The solid white line indicates the separated region. (b),(d), and (f) A wall-parallel plane $y/\theta_0 = 0.93$. The solid magenta line indicates the two-dimensional roughness element. (a),(b) $R_0$, (c),(d) $2d_1$, and (e),(f) $2d_1h$.](image)

![Fig. 4 Effect of roughness on the streamwise velocity fluctuations. The solid white line indicates the mean separated region. (a) $R_0$, (b) $2d_1$, and (c) $2d_1h$.](image)
figure with thick solid lines. The fluctuations originate on the inflection point of the shear layer formed by the separation bubble. The position of the maximum streamwise intensity approximately matches with the position of the inflection points up to the maximum height of the separation point. For the smooth and low roughness cases, this can be explained by the fact that the large shear near the point of inflection enhances the energy transfer from the mean flow to the fluctuations. For the high roughness case, the shear layer development is moved to the edge of the recirculation bubble. The streamwise fluctuations are enhanced by the shear layer formed after the roughness element. Note the levels of the streamwise velocity fluctuations in Fig. 4. For the smooth case, the 2D instabilities grow in the detached shear layer that is located relatively away from the surface. In this case, it is the 2D instability accompanied by the inviscid Kelvin–Helmholtz instability that is responsible for the breakdown to turbulence [4]. The Kelvin–Helmholtz instability is characterized by the formation of large two-dimensional vortices in the separated shear layer. The large amplitude fluctuations seen in Fig. 4(a) are likely due to the regular shedding of these vortical structures. For the rough cases (see Figs. 4(b) and 4(c)) the long 2D growth mechanism is destroyed due to the effect of roughness. For the short roughness case, the shear layer is located relatively close to the surface, causing a significant effect of wall-damping on the shear layer and this results in lower intensities. For all cases, the shear layer spreading in the reattachment region and the development of high velocity gradients near the wall in the turbulent region are clear. The separated region becomes quite thin and short in the rough cases. The time-averaged skin friction coefficient distribution, as shown in Fig. 5(a), gives a quantitative measure of the length of the separated region, which has significantly decreased for the rough cases. For the strong roughness element, a big recirculation bubble is formed after the roughness element. Due to the very high disturbance level, flow transitions in the reattachment region and becomes turbulent. The fuller velocity profile prevents the formation of the laminar separation bubble due to the APG. As the size of the roughness element is halved, the recirculation bubble becomes shorter. As can be seen from the figure, skin friction recovers the $C_f$ value of the smooth case after the recirculation bubble and follows the same functional behavior downstream, showing the dominant effect of the pressure gradient until the separation location. However, since the growth rate of the disturbances are amplified due to the roughness element, the transition location moved upstream, compared to the smooth case. The wall static pressure coefficient $C_{p_{\text{w}}}$ calculated based on a reference pressure and velocity at the free-stream of the outflow plane for the rough cases, is presented in Fig. 5(b) along with the smooth case. For the smooth case, the pressure steadily increases and reaches a constant level, followed by a sharp recovery further downstream. These results indicate that due to the roughness, the large laminar separation region, as suggested by the plateau present in the $C_{p_{\text{w}}}$ distribution, disappeared for the strong rough case and shortened for the weak rough case. Increasing the roughness height moves the onset of transition upstream. Due to the high disturbances after the roughness element and the earlier transition, the separation bubble is much smaller than that on the smooth surface on both the length and height. Thus, the pressure induced losses are reduced. However, the increased roughness height causes a larger turbulent area and more turbulent mixing. Therefore, the friction losses increase with increasing height.

Effect of Roughness Location. To study the effect of the location of the roughness elements on the development of the boundary layer, the two-dimensional straight step element with a height of $h_0/\theta_0 = 0.7$ is placed at four different streamwise locations between the in-flow and the separation onset location. Figure 6 shows the time-averaged separated region. The effect of the location of the roughness element on the separation and reattachment locations and, hence, on the bubble size and shape is clear. It is interesting to note that the significant effect of the roughness is to move the reattachment point upstream, owing to transition and, hence, increased wall-normal mixing. On the contrary, the separation point is moved slightly upstream. The separated region becomes quite thin and short when the roughness is located further upstream of the pressure-induced separation point. The height of the bubble peak is less than 50% of that on the smooth surface. A recirculation region forms after the roughness element. If the roughness element is located further upstream, this region does not interact with the pressure-induced separation. However, when the roughness is moved downstream to $x_r/\theta_0 = 110$, the recirculation region after the roughness element merges with the separation bubble due to the pressure gradient. The combined bubble becomes larger, especially in length. For all cases, the more significant difference is in the wall-normal extension of the separation bubble, which is significantly reduced, as compared to the smooth one.

The time-averaged mean flow properties are shown in Fig. 7 with and without roughness. It can be seen that the smooth case results in a much longer region of separated flow than in the cases with roughness. Figure 7(a) shows a comparison of the time-averaged shape factor $H$. In the laminar region, the recirculation thickness $\delta_r$ increases slightly due to the recirculation region after the roughness element and results in the slight increase in the shape factor. As the recirculation bubble starts to recover, the increase in $\delta_r$ slows down. Thus, $H$ decreases to the value of the
smooth case, followed by a small increase due to the small separation bubble. The small peak of the bubble does not cause a significant increase in the displacement thickness. The roughness element distorts the boundary layer development, resulting in a significant decrease in $H$. The Reynolds number, based on the momentum thickness which gives a measure of aerodynamic loss arising from the boundary layer, is shown in Fig. 7(b). The growth of $\theta$, as a result of the APG and the separation bubble, is the reason that $Re_0$ increases. Note that in the smooth case, the sharp increase in $Re_0$ starts before the reattachment; its largest growth occurs just after transition. It is evident that the momentum thickness is significantly decreased due to the roughness effect.

Figure 7(c) shows the spatial development of the total velocity fluctuation and, hence, provides a direct measure of the transition and turbulent development. For the controlled flow, the growth of the disturbances in the initial part of the separated region is slow, whereas they grow much faster close to the reattachment. This sudden growth of the streamwise fluctuations triggers a slowdown of the bubble growth due to the turbulent energy diffusion and is responsible for the sudden increase in $C_f$ (see Fig. 7(d)).

As the roughness elements are moved upstream, the roughness elements induce transition earlier due to the higher local velocity and result in smaller separation bubbles. When the roughness element is located at the separation onset location, the size of the bubble significantly increases, especially in height. This is due to the downstream displacement of the transition location, since fluctuations do not have time to grow; that results in a large separation bubble. However, note that even this case significantly affects the extent of the bubble; hence, the bubble-induced losses, as compared to the smooth case. In Fig. 7(d), the time averaged skin friction coefficient distribution shows the extent of the turbulent region due to roughness. A large part of the flat-plate is now covered by the reattached turbulent flow. This is a negative effect for the loss variation.

Overall, it is found that the two-dimensional roughness elements affect the transitional boundary layer by moving the transition location upstream. Thus, the size of the boundary layer separation; therefore, the losses due to the separation bubble are reduced. This parametric study suggests that the optimum location of the surface roughness is far away from the separation point.

Effect of Roughness Type. In this section, the results for a roughness type whose height is not uniform but a function of the spanwise coordinate is discussed.

Figure 8 shows the influence of the roughness in comparison with the unforced flow. The roughness both reduces the extent of the separation bubble along with its height. Interestingly, it also moves the separation point downstream. This is remarkable since the separation point moves upstream downstream in the case of the roughness element the flow clearly separates downstream of this position. This downward movement of the separation point is not the result of the earlier transition, as can be seen from Fig. 9, which clearly shows that the roughness forced flow is still laminar or in the early phases of transition at the point of separation. In both cases, the reattachment of the flow is accompanied by an overall maximum in the turbulent intensity.

A comparison of Figs. 8 and 9 shows that the perturbations introduced due to the roughness element barely grow until the bubble starts to form at around $x/\theta_0 \approx 275$. This result is somewhat different from what is obtained from Ref. [9], since, in their experiments, a nonuniform height induced high r.m.s velocity fluctuations, while that was not observed in our simulations. This discrepancy might be due to the different shape of the roughness elements. In our case, the openings in the roughness element are very narrow and the peaks are not very sharp, which prevents the development of fluctuations.

The reason the separation point moves downstream in the case of the 3D roughness is due to the acceleration of the flow close to the wall, as can be seen from Fig. 10. The flow accelerates locally where the fluid is forced through the openings in the roughness barrier. First, these figures illustrate the correct functioning of the immersed boundary method and the code as a whole. Close to $y = 0$ the velocity in the valleys of the roughness elements is almost zero due to the viscosity in both the $y$ and $z$ directions. With increasing height, the velocity increases and the velocity profile widens. It should, therefore, be clear that Fig. 10 does not show how large the roughness elements and the space between
them really is, since the viscosity causes the velocity to be zero in an area much larger than only the roughness itself. Moreover, it is noted that the effects seen in Fig. 10 would be absent in the case where spanwise periodic continuous blowing would be applied. Furthermore, it is shown that before the position of the roughness element the flow accelerates at the position of the valleys, as the flow is being forced through them. Within the roughness, the flow is even accelerated slightly more with respect to before the roughness. Just after the roughness, the flow does not separate as a consequence of the roughness, due to the flow being accelerated over the whole spanwise length as the flow emerges from the valleys. This acceleration is being diffused over the whole spanwise length due to the influence of the spanwise viscosity. This higher flow velocity is quite persistent and, close to the separation point, it is still clearly visible, as can be seen from Fig. 10. Furthermore, Fig. 11 shows that, even within the separation bubble, traces of the roughness induced perturbation can be found. These traces, although small, seem to be important in triggering the transition to turbulence.

Wakes and Roughness. The roughness is a steady forcing that influences the location of the separation point and the laminar-turbulence transition location. For unsteady forcing, transition onset is influenced by the forcing in a similar way, as shown in our previous study [4], where we systematically investigated the wake forcing effect on boundary layer development by varying the wake passing frequency and shape. In that study, we found that the wake passing frequency is the key parameter to control the separation bubble. If the wake passing time is smaller than the time required for the bubble to recover itself after the wake passing, then the bubble size and, therefore, the separation induced losses decrease by almost up to 60%. On the contrary, if the wake passing time is increased, the wake does not alter the boundary development since the recovery time of the bubble is long enough to fully develop. In addition, it was found that the separation location moves downstream due to extra momentum carried by the wake and transition moves upstream due to the disturbances generated as a result of wake passing at the inflow, which reduces the separation bubble size and results in smaller pressure losses.

Figure 12 illustrates the individual effects of roughness and wakes on the shape factor and turbulent intensity. The roughness results are compared with two different wake-passing frequencies.

Fig. 10 Instantaneous snapshots of the U-velocity in the yz-plane for $\text{Re}df$. In the clockwise direction the $x$-portion varies as $x/\theta_0 = 47$ (slightly upstream of the roughness element), $x/\theta_0 = 58$ (within the roughness element), $x/\theta_0 = 106$ (slightly downstream of the roughness element), and $x/\theta_0 = 271$ (slightly upstream of the separation point). Note the different scale of the $y$ axis in comparison with the $z$ axis.

Fig. 11 An instantaneous snapshot of the U-velocity at $y/\theta_0 = 0.9$. Left: $\text{Re}d/f$; and right: $\text{Re}d/c$. The solid line marks the beginning of the roughness element and the end, respectively.
St = 0.78 and 2.90 for the low- and high-frequencies, respectively. It is surprising to note that both control methods alter the boundary layer development in a similar manner. The shape factor shown in Fig. 12(a) clearly shows the change of the separation bubble in both length and height, which is associated with either roughness or wake-passing. Similar to the 3D bubble in both length and height, which is associated with either. However, the flow close to the wall is accelerated when the roughness and wake elements are introduced well upstream of the separation point. Figure 13 provides a summary of the cases presented in this study along with the ones from Ref. [4]. The size of the bubble significantly reduces as the roughness element is located further upstream of the separation location. Similarly, the unsteady forcing data indicates that if the forcing period is much lower than the time required for the bubble to recover itself after the wake passing, then the size of the bubble decreases up to 60%. In conclusion, the combined effect would be effective as long as the roughness is located further upstream of the separation point and the wake passing period is low, which will be investigated in future studies.

Conclusions

We have presented results for two different types of roughness elements, namely, with a constant height in the spanwise direction and with a height that varies in a periodic manner in the spanwise direction.

In the first case, two different heights for the two-dimensional straight roughness elements are studied. When the roughness height is $h_1/\theta_0 = 1.8$, the flow transitions before the pressure-induced separation point and the laminar separation bubble due to the APG does not form. Only a small separation bubble is formed as a consequence of the roughness itself. Roughness heights of $h_1/\theta_0 = 0.7$ do not cause the flow to transition, but are responsible for generating perturbations that hasten the reattachment of the separation bubble. For these two-dimensional roughness element studies, it is shown that in our numerical domain the optimum position for the roughness is as far upstream of the separation point as possible. The aforementioned conclusions are qualitatively the same as the results obtained in Ref. [9]. It is worthwhile to note that there is, indeed, an agreement on the negative influence on losses of this high roughness elements that induce turbulence far upstream of the separation bubble. Furthermore, our conclusions on the location of the roughness element also roughly coincide with what was found in Ref. [9].

In the second case where the roughness height varies in the spanwise direction, the roughness does not induce transition either. However, the flow close to the wall is accelerated resulting in a separation point that is moved downstream. Once the boundary layer separates, perturbations present in the flow grow rapidly, causing the boundary layer to transition...
and, as a consequence, reattach. The length of the separation bubble was not influenced by increasing the wavenumber by a factor of two.

We thus show that it is possible to use roughness elements in such a way as to reduce the extent of the separation bubble while maintaining a laminar velocity profile for the same extent as in the unforced case. It is thus possible to reduce the profile losses related to a large separation bubble without incurring high losses as a consequence of turbulent skin friction.

Finally, we compare the individual influence of wakes and roughness on the boundary layer development. It is found that the effect of roughness and wakes modifies the spatial development of the laminar boundary layer by promoting the transition. Future studies will focus upon examining the combined effects of unsteady wakes and surface roughness on boundary layer development.

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Nomenclature

\( C_f \) = skin friction coefficient \( \tau_w / (1/2) \rho U_e^2 \)

\( C_p \) = pressure coefficient \((P - P_{ref})/(0.5 \rho U_e^2)\)

\( H \) = shape factor \( \delta^+ / \delta \)

\( h_e \) = height of roughness element (m)

\( k_e \) = wavenumber of roughness element (1/m)

\( L_0 \) = length of the separated region (m)

\( L_{b0} \) = length of the unforced separated region (m)

\( L_x, L_y, L_z \) = domain length in x, y, and z (m)

\( N_x, N_y, N_z \) = number of grid points in x, y, and z

\( \text{Re} \) = Reynolds number \( U_{ref} \theta / \nu \)

\( S_t \) = Strohual number \( f L_e / U_{ref} \)

\( T \) = maximum turbulent intensity

\( \mathcal{F} \) = wake passing period \( 1/f \)

\( U_{ref} \) = reference velocity at the inflow (m/s)

\( \delta \) = displacement thickness (m)

\( \Delta x, \Delta y, \Delta z \) = grid size in x, y, and z (m)

\( \eta \) = Kolmogorov length scale (m)

\( \theta_e \) = momentum thickness at exit (m)

\( \theta_s \) = momentum thickness at separation (m)

\( \theta_i \) = momentum thickness at inlet (m)

\( \lambda \) = wavelength (m)

\( \Lambda_p \) = pressure gradient parameter at separation \((\partial^2 \theta / \nu)(dU_e / dx)_{\theta_s}\)

\( \nu \) = kinematic viscosity (m\(^2\) s\(^{-1}\))

References


