Experimental investigation on friction drag reduction on an airfoil by passive blowing

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Received: 30 September 2019; Revised: 27 November 2019; Accepted: 12 December 2019

Abstract
Friction drag reduction effect of a passive blowing on a Clark-Y airfoil is investigated. Uniform blowing, conducted in a wall-normal direction on a relatively wide surface, is generally known as an active control method for reduction of turbulent skin friction drag. In the present study, uniform blowing is passively driven by the pressure difference on a wing surface between suction and blowing regions. The suction and the blowing regions are respectively set around the leading edge and the rear part of the upper surface of the Clark-Y airfoil in order to ensure a sufficient pressure difference for passive blowing. The Reynolds number based on the chord length is \(0.65 \times 10^6\) and \(1.55 \times 10^6\). The angle of attack is set to \(0^\circ\) and \(6^\circ\). The mean streamwise velocity profiles on the blowing region and the downstream, measured by a traversed hot-wire anemometry, are observed to shift away from the wall by passive blowing. This behavior qualitatively suggests reduction of local skin friction on the wing surface. A quantitative assessment of the friction drag is performed using the law of the wall accounting for pressure gradients (Nickels, 2004), coupled with a modified Stevenson’s law (Vigdorovich, 2016) to account for the weak blowing. From this assessment, the local friction drag reduction effect of passive blowing is estimated to reach \(4\% – 23\%\).

Keywords: Friction drag, Airfoil, Wind-tunnel experiment, Uniform blowing, Passive control

1. Introduction
Along with the growth of aircraft demand, necessity of developing practical techniques for reducing friction drag of aircraft toward improvement of energy efficiency is also growing. Reducing the aerodynamic drag on the aircraft leads to energy efficiency improvement. The fluid drag of aircraft is mainly divided into pressure drag and friction drag, and the friction drag accounts for about 50% of the total drag (Abbas et al, 2013). The pressure drag has been reduced by shape optimization of aircraft, whereas practical techniques for reducing friction drag has not been established yet. Riblets are known as one of the passive control methods aiming at reduction of friction drag by the micro longitudinal grooves, and their effects had been investigated experimentally (e.g., Walsh, 1983) and numerically (e.g., Choi et al., 1993). In flight tests, too, McLean (1987) assessed the performance of riblets on the upper surface of a wing and they confirmed the friction drag reduction over the surface as well. The drag reduction performance of riblets has been confirmed as such, but their practical application is hindered by issues such as maintenance costs.

Uniform blowing (UB), pioneered by Stevenson (1963), is a method to use a relatively weak wall-normal blowing from the surface. As another blowing method for the airfoil, a jet from a slit with a few percent of the chord length is known, and it has been reported that it is effective for increasing the lift to drag ratio or suppressing a separation (Huang et al. 2004; Yousefi et al. 2014). Compared with such control methods, UB is performed at a few percent of the free-stream velocity on a relatively wide surface. Park and Choi (1999) investigated the effect of uniform blowing (UB) and uniform suction (US) from a slit in a turbulent boundary layer by direct numerical simulation (DNS), and it was reported that the skin friction on blowing region was decreased by UB. The effects of UB were investigated in detail by Kametani and
Fukagata (2011). They performed DNS of a spatially-developing turbulent boundary layer at a low Reynolds number with UB or US and demonstrated that the local friction drag can be reduced by 20%–70% using UB at 0.1%–1% free-stream velocity. They also elucidated the reduction mechanism of turbulent skin friction by an analysis using Fukagata-Iwamoto-Kasagi (FIK) identity (Fukagata et al., 2002). In addition, friction drag reduction effect of UB was also confirmed at higher Reynolds numbers (Kametani et al., 2015) and Mach numbers (Kametani et al., 2017), and with intermittent slots (Kametani et al., 2016) and on a rough wall (Mori et al., 2017).

As a situation closer to the actual flow around an airfoil, Noguchi et al. (2016) confirmed by means of Reynolds-average Navier-Stokes simulation (RANS) at a practically high Reynolds number the effect of combined control of US in a laminar boundary layer to delay transition and UB in a turbulent boundary layer to reduce turbulent friction drag. Towards practical application of UB, which requires energy and air supply, Noguchi et al. (2016) mentioned the need for a combination of these two controls since US can continuously supply air for UB without additional energy input.

The friction drag reduction effect of UB on wing configuration has also been investigated numerically and experimentally. Kondo et al. (2017) conducted a RANS based on the immersed-boundary method and investigated the effect of UB on an airfoil. A qualitative friction drag reduction effect was reported from the results of changes in the streamwise mean velocity profiles. Atzori et al. (2018) confirmed the friction drag reduction effect of UB in an adverse pressure gradient turbulent boundary layer over a suction side of NACA 4412 airfoil by means of large eddy simulation (LES). Eto et al. (2019) conducted a wind-tunnel experiment of UB at 0.14% free-stream velocity on an airfoil using air supply from an external compressor, i.e., active UB, and confirmed 20%–40% local friction drag reduction through a hot-wire measurement of velocity profiles and a quantitative assessment taking into account the pressure gradient. Although UB is generally known as an active control, Eto et al. (2017) also attempted a passive blowing, which is driven by the pressure difference on a wing surface between suction and blowing region. They did not achieve an effective passive blowing due to the pressure loss mainly caused by the tubes and internal structure; however, they confirmed the feasibility of passive blowing and suggested structure of an airfoil to attain passive blowing with low pressure loss.

As mentioned above, investigation of the friction drag reduction effect of active UB has been conducted by numerical simulations and experiments. At the same time, it has been suggested that a passive blowing on an airfoil which does not require external continuous energy supply is also feasible. Friction drag reduction effect by passive blowing on an airfoil is of great interest from a viewpoint of energy efficiency of aircraft. In the present study, therefore, we quantitatively investigate the friction drag reduction effect of such a passive blowing by a wind-tunnel experiment.

2. Experimental details
2.1. Wind-tunnel setup

Measurements were carried out in 0.65 m × 0.55 m Low-Turbulence Wind Tunnel at Japan Aerospace Exploration Agency (JAXA). A schematic of the experimental apparatus is shown in Fig. 1. The test section is 0.65 m in height, 0.55 m in width, and 1.5 m in length.
Fig. 2 Structure of the Clark-Y airfoil model: (a) overview; (b) top view; (c) A-A cross section.

Fig. 3 The airfoil model actually built.

Fig. 4 Relationship between the free-stream velocity $U_\infty$ and the induced blowing velocity $w$.

m in width and 1.5 m in length. An airfoil model was mounted at 677.5 mm downstream from the entrance of the test section. The $x$, $y$ and $z$ coordinates are set in the streamwise, spanwise and wall-normal directions, respectively, with their origins set at the leading edge, the center of the span, and the leading edge.

The velocity profiles are measured by a hot-wire anemometry traversed in $x$ and $z$ direction. We employed Dantec 55P15 probe with a hot wire of 5 $\mu$m in diameter with a sensing length of 1.25 mm. The output of the hot-wire was recorded at a sampling frequency of 20 kHz and the number of sample at each measurement point was 32768. The uncertainty in the hot-wire measurement was 0.4% at a confidence level of 95% based on the ASME measurement uncertainty method (Abernethy et al., 1985). The free-stream velocity is measured by a Pitot tube at the entrance of the test section, and the temperature in the test section is measured by a thermocouple.

2.2. Details of the airfoil model

The structure of our custom made Clark-Y airfoil model is shown in Fig. 2. The chord length is $c = 400$ mm, and the span is $2b = 548$ mm. We set the suction region around the leading edge and the blowing region on the rear part of the upper surface. An electromagnetic valve (SMC, VX230MA) to control the switching of blowing and a flow meter (KEYENCE, FD-A50) for measuring the flow rate are installed between the suction and blowing chambers. In addition, the airfoil model has pressure taps, which are connected to multiple pressure scanners (Pressure Systems Inc., Model 9116 and Model 9016), for static pressure measurement on the surface in the cross sections of $y/b = 0.64$ and $y/b = 0$. The airfoil model actually built is shown in Fig. 3. Polycarbonate thin plates are used for the outer wing surface to cover the
internal structure. Figure 4 shows a relationship between the free-stream velocity $U_\infty$ and the blowing velocity $w$, which indicates the passive blowing performance of the present model.

A 0.4 mm-thick perforated metal plate with holes of 0.5 mm in diameter spaced with 1.0 mm between centers is used as the wing surface of suction and blowing regions. The schematic of the perforated metal plate is shown in Fig. 5. Figure 6 shows the uncontrolled mean streamwise velocity profiles on the perforated metal plate and on the smooth surface in the present study, compared with the previous experimental result using a Clark-Y airfoil model (Eto et al., 2019) which is different from the one used in the present study, and the simulation result by means of RANS (Ohashi et al., 2019). The velocity profiles without blowing are measured at the angle of attack of $\alpha = 0^\circ$ and the Reynolds number based on the chord length of $Re_c = 1.55 \times 10^6$. The mean velocity $\bar{u}$ is normalized by using the mean edge velocity $U_e$ of each boundary layer. The vertical axis represents the wall-normal distance from the wing surface $z_s$. The reliability of the present velocity measurement is confirmed by the good agreement with the previous experiment by Eto et al. (2019) and the reasonable agreement with the simulation result by Ohashi et al. (2019). The difference between the experimental and simulation results may be attributed to the relatively high blockage ratio in the present experiment (about 7%) in contrast to that in the simulation (about 0.6%), a slight difference in the transition location, the use of turbulence model, and so on; however, definite reasons for this difference cannot be identified. The profile on the perforated metal plate indicates larger velocity defect in the boundary layer, which implies some roughness effect caused by the holes. Although smoother materials such as a porous media have also been examined as the wing surface in the control region, the larger pressure loss has obstructed realization of passive blowing in our preliminary experiment.

### 2.3. Experimental conditions

As shown in Table 1, the angle of attack is set to $\alpha = 0^\circ$ or $6^\circ$ since the present study focuses on the friction drag in a cruising state, and the Reynolds number based on the chord length is set to $Re_c = 0.65 \times 10^6$ or $1.55 \times 10^6$. The number in the case name (“0” or “6”) indicates the angle of attack and the following letter (“H” or “L”) indicates the higher or lower Reynolds number. In each case, measurements of the turbulent boundary layer were performed at five different streamwise stations, $x/c = 0.65, 0.70, 0.75, 0.80, 0.90$ along the $y/b = 0$ line. The blowing intensity shown in Table 1 is nondimensionalized by the free-stream velocity $U_\infty$ measured by the Pitot tube at the inlet of the test section.

![Fig. 5 Schematic of the perforated metal plate.](image)

![Fig. 6 Mean velocity profiles on the perforated metal plate and on the smooth surface at $x/c = 0.70$ (without blowing, $\alpha = 0^\circ$, $Re_c = 1.55 \times 10^6$). The ordinate is the distance from the surface location $z_s$, normalized by the chord length $c$.](image)

| Case | $\alpha$ [$^\circ$] | $Re_c$ | Intensity of blowing $w/U_e$ |
|------|-----------------|------|-----------------|
| Case 0L | 0 | $0.65 \times 10^6$ | 0.05% |
| Case 0H | 0 | $1.55 \times 10^6$ | 0.06% |
| Case 6L | 6 | $0.65 \times 10^6$ | 0.05% |
| Case 6H | 6 | $1.55 \times 10^6$ | 0.06% |

Table 1 Experimental conditions.
3. Results and discussion

The measured mean streamwise velocity profiles are shown in Fig. 7. In the boundary layer, the mean velocity in the controlled case is statistically lower than that in without control cases at a significance level of 95%. The mean velocity profiles are observed to be shifted away from the wing surface by passive blowing, which means reduction of velocity gradient on the wing surface and increase in the boundary layer thickness. Figure 8 shows the root-mean-square (RMS) of velocity fluctuations. In both cases without and with blowing, the peak near the wall is weaker for $\alpha = 6^\circ$ cases due to the stronger adverse pressure gradient, as reported by Dródz et al. (2015) and Monty et al. (2011) — the Clauser pressure gradient parameter $\beta$ is larger in Case 6L and Case 6H ($\beta \approx 10$) than Case 0L and Case 0H ($\beta \approx 3$). The RMS velocity profiles are found to be increased by passive blowing. The modifications on the mean and RMS velocity profiles observed above are similar to those in the previous studies (Kametani and Fukagata, 2011; Eto et al., 2019) where local friction drag reduction was confirmed. Therefore, the present change in the mean velocity profiles suggests the local skin friction reduction effect by passive blowing.

The friction drag reduction effect is quantitatively assessed based on the mean velocity profiles. Since we cannot directly measure the wall shear stress $\tau_w$, we rely on an indirect assessment based on the law of the wall by taking into...
account the pressure gradient and wall roughness caused by the perforated metal plate for blowing. In this assessment, \( z^+ \) indicates the distance from the wall in the wall-normal direction. In general, the inner-scaled mean velocity profile \( u^+ \) is shifted downward while keeping the slope in a log-law region by the effect of wall roughness, characterized by the roughness function \( \Delta U^+ \) (Jiménez, 2004). We determine the friction velocity \( u_* \) and distance from the wall which reasonably fit the slopes of the theoretical wall law taking into account the effect of pressure gradient (Nickels, 2004) and the measured profile in the logarithmic region. Although excessive heat loss to the wall is inevitable in velocity measurement by hot-wire anemometry, the effect is limited to the viscous sublayer (Ikeya et al., 2017). Therefore, heat losses are considered not to affect the result of this quantitative assessment since only the velocity profiles in the logarithmic region are used for the present velocity fitting. The theoretical mean velocity profile proposed by Nickels (2004) is expressed as

\[
\bar{u}^+ = z^+ 
\left(1 - \exp\left(-\frac{3z^+}{\varepsilon^+}\right)\right) \left(1 + 2 \left(\frac{z^+}{\varepsilon^+}\right) \left(\frac{z^+}{\varepsilon^+}\right)^2 - \frac{3}{2} p_x z^+ \left(\frac{z^+}{\varepsilon^+}\right)^{3/2}\right)
\]

\[
+ \sqrt{1 + p_x z^+ \ln\left(1 + \frac{0.6(z^+/\varepsilon^+)^6}{1 + \eta^6}\right)} + B \left(1 - \exp\left(-\frac{5(\eta^4 + \eta^6)}{1 + 5\eta^3}\right)\right)
\]

where \( \varepsilon_0 = 0.39 \), \( \eta \) is the \( z \) coordinate non-dimensionalized by the boundary layer thickness \( \delta \), \( p_x \) is a pressure gradient parameter, and \( z_c \) obtained from

\[
p_x z_c^3 + z_c^2 - R_c^2 = 0
\]

where \( R_c = 12 \) is a critical value of \( z \) at which the sublayer becomes unstable. Note that the range of the pressure gradient in the present study is within the recommended range \((-0.02 < p_x^+ < 0.06)\) for the use of the law of the wall by Nickels (2004). The effect of pressure gradient on \( z \) at which the sublayer becomes unstable is modeled by Eq. (2). The difference

![Fig. 9 Non-dimensionalized mean velocity profiles at \( x/c = 0.70 \): (a) Case 0L; (b) Case 0H; (c) Case 6L; (d) Case 6H. Gray area indicates the logarithmic region assumed in the present study.](image-url)
in \( z^+ \) computed by solving Eq. (2) and that computed using DNS data is reported to amount up to 9\% (Nickels, 2004); however, the effect of this error in the assessment of the friction velocity as well as the friction drag reduction rate is less than 1\%. The boundary layer velocity profile affected by wall blowing does not follow the universal wall law. Therefore, before fitting to Eq. (1), the velocity profile measured for the controlled case was corrected using Stevenson’s wall law modified by Vigdorovich (2016), which reads

\[
\frac{2u_*}{\sqrt{1 + \left( \frac{w^*}{\nu} \right)^2}} = \frac{1}{\kappa} \left( \ln z^+ + C_0 + C_1 w^+ \right) + 1
\]  

(3)

where \( w \) is the blowing velocity, \( \kappa \) is a von Kármán constant (\( \kappa = 0.41 \)) and \( C_0 \) and \( C_1 \) are constants (\( C_0 = 2.05, \ C_1 = 3.51 \)). The blowing velocity in the present study is \( w^+ < 0.03 \) which satisfies the assumption for Eq. (3) that \( w^+ \) is sufficiently small.

Figure 9 shows the mean velocity profiles non-dimensionalized by the friction velocity \( u_* \) obtained from the above quantitative assessment. Especially in the logarithmic region \((30 \leq z^+ \leq 100)\) represented by the gray area in Fig. 9, the slope of the theoretical profile on a smooth surface is in good agreement with that of the experimental profiles with and without control. The roughness function \( \Delta U^+ \) representing the shift amount from a profile on a smooth surface is \( 3.4 \leq \Delta U^+ \leq 12.0 \).

The local friction coefficient, defined as

\[
c_f = \frac{\tau_w}{\frac{1}{2} \rho U^2_\infty}
\]

(4)

is presented in Fig. 10. It is apparent that \( c_f \) is reduced by passive blowing in all cases. The friction drag was locally reduced by passive blowing not only in the blowing control region \((x/c = 0.65, 0.70, 0.75, 0.80)\) but also in the downstream \((x/c = 0.90)\). This is because the influence of the thickened boundary layer by passive blowing still remains downstream of the control region (Noguchi et al., 2016; Stroh et al., 2016).

Figure 11 shows friction drag reduction rate \( R \), defined as

\[
R = \frac{c_{f,ab} - c_{f,wb}}{c_{f,ab}}
\]

(5)

where \( c_{f,wb} \) and \( c_{f,ab} \) denote the local skin friction coefficient in the case of with and without blowing. The local skin friction is reduced by 4\% - 19\% in the case of the blowing velocity \( w = 0.05\% U_\infty \) (Case 0L and Case 6L) and by 12\% - 23\% in the case of the blowing velocity \( w = 0.06\% U_\infty \) (Case 0H and Case 6H). Larger friction drag reduction effect is obtained in Case 0H and Case 6H due to the slightly higher blowing velocity compared with Case 0L and Case 6L. As compared to the active UB at \( w = 0.14\% U_\infty \) (Eto et al., 2019), the friction drag reduction effect of the present passive blowing is weaker due to the lower blowing intensity. However, it should be emphasized here that we have confirmed the friction drag reduction on an airfoil by passive blowing, which does not require an external power input. Also, friction drag reduction by UB on the rough surface has been experimentally confirmed similarly to the numerical simulation of turbulent channel flow on a rough wall with UB reported by Mori et al. (2017). Further development of smooth materials for blowing with low pressure loss is expected for practical application of passive blowing. We focused...
on friction drag in the present study. Meanwhile, the effect of passive blowing on the total drag should also be discussed. While the boundary layer thickness locally increases in the blowing region, the overall distribution of static pressure on the wing surface is affected by suction and blowing, which leads to a change in the pressure drag. Further investigation is expected for concluding the effect of blowing on the total drag.

4. Conclusions

Friction drag reduction effect of passive blowing on a Clark-Y airfoil was investigated through a wind-tunnel experiment. The air is passively sucked around the leading edge and blown to the rear part of the upper surface by utilizing the pressure difference on the wing surface. Passive blowing is successfully driven by suppressing the pressure loss caused by the structure of the airfoil, and we were able to investigate the effect of the passive blowing on friction drag via a hot-wire technique.

Modifications of the mean velocity profiles suggested decrease in the velocity gradient on the wing surface, which qualitatively confirmed the friction drag reduction effect by passive blowing. Subsequently, we quantitatively assessed the local skin friction from the mean streamwise velocity profiles by taking into account the pressure gradient and wall roughness. As a result of the quantitative assessment using the law of the wall accounting for the pressure gradient (Nickels, 2004) and the transformation of log law to account for the wall transpiration (Vigdorovich, 2016), the local friction drag reduction effect is estimated to reach 4% – 23%. Although development of more ideal materials for the blowing surface is still expected, the present experimental results suggest that the passive blowing has a great potential to serve as a practical and effective control method for reducing friction drag on an airfoil.

Acknowledgments

The authors are grateful to Dr. Shinnosuke Obi and Dr. Keita Ando (Keio University) for fruitful discussion. This work was conducted as a part of the JAXA-Keio University collaborative research and also supported by JSPS KAKENHI Grant No. JP16K06900.

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