Parametric study toward optimization of blowing and suction locations for improving lift-to-drag ratio on a Clark-Y airfoil

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Abstract
Reynolds-averaged Navier–Stokes simulations (RANS) of flows around a Clark-Y airfoil with uniform blowing (UB) and uniform suction (US) are performed aiming at improvement of the airfoil performance. First, the control effect in the case with single UB or US applied on the airfoil surface is investigated at the various control locations. The magnitude of UB/US is 0.14% of the free-stream velocity, and the control region is set at four different locations on the upper and lower surfaces. The Reynolds number based on the chord length and the angle of attack are $1.5 \times 10^6$ and $0^\circ$, respectively. It is found that the friction drag is decreased/increased by single UB/US control. It is also found that UB on the lower surface or US on the upper surface improves the lift-to-drag ratio, while UB on the upper surface or US on the lower surface worsens it. In the combined control of UB and US having the equal flow rate, the magnitude of blowing and suction is set at 0.14% or 0.26% of the free-stream velocity. The locations of blowing/suction and flow conditions are the same as those in the cases with either UB or US only. The simulation result suggests that the lift-to-drag ratio is improved by the combined control of UB on the lower surface and US on the upper surface. In particular, the lift-to-drag ratio is most improved by a combination of UB on the lower rear surface and US on the upper rear surface. In contrast, a combined control of UB on the upper front surface and US on the lower rear surface is identified as the most effective case for the friction drag reduction only.

Keywords: Airfoil, Blowing, Suction, Lift-to-drag ratio, Reynolds-averaged Navier-Stokes simulation

1. Introduction

In order to solve environmental issues such as exhaustion of natural resources and global warming, it is of significant importance to improve the energy efficiency of high-speed transportation such as aircraft. The fluid drag can be decomposed into the pressure drag and the friction drag when the wave drag due to compressibility effects can be neglected. Although shape optimizations have been implemented for reduction of the pressure drag, there is few practical methods for reduction of the friction drag despite the fact that it accounts for approximately half of the total drag (Abbas et al., 2013).

Flow control methods can be classified into passive control and active control. In the passive control, e.g., riblets (Choi et al., 1993), energy input from the external system is not required so that it is relatively easy to implement. However, due to the expensive maintenance cost beyond the drag reduction effect, there is few passive control methods in practical use. On the other hand, in the active control, which requires energy input from the external system, large drag reduction effect has been achieved numerically and experimentally.

Of various active control methods, uniform blowing (UB) and uniform suction (US) have been known to be the simplest active control methods. Kametani & Fukagata (2011) performed a direct numerical simulation (DNS) of a spatially developing turbulent boundary layer with UB or US at the Reynolds number based on the boundary layer thickness of
Re₅ = 3000. According to their study, UB/US at 0.1%–1% of the free-stream velocity $U_\infty$ is able to reduce/increase the skin friction drag by 20%–70% despite the enhancement/suppression of turbulent fluctuations. Also, their analysis using the Fukagata-Iwamoto-Kasagi (FIK) identity (Fukagata et al., 2002) revealed that the main reason for friction drag reduction with UB is the large negative contribution by the mean wall-normal convection. To investigate the effects of UB and US at higher Reynolds numbers, Noguchi et al. (2016) performed Reynolds-averaged Navier–Stokes simulations (RANS) of a spatially developing boundary layer with UB and US at Re₅ = 4.5 × 10⁷. They revealed that the overall friction drag is most reduced by combining US in the laminar region so as to delay transition and UB in the turbulent region to reduce turbulent friction drag. For more practical configurations, a RANS of the flow around a Clark-Y airfoil with UB and US was performed separately by Kondo (2018) and Fahland (2019). Both of them show that the local skin friction is reduced by UB, and a combination of UB on the upper surface and US on the lower surface reduces the lift-to-drag ratio, which suggests that there is a possibility to improve the lift-to-drag ratio by optimizing the locations of UB and US sections. Recently, Eto et al. (2019) investigated the control effect of UB in the flow around a Clark-Y airfoil experimentally. They realized UB at 0.14% $U_\infty$ from a chamber covered by a porous metal surface and attained 20%–40% local friction drag reduction. According to their experiments, although the friction drag is substantially reduced by UB, the total drag coefficient is slightly increased. Through these studies, we can see the capability of UB/US based control for not only reducing the friction drag but improving the lift-to-drag ratio.

For achieving more efficient flow control via blowing and suction, some researchers have attempted parametric studies. Yousefi et al. (2014) performed a RANS of a NACA0012 airfoil with blowing or suction, and investigated the dependence on various control parameters. The velocity of the jet was relatively strong, i.e. 30% or 50% of free-stream velocity. Control was conducted with single blowing or suction slot on the upper surface. According to their parametric study, the suction in the normal direction of the surface at the leading edge results in suppression of separation and improvements in the stall angle and the lift-to-drag ratio. Huang et al. (2004) investigated using RANS the control effect of blowing/suction on the upper surface of a NACA0012 with various angles of jet. The magnitude of jet was from 1% to 50% of the free-stream velocity, which is also relatively strong. They indicated that the vertical suction near the leading edge and the tangential blowing near the trailing edge improves the lift-to-drag ratio. As discussed above, the effects of blowing and suction based control have been extensively examined. However, the proposed control designs based on these parametric studies have lacked the practical viewpoint because of the strong jet velocity or limitation in terms of the controlled surface area. Therefore, of particular interest in the present study is to focus on UB and US at a very weak amplitude (i.e., ~ 0.1% $U_\infty$, similar to Kametani & Fukagata (2011) and Eto et al. (2019)), which can be utilized as practical control methods against the mentioned controls above. The objective of this study is to seek for the optimum locations of UB and US for reduction of the friction drag and improvement of the lift-to-drag ratio of a Clark-Y airfoil, via a parametric study using RANS.

2. Numerical methods

2.1. Governing equations

The governing equations are the compressible continuity equation, the Navier–Stokes equation, and the energy equation, i.e.,

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0, \tag{1}
\]

\[
\frac{\partial \rho u_i}{\partial t} + \frac{\partial (\rho u_i) u_i}{\partial x_j} + \frac{\partial p}{\partial x_j} = \frac{\partial \tau_{ij}}{\partial x_j} = 0, \tag{2}
\]

\[
\frac{\partial e}{\partial t} + \frac{\partial (u_i e + p u_i)}{\partial x_i} + \frac{\partial}{\partial x_j} \left( -\tau_{ij} u_i + q_j \right) = 0, \tag{3}
\]

where $u_i$, $\rho$, $p$, and $e$ denote the velocity component, the fluid density, the pressure, and the specific internal energy, respectively. All variables are made dimensionless by the density of the free-stream, $\rho_\infty^*$, the speed of sound of the free-stream, $a_\infty^*$, the chord length, $c^*$, and the gas constant of air, $R_{\text{air}}^*$. The superscript * represents dimensional quantities. Also, $\tau_{ij}$ and $q_j$ are the stress tensor and the heat flux, respectively, i.e.,

\[
\tau_{ij} = \left( \mu + \mu_I \right) \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right), \tag{4}
\]

\[
q_j = \left( \frac{\mu}{\text{Pr} (\gamma - 1)} + \frac{\mu_I}{\text{Pr}_I (\gamma - 1)} \right) \frac{\partial T}{\partial x_i}. \tag{5}
\]
where \( \mu, \mu', T, \gamma, Pr, \) and \( Pr' \) are the molecular viscosity, the turbulent eddy viscosity, the temperature, the specific heat ratio, the Prandtl number, and the turbulent Prandtl number, respectively. In the present study, \((\gamma, Pr, Pr')\) are set to be \((1.40, 0.72, 0.90)\). Using the Sutherland’s law (Sutherland, 1893), the molecular viscosity, \( \mu \), is computed as
\[
\mu = \frac{1}{Re_a} \left( \frac{\mu_T}{T_0} \right)^{1.5} \left( \frac{T_0 + S_t}{T + S_t} \right),
\]
where \( Re_a, T_0, \) and \( S_t \) are the Reynolds number based on the chord length and the speed of sound of the free-stream, the reference temperature, and the Sutherland temperature. In the present study, \((T_0, S_t)\) is set to be \((1/\gamma, 0.25)\). The Reynolds number based on the chord length and the speed of sound of the free-stream, \( Re_a \), is calculated from the Reynolds number based on the chord length and the free-stream velocity, \( Re_c \), and the Mach number, \( Ma \), as \( Re_a = Re_c / Ma \).

In the present RANS, Spalart–Allmaras model (Spalart and Allmaras, 1994) is adopted as the turbulence model. The Reynolds stress is modeled by
\[
\rho \bar{u}_i \bar{u}_j = \mu_t \left( \frac{\partial u_i}{\partial x_i} + \frac{\partial u_i}{\partial x_j} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right).
\]
The turbulent eddy viscosity, \( \mu_t \), in Eq. (7) is computed as
\[
\mu_t = \rho \bar{v} f_{\alpha 1},
\]
where \( \bar{v} \) is the external variable. This variable is determined by computing the transport equation, i.e.,
\[
\frac{\partial \bar{v}}{\partial t} + \frac{\partial u_i \bar{v}}{\partial x_i} = c_b \bar{S} \bar{v} + \frac{1}{\sigma} \left[ \frac{\partial}{\partial x_i} \left( \mu + \bar{v} \right) \frac{\partial \bar{v}}{\partial x_i} \right] + c_{b 2} \frac{\partial \bar{v}}{\partial x_i} \frac{\partial \bar{v}}{\partial x_i} - c_{w 1} f_w \left( \frac{\bar{v}}{d} \right)^2.
\]
The functions appearing in Eq. (9) are given as
\[
\bar{S} = \Omega + \frac{\bar{v}}{k^2 d^2} f_{\omega 2},
\]
\[
\Omega = \left(2 W_{ij} W_{ij} \right)^{1/2},
\]
\[
W_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right),
\]
\[
f_{\omega 1} = \frac{\chi^3}{\chi^3 + c_{\omega 1}},
\]
\[
f_{\omega 2} = 1 - \frac{\chi}{1 + \chi f_{\omega 1}},
\]
\[
f_w = \left( \frac{1 + c_w^6}{g^6 + c_w^{6}} \right)^{1/6},
\]
\[
g = r + c_{w 2} \left( \rho^6 - r \right),
\]
\[
r = \frac{\bar{v}}{3 \kappa^2 d^2}.
\]
where \( c_{b 1} = 0.1355, \sigma = 2/3, c_{w 2} = 0.622, \kappa = 0.41, c_{\omega 1} = c_{b 1} / \kappa^2 + (1 + c_{w 2}) / \sigma, c_{w 2} = 0.3, c_{w 3} = 2, c_{\alpha 1} = 7.1 \). Here, \( d \) is the distance to the closest airfoil surface.

2.2. Numerical schemes and conditions

The RANS code in this study is developed by JAXA, i.e., UPACS (Yamamoto et al., 2000). For the evaluation of numerical flux for the advection term, the second-order Roe scheme with the MUSCL reconstruction is applied. A limiter function is not used here because the Mach number in the present study is relatively low. The second-order finite difference scheme is applied for the discretization of the viscous term, and the first-order Euler implicit method is employed for the time integration. For the time step, the steady computation is performed using the local time step, where the Courant number is 100. In addition, the Weiss & Smith preconditioning (Weiss and Smith, 1995) is used to improve the convergence and the accuracy. The Reynolds numbers based on the chord length and free-stream velocity are set to be \( Re_c = 0.47 \times 10^6 \) and \( 1.5 \times 10^6 \) and the Mach numbers are \( Ma = 0.072 \) and 0.178, respectively. The angle of attack is set to be 0° in all cases.
Figure 1 shows the schematic of the computational domain and grid. As the boundary conditions on the airfoil surface, no slip, adiabatic, and zero pressure gradient conditions are applied so that the density gradient on the wall is also zero via the equation of state for ideal gas. Note that for the controlled cases, the blowing/suction velocity, \( V_w^* \) (\( V_w^* > 0 \) for blowing, \( V_w^* < 0 \) for suction), is imposed on the surfaces in the control regions, i.e., \( u^*_i = V_w^* n_i \) with \( n_i \) being the unit outward normal vector on the surface. For the outlet condition, the zeroth-order extrapolation is applied. The constant velocity, pressure, and temperature are given as the far-field condition. The other quantities on the boundaries are calculated with the equation of state for ideal gas and the equation of the specific internal energy. The length of the computational domain is \( 10c^* \) in front of the airfoil with respect to the chord horizontal direction, \( 9c^* \) on the downstream side and \( 20c^* \) in the wall-normal direction.

In the present study, a C-type boundary-fitted grid system is adopted as shown in Fig. 1. In the regions 1 and 3 shown in Fig. 1, 61 grid points are arranged in the tangential direction of the airfoil surface and 75 grid points are arranged in the airfoil wall-normal direction. In the regions 2 and 4, 50 grid points are prepared in the streamwise direction and 75 grid points are prepared in the wall-normal direction. The maximum width of the computational cell adjacent to the airfoil surface is 0.4 wall units.

3. Results and discussion
3.1. Validation

In order to validate the present code, some physical quantities are compared with those in the previous studies (Ihsan and Mustafa, 2016; Kondo, 2018; Eto et al., 2019) by using the pressure coefficient, \( c_p \), on the airfoil surface, the local skin friction coefficient, \( c_f \), on the upper surface in the baseline case, the drag coefficient, \( C_D \), and the lift coefficient, \( C_L \), in the baseline case at two different Reynolds numbers. The local pressure coefficient, \( c_p \), and the local skin friction coefficient, \( c_f \), are defined as

\[
c_p = \frac{p^* - p_{∞}^*}{\frac{1}{2} \rho_{∞} U_{∞}^2},
\]

\[
c_f = \frac{\tau_w^*}{\frac{1}{2} \rho_{∞} U_{∞}^2},
\]

where \( p^* \), \( p_{∞}^* \), \( U_{∞} \), and \( \tau_w^* \) are the local static pressure, the static pressure of the free-stream, the free-stream velocity, and the local wall shear stress, respectively. The lift coefficient, \( C_L \), and the drag coefficient, \( C_D \), are defined as

\[
C_L = \frac{F_L^*}{\frac{1}{2} \rho_{∞} U_{∞}^2},
\]

\[
C_D = \frac{F_D^*}{\frac{1}{2} \rho_{∞} U_{∞}^2},
\]

where \( F_L^* \) and \( F_D^* \) are the drag and lift forces, i.e.,

\[
F_D^* = e_x \cdot \int_S p^*(n)dS + e_x \cdot \int_S \tau_w^* n dS,
\]

\[
F_L^* = e_y \cdot \int_S p^*(n)dS + e_y \cdot \int_S \tau_w^* n dS,
\]
with $S$ being the entire airfoil surface including the control regions and $(e_x, e_y)$ being the unit directional vectors. Note that the repulsive forces due to the blowing and suction are negligibly small in the present cases, i.e., about $10^5$ times smaller than the lift force.

Figure 2 shows the comparison of the pressure coefficient, $c_p$, and the friction coefficient, $c_f$, in the baseline case, where $x$ denotes the streamwise location on the airfoil surface. As shown in Fig. 2, the distributions of $c_p$ and $c_f$ in the present study are in reasonable agreement with those in the previous studies (Ihsan and Mustafa, 2016; Eto et al., 2019; Kondo, 2018). Table 1 shows the drag coefficient, $C_D$, and the lift coefficient, $C_L$, in the baseline case at two different Reynolds numbers. As can be seen, the drag and lift coefficients are in reasonable agreement with those in the previous studies (Ihsan and Mustafa, 2016; Kondo, 2018). Therefore, it is confirmed that our code can reproduce the flow around the airfoil at a reasonable accuracy.

### 3.2. Control conditions

As for the controlled cases, not only the single control of either UB or US but also the combined control of UB and US at the equal flow rate are considered assuming a practical situation where the air required for UB is taken from the other region of the airfoil, as has been attempted in the recent experiment by Hirokawa et al. (2020). In the single UB/US cases, we apply the blowing or suction velocity of 0.14% $U_\infty$, denoted as B014 and S014, respectively. In the combined control of UB and US cases, we apply the blowing and suction velocity of 0.14% $U_\infty$ or 0.26% $U_\infty$, denoted as BS014 and BS026, respectively. Note that these magnitude for UB/US are decided from the previous experimental study (Eto et al., 2019). In the names of control cases, the character strings and numbers indicate the control conditions as summarized in Fig. 3. The center position of the control area in the streamwise direction is represented by $x_{ctrl}$.

### 3.3. Single control of UB/US

Let us first examine the effect of the single control with UB/US. The streamlines around the airfoil in the baseline

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**Table 1** The comparison of the drag coefficient, $C_D$, and the lift coefficient, $C_L$, in the baseline case.

| Case                  | Re     | $C_D$   | $C_L$   |
|-----------------------|--------|---------|---------|
| Sim. (Present)        | $4.7 \times 10^5$ | 0.014   | 0.327   |
| Exp. (Ihsan and Mustafa, 2016) |          | 0.015   | 0.375   |
| Sim. (Present)        | $1.5 \times 10^6$ | 0.0113  | 0.341   |
| Sim. (Kondo, 2018)    |        | 0.0128  | 0.355   |
Fig. 3  Control conditions: (a) schematic of the target locations for UB/US; (b) notations of the cases.

| Character strings | Control type               |
|-------------------|-----------------------------|
| BU                | UB on upper surface         |
| BL                | UB on lower surface         |
| SU                | US on upper surface         |
| SL                | US on lower surface         |

| Number | Control region | \( x_{ctrl} \) |
|--------|----------------|----------------|
| 02     | 0.10 < \( x \) < 0.28 | 0.19            |
| 04     | 0.30 < \( x \) < 0.48 | 0.39            |
| 06     | 0.50 < \( x \) < 0.68 | 0.59            |
| 08     | 0.70 < \( x \) < 0.88 | 0.79            |

Fig. 4  Streamlines around the airfoil: (a) Baseline case; (b) B014BU04; (c) S014SU04. The contour represents the isolines of the stream function. Note that no clear difference can be observed among these three cases due to the very weak blowing and suction, i.e., \( V_w = 0.14\% U_\infty \).

case, Case B014BU04, and Case S014SU04 are shown in Fig. 4. We can see that the streamlines around the airfoil are hardly changed in spite of the control. This is due to the very weak UB and US, which can be quantified by the jet momentum coefficient, \( C_\mu \), defined as

\[
C_\mu = \frac{\rho_w h^* V_w^2}{\rho_\infty c^* U_\infty^2},
\]

where \( \rho_w \) and \( h^* \) are the density of the control surface and the width of the control region. The value of \( C_\mu \) in the present case is \( C_\mu \approx 5 \times 10^{-4} \), and this is much smaller than the value where flow modifications become noticeable according to Gilarranz & Rediniotis (2001), i.e., \( C_\mu \approx 2 \times 10^{-3} \).

Figure 5 shows the distribution of the local skin friction coefficient, \( c_f \), on the upper surface with UB or US at four different locations on the upper surfaces. It is found that UB reduces \( c_f \) by approximately 20% in each control region, while US increases it by approximately 30%. These control effects are observed to partly remain downstream of the control region in both cases.

We compare in Fig. 6 the tangential velocity, \( u_t \), of the baseline case and the controlled cases (\( x_{ctrl} = 0.39 \)) with three different locations at \( x = 0.25 \) (upstream of the control region), \( x = 0.41 \) (the control region), and \( x = 0.53 \) (downstream of the control region). In the control region and its downstream, the tangential velocity shifts upward with UB, while it shifts downward with US. These effects result in reduction of \( c_f \) with UB in the control region and downstream of this region as shown in Fig. 5. This is because UB increases the boundary layer thickness, while US decreases it, and these effects remain in the downstream of control region (Stroh et al., 2016; Noguchi et al., 2016).
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Fig. 5 Distribution of the skin friction coefficient, $c_f$, on the upper surface: (a) UB control; (b) US control. Black, blue, red, green, and yellow indicate baseline case and the control in the region of $x_{vel} = 0.19, 0.39, 0.59,$ and $0.79$, respectively.

Fig. 6 The comparison between the tangential velocity profile in the baseline case and that in the case with B014BU04 or S014SU04 on the upper surface: (a, d) $x = 0.25$; (b, e) $x = 0.41$; (c, f) $x = 0.53$. (a, b, c) UB; (d, e, f) US. Blue, baseline case; red, controlled case.

In order to assess the global influence of UB/US, we present the lift coefficient, $C_L$, and the drag coefficient, $C_D$, in the controlled cases on eight different surfaces as shown in Fig. 7. Here, $C_{D,0}$ and $C_{L,0}$ are the drag and lift coefficients in the baseline case. The cases in the red region in the Fig. 7 indicates that the lift-to-drag ratio is improved, while lift-to-drag ratio is worsened in the blue region. A noteworthy observation is that the change in the lift coefficient is larger than that of the drag coefficient, which significantly changes the lift-to-drag ratio. Figure 7 suggests that the lift-to-drag ratio improves with UB on the lower surface and the US on the upper surface, while it worsens with UB on the upper surface or US on the lower surface.

Let us analyze in Fig. 8 the change in the pressure coefficient, $\Delta c_p$, on the upper surface with the UB/US control on the upper surface in order to examine the observation regarding the lift-to-drag ratio as mentioned above. The change in...
the pressure coefficient, $\Delta c_p$, is defined as

$$\Delta c_p = c_{p,x} - c_{p,0},$$ \hspace{1cm} (26)

where $c_{p,x}$ and $c_{p,0}$ are the pressure coefficients in the controlled and baseline cases, respectively. As shown in Fig. 8, UB increases the pressure coefficient in the upstream of the control region, while US decreases it. Also, although not shown, a similar trend is observed when UB/US is applied on the lower surface. By these changes in $c_p$ distribution, UB on the lower surface and US on the upper surface increases the pressure difference between the upper and lower surfaces, which eventually increases the lift coefficient as observed in Fig. 7.

### 3.4. Combined control of UB and US

Finally, we present the effect of combined control by UB and US. Figure 9 shows the lift coefficient, $C_L$, and the drag coefficient, $C_D$, with all cases of the combined control. As shown here, the combined control of UB on the lower surface and US on the upper surface enable us improve the lift-to-drag ratio. This is due to the combined effects of UB and US to improve the lift-to-drag ratio. Moreover, the larger control amplitude (i.e, $0.26% U_\infty$ UB/US) enhances the effect on the lift-to-drag ratio, especially in the case where UB and US are applied on the opposite surfaces (e.g., Cases BS026BUSL and BS026BLSU). This is because the stronger UB/US enhances the modification in $c_p$ distribution observed in Fig. 8 and results in larger pressure difference between the upper and lower surfaces.

The best case in terms of the lift-to-drag ratio is the combined control of UB on the lower surface nearest the trailing

|        | Total drag | Total lift |
|--------|------------|------------|
| Friction drag | 1.4% increase | 40% decrease |
| Pressure drag | 7.0% decrease | 8.9% increase |
edge and US on the upper surface nearest the trailing edge at $|V_w| = 0.26\% U_\infty$. The changes in the drag and lift coefficient in this case are summarized in Table 2. In the best case, although the friction drag is increased, mainly due to the improvement of the lift coefficient, the lift-to-drag ratio is most improved as much as 9.7%. The spatial distribution of the change in the pressure coefficient in this case is shown in Fig. 10. It can be confirmed that the pressure above the airfoil is substantially decreased so as to increase the lift force.

In contrast, when we focus on the friction drag reduction only, the combined control of UB on the upper surface nearest the leading edge and US on the lower surface nearest the trailing edge at $|V_w| = 0.26\% U_\infty$ is found to be the best case, which yields 3.0% overall friction drag reduction. Under the present condition of combined control with UB and US at the equal flow rate, the drag reduction effect by UB exceeds the drag increase effect by US the most by these placements of UB and US.

4. Conclusions

In this study, Reynolds-averaged Navier–Stokes simulations (RANS) of the single control of UB/US and the combined control of UB and US on Clark-Y airfoil were performed. In the single control, UB/US decreased/increased the friction drag in the control region and its downstream. In addition, the lift-to-drag ratio was increased by the UB control on the lower surface or the US control on the upper surface, and decreased by the UB control on the upper surface or the US control on the lower surface. In the combined control of UB and US, the combined control of UB on the lower surface and US on the upper surface improved the lift-to-drag ratio more. In particular, the lift-to-drag ratio was most improved by the combined control of UB on the lower surface nearest the trailing edge and US on the upper surface nearest the trailing edge and 9.7% lift-to-drag ratio improvement was achieved. In contrast, concerning the friction drag only, the combined control of UB on the upper surface nearest the leading edge and US on the lower surface nearest the trailing edge was able to accomplish 3.0% friction drag reduction as the best case.

Parametric studies were conducted in the present study to seek for the possibility to increase the lift-to-drag ratio by UB and US, and the obtained results suggest about 10% improvement is possible. Further improvement may be possible
by optimizing the locations of UB and US by conducting an optimization study, which will be left for future work.

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