Rotating Air Scoop as Airfoil Boundary-Layer Control

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Nomenclature

C = airfoil chord
C_L = lift coefficient
$C_{L\max}$ = maximum coefficient of lift
C_P = pressure coefficient
Re = Reynolds number
U = freestream velocity
U_c = cylinder surface velocity
X = distance along chord
α = angle of attack

Introduction

THROUGH a recent study, Mokhtarian and Modi[1] have assessed moving surface boundary-layer control effectiveness with reference to a symmetrical Joukowsky airfoil modified with a leading-edge rotating cylinder. Results of the test program and the numerical models suggest the following:

1) The numerical scheme, accounting for wall confinement and separated-flow effects, gives useful information concerning moving surface boundary-layer control. The predicted pressure distributions are in good agreement with experiment almost up to the point of complete separation from the airfoil surface except near the trailing edge where more accurate results of the flowfield would require the modeling of the separated-flow region using the full Navier-Stokes equations.

2) The concept of moving surface boundary-layer control appears to be quite promising. In general, the leading-edge rotating cylinder extends the lift curve without substantially affecting its slope, thus effectively increasing the maximum lift and delaying stall.

This Note represents an extension of the preceding study and investigates the effect of the leading-edge cylinder geometry. A symmetrical Joukowsky model, of ≈15% maximum thickness-to-chord ratio, is considered with three different configurations of the leading-edge cylinder. These include a) a solid circular cylinder, b) a scooped cylinder, and c) a reversed scooped cylinder (see Fig. 1). The cylinders were designed for clockwise rotation to inject momentum into the upper-surface boundary layer. Configuration b) was designed as an "air scoop" to enhance the cylinder's effect in displacing the air. It would slow down the flow over the lower surface and redirect more flow over the upper surface. Configuration c, on the other hand, was designed as a vortex generator.[2]

The relatively large angles of attack used in the experiments result in a considerable blockage of the wind-tunnel test section, from 21% at $\alpha = 30$ deg to 30% at $\alpha = 45$ deg. The wall confinement leads to an increase in local wind speed, at the location of the model, thus resulting in an increase in aerodynamic forces. Several approximate correction procedures have been reported in the literature to account for this effect. However, these procedures are applicable mostly to streamlined bodies with attached flow. A satisfactory procedure applicable to bluff bodies with large blockage is still not available.

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With rotation of the cylinder(s), the problem is further complicated. As shown by the pressure data and confirmed by the flow visualization, the unsteady flow can be separating and reattaching over a large portion of the top surface. In the absence of any reliable procedure to account for wall confinement effects in the present situation, the results are purposely presented in the uncorrected form.

Leading-Edge Cylinder

The symmetrical Joukowsky airfoil model I was tested systematically at a Reynolds number of 2.31×10^5 over a range of angles of attack and cylinder speeds. The pressure plots were integrated for each case to obtain the corresponding lift coefficient. The amount of information obtained is rather extensive, however, only a few of the typical results useful in establishing trends are recorded here.

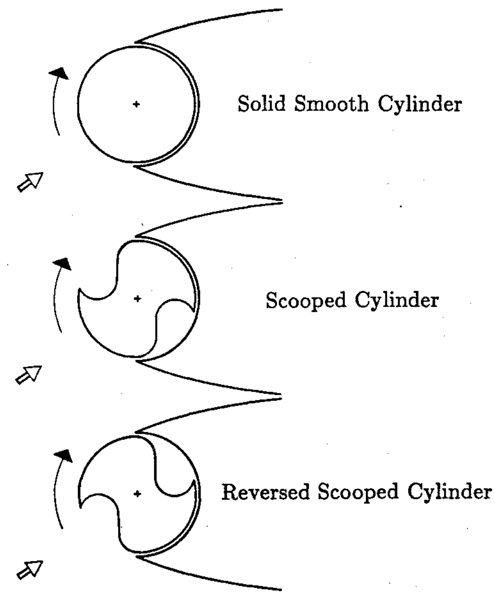

Fig. 1 Various geometries of the leading-edge cylinder used in the experiments.

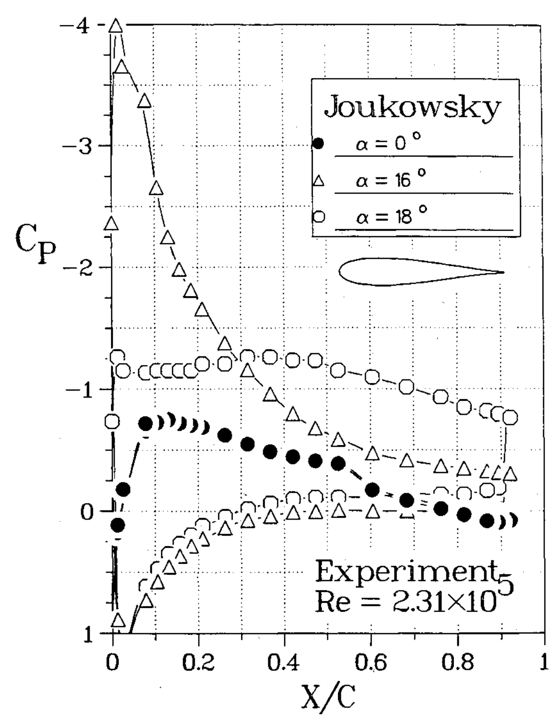

Fig. 2 Typical experimentally obtained pressure distribution plots for a conventional Joukowsky airfoil. These results serve as a reference to assess the effect of airfoil modifications and cylinder rotation.

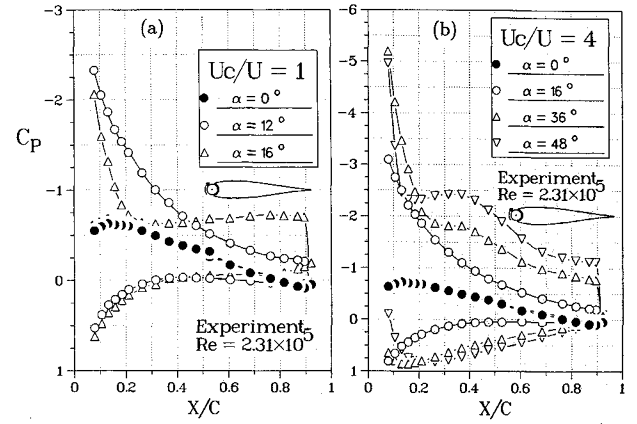

Fig. 3 Effect of cylinder rotation on the pressure distribution around the Joukowsky airfoil: a) $U_c/U=4$.

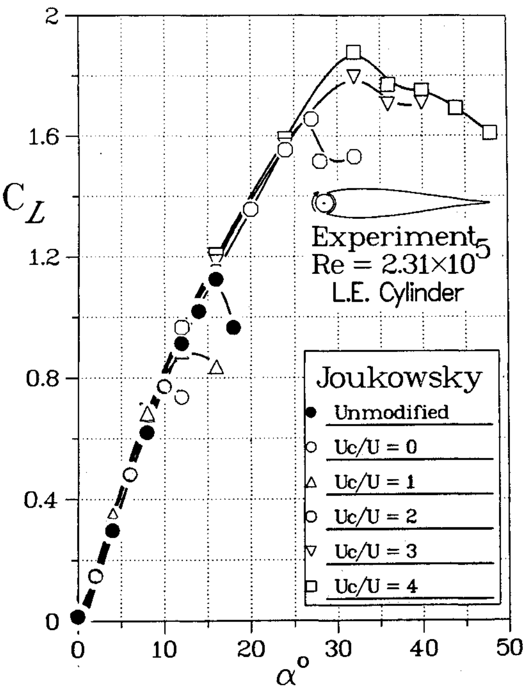

Fig. 4 Plots showing variation of the lift coefficient with an angle of attack as affected by the leading-edge cylinder and its rotation.

Figure 2, which serves as a reference, shows pressure distribution on the surface of a conventional Joukowsky airfoil, i.e., without a rotating cylinder replacing its nose. As a result of the practical difficulty in locating pressure taps in the cusp region, there is an apparent discontinuity in the pressure plots near the trailing edge. However, the region has little importance in the present discussion. It is apparent that the airfoil, in the absence of any modification to its nose geometry, stalls at an angle of attack somewhere between 16–18 deg.

Figure 3 shows the effect of cylinder rotation on the pressure distribution and the onset of stall. Two typical cases of $U_c/U=1$ and 4 are considered. The plots bring to light several interesting points:

1) In general, the effect of the leading-edge rotating cylinder is to increase the peak negative pressure. However, the relative increase is less at higher U_c/U. Physically, this is understandable. Although the available momentum for injection increases with an increase in U_c/U, the time available to absorb the momentum diminishes. Hence, there appears to be a practical limit beyond which the cylinder rotation has a negligible influence on further improvement in the performance.

2) With an increase in cylinder surface velocity to the free-stream velocity ratio, the stall angle corresponding to complete separation (i.e., no reattachment) is delayed. Note that without rotation, the separation (on the top surface) occurs at around 12 deg, however, with rotation a part of the surface always has an attached flow up to $x/c\approx 0.25$.

3) With higher rates of rotation, the onset of flow separation occurs at a higher angle of attack and there is a tendency for the boundary layer to reattach toward the trailing edge, as evident in Fig. 3b.

4) One would expect the cylinder rotation to increase $C_{L\max}$ due to the delayed stall and give a higher C_L/C_D at any given angle of attack.

The lift data for different rates of rotation of the cylinder are summarized in Fig. 4. The basic (i.e., unmodified) Joukowsky airfoil has a maximum lift coefficient of around 1.1. However, with modification, bluffness of the cylinder and the associated gap cause the $C_{L\max}$ to diminish. Note that the slope of the lift curve remains virtually unaffected. In the absence of the cylinder rotation, the modified airfoil was found to stall at around 12 deg, resulting in a uniform pressure distribution on the top surface. The stall sets in rather abruptly, as shown by a sudden drop in lift. However, with the cylinder rotation, a large well-developed suction peak at the leading edge of the wing suggests a delay in the stall. In fact, the data show the stall to occur at around 32 deg ($U_c/U=4$) with an increase in the lift coefficient by about 68%. Note that an increase in cylinder speed beyond $U_c/U=3$ improves the situation only marginally, suggesting the existence of a critical speed ratio beyond which momentum injection by means of a moving surface appears to have little effect.

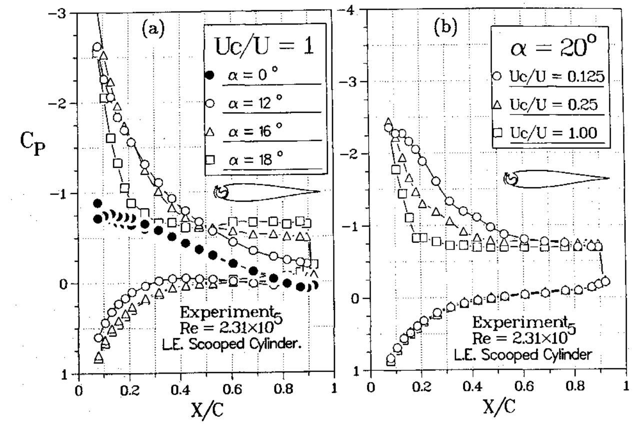

Fig. 5 Pressure plots for the Joukowsky airfoil with a leading-edge scooped cylinder: a) effect of angle of attack; b) effect of cylinder speed.

Leading-Edge Scooped Cylinder

Typical pressure distribution plots for the Joukowsky model with the leading-edge scooped cylinder rotating at $U_c/U=1$ are shown in Fig. 5a. The plots, compared to those of Fig. 3a, show an improvement (in terms of larger suction and delayed separation), suggesting higher effectiveness of the scooped cylinder. The flow is now essentially attached at $\alpha=16$ deg, with a much higher suction peak at the leading edge than that with the solid cylinder.

At higher rates of rotation, the scooped cylinder apears to the flow as effectively solid and there is no particular advantage in having the scoop. On the other hand, slower speeds of rotation appear to enhance the effect of the scoop (Fig. 5b). For example, even at the cylinder rotation speed as low as $U_c/U=0.125$ (the lowest speed used in the test program), the flow remains virtually attached at $\alpha=20$ deg. This is in contrast to the mostly separated flow at $\alpha=16$ deg, with the normal cylinder rotating at $U_c/U=1$ (Fig. 3a).

In effect, the rotating air scoop appears to slow down the flow over the lower surface and redirect more air over the upper surface. Therefore, reversing the scoop should have the opposite effect. This is precisely the case as shown in Fig. 6.

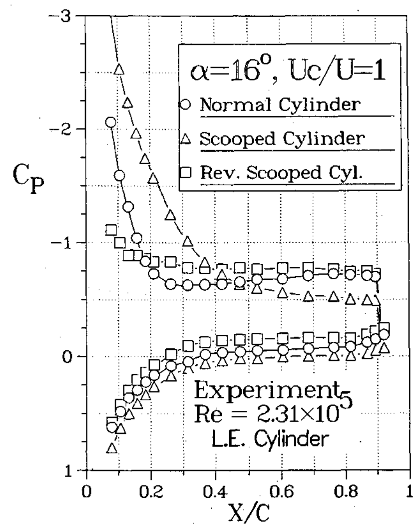

Fig. 6 Effect of different leading-edge cylinder configurations on the pressure distribution around the Joukowsky airfoil: $U_c/U = 1$; $\alpha = 16$ deg.

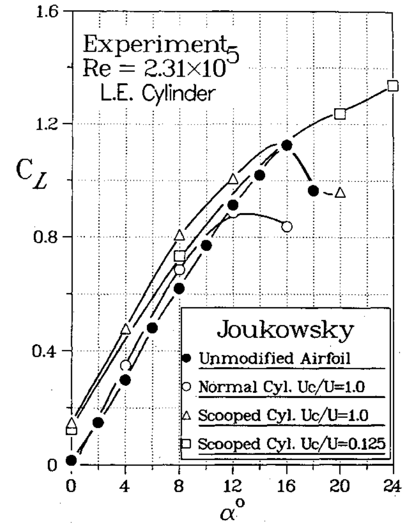

Fig. 7 Plots showing improvements in the lift coefficient of a Joukowsky airfoil with various leading-edge cylinder configurations and speeds.

The partially separated flow with the solid cylinder is reattached when the normal scoop configuration is used but completely detaches with the reversed scoop.

The corresponding lift data are summarized in Fig. 7. Typical results for a normal solid cylinder at $U_c/U = 1$ are also included to facilitate comparison. A slight shift of the lift plots to the left suggests a small increase in circulation due to the scooped geometry. The main advantage of the scooped geometry is that it can provide the same beneficial effect of the normal rotating cylinder but at a much lower speed. Note that this configuration substantially delays separation leading to higher $C_{L\max}$ and delayed separation, however, at a relatively lower speed. The concept appears promising and needs to be explored further.

It may be pointed out that the wind-tunnel test results were complemented by an extensive flow-visualization study carried out in a closed-circuit water channel. The model was constructed from Plexiglas and fitted with a leading-edge cylinder driven by a compressed-air motor. A suspension of fine polyvinylchloride powder was used in conjuction with slit lighting to visualize streaklines. Both angle of attack and cylinder speeds were changed systematically, and still photographs as well as a video movie were taken. The study showed, rather dramatically, effectiveness of this form of boundary-layer control.[3]

Conclusions

Effectiveness of the leading-edge cylinder can be improved at lower speeds of rotation by using a scooped configuration. The rotating air scoop appears to redirect more air over the upper surface. However, at high rates of rotation, it appears to the flow effectively as a solid cylinder, and there is no particular advantage in using the scoop configuration.

Acknowledgments

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References

[1]Mokhtarian, F. and Modi, V. J., "Fluid Dynamics of Airfoils with Moving Surface Boundary-Layer Control," *Journal of Aircraft*, Vol. 25, 1988, pp. 163–169.

[2]Mokhtarian, F., "Fluid Dynamics of Airfoils with Moving Surface Boundary-Layer Control," Ph.D. Thesis, University of British Columbia, Vancouver, Canada, Feb. 1988.

[3]Mokhtarian, F. and Modi, V. J., "On the Effect of Moving Surfaces on Airfoil Boundary-Layer Control," AIAA paper 88-4337, Aug. 1988.

Technical Comments

Comment on "Aeroelastic Oscillations Caused by Transitional Boundary Layers and Their Attenuation"

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WHILE the experimental results in Ref. 1 are important and merit publication, the accompanying explanation of the physical flow phenomenon does not, as it is replete with errors, including a complete misinterpretation of the quasisteady flow concept. According to the classical quasisteady flow concept, for small perturbations around $\alpha = \alpha_0$, the lift coefficient can be expressed in the following linearized form:

$$C_L = C_L(\alpha_0) + C_{L\alpha}\tilde{\alpha}, \quad \tilde{\alpha} = \theta + \dot{z}/U_\infty \tag{1}$$

For the bending oscillations in Ref. 1, $\alpha_0 = 0$ and the generalized angle of attack is $\tilde{\alpha} = \dot{z}/U_\infty$. According to the discussion in the last paragraph on p. 466 of Ref. 1, "...the lift curve slope with natural transition is close to zero," one would conclude that $C_{L\alpha}$ in Eq. (1) can be written as

$$C_{L\alpha} = (C_{L\alpha})_{FT} - (\Delta^i C_{L\alpha})_{TR} \tag{2}$$

where $(C_{L\alpha})_{FT}$ is the lift slope with fixed transition and $(\Delta^i C_{L\alpha})_{TR}$ is the lift loss due to free transition, reducing the lift

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