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Drag Reduction of Bluff Bodies Through Momentum Injection

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Effectiveness of the moving surface boundary-layer control in increasing lift and/or reducing drag at a subcritical Reynolds number is studied, using a two-dimensional wedge-shaped airfoil and a flat plate at high angles of attack, through an extensive wind-tunnel test program. Results suggest that injection of momentum, achieved here by introduction of bearing mounted, motor driven, hollow cylinders, can significantly delay separation of the boundary layer, resulting in a narrow wake and the associated reduction in the pressure drag. Results show that both the cylinder surface velocity as well as the surface roughness have significant effect on the boundary-layer control. The wedge airfoil showed an increase in C_L/C_D from 2 to 80, whereas the flat plate at 90 deg showed a reduction in drag coefficient by around 75%. A flow visualization study, conducted in a closed-circuit water tunnel using slit lighting and polyvinyl chloride tracer particles, complements the wind-tunnel tests. It shows, rather dramatically, the effectiveness of the moving surface boundary-layer control.

Introduction

EVER since the introduction of the boundary-layer concept by Prandtl, there has been a constant challenge faced by scientists and engineers to minimize its adverse effects and control it to advantage. Methods such as suction, blowing, vortex generators, turbulence promoters, etc., have been investigated at length and employed in practice with a varying degree of success. A vast body of literature accumulated over years has been reviewed rather effectively by several authors including Goldstein,[1] Lachmann,[2] Rosenhead,[3] Schlichting,[4] Chang,[5] and others. However, the use of a moving wall for boundary-layer control has received relatively less attention.

Irrespective of the method used, the main objective of a control procedure is to prevent, or at least delay, the separation of the boundary layer from the wall. A moving surface attempts to accomplish this in two ways: 1) it retards growth of the boundary layer by minimizing relative motion between the surface and the freestream, and 2) it injects momentum into the existing boundary layer.

A practical application of a moving wall for boundary-layer control was demonstrated by Favre.[6] Using an airfoil with the upper surface formed by a belt moving over two rollers, he was able to delay separation until the angle of attack reached 55 deg, where the maximum lift coefficient of 3.5 was realized. Alvarez-Calderon and Arnold[7] carried out tests on a rotating cylinder flap to develop a high lift airfoil for STOL-type aircraft. The system was flight tested on a single engine, high-wing research aircraft.

Of some interest is the North American Rockwell designed OV-10A aircraft, which was flight tested by NASA Ames Research Center.[8-10] Cylinders located at the leading edges of the flaps were rotated at high speed with the flaps in lowered position. The main objective of the test program was to assess handling qualities of the propeller powered STOL-type aircraft at higher lift coefficients. The aircraft was flown at speeds of 29–31 m/s, along approaches up to −8 deg, which corresponded to a lift coefficient of about 4.3. In the pilot's opinion any further reductions in approach speed were limited by the lateral-directional stability and control characteristics.

In terms of trying to understand the phenomenon at the fundamental level, Tennant's contribution to the field is significant. Johnson et al.[11] have conducted tests with a wedge-shaped flap having a rotating cylinder as the leading edge. Flap deflection was limited to 15 deg and the critical cylinder velocity necessary to suppress separation was determined. The effect of increasing the gap size (between the cylinder and the flap surface) was also assessed. No effort was made to observe the influence of an increase in the ratio of cylinder surface speed U_c to the freestream velocity U beyond 1.2. The influence of the cylinder surface characteristics on the effectiveness of the momentum injection process also was not assessed.

The present study builds on this background and explores application of the concept of the moving surface boundary-layer control (MSBC) through an extensive wind-tunnel test program followed by a flow visualization study using 1) a two-dimensional wedge-shaped airfoil with a rotating cylinder at its leading edge, in the subcritical range of the Reynolds number, and the angle of attack α varying from 0–55 deg; and 2) a two-dimensional flat plate, with a rotating cylinder at one or both the edges, also in the subcritical range of the Reynolds number, and the angle of attack varying from 0–90 deg.

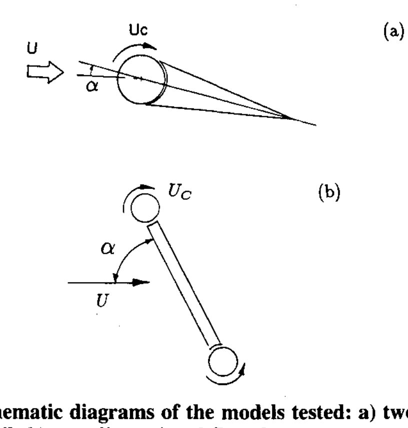

Fig. 1 Schematic diagrams of the models tested: a) two-dimensional wedge airfoil; b) two-dimensional flat plate.

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A schematic diagram of the configurations studied is presented in Fig. 1. An important parameter in the study is the ratio of the cylinder surface velocity U_C to the freestream velocity U, which was systematically varied during the test program conducted in the smooth flow condition.

It is important to emphasize that the simple geometries were purposely selected for study to help focus attention on the effects of momentum injection with minimum influence from the models' thickness and camber variations. Furthermore, flat plate and wedge-shaped airfoils have served in the past as basic elements in the evolution of more complex geometries.

Models and Test Program

Two dimensional wedge-airfoil and flat plate models were tested in a 45 × 45-cm cross-section wind tunnel with a maximum speed of 50 m/s. The large converging nozzle at the entrance of the tunnel (contraction ratio = 10:1) made the flow in the test section uniform with a level of turbulence <0.5%. The tunnel speed was adjusted by a variac transformer and measured using a pitot static tube connected to an inclined alcohol manometer.

The wedge model, having a chord length of 11.5 cm and a tail angle of ≈14 deg, was constructed from Plexiglas with its nose replaced by a cylinder of 2.54-cm diam and of desired surface roughness. Five different surface roughnesses were used in the test program (see Fig. 2): 1) smooth, 2) helical groves, 3) roughness squares, 4) spline-1, and 5) spline-2. The difference between spline-1 and spline-2 was essentially characterized by the number of splines, i.e., circumferential spacing between the longitudinal slots. In all of the cases, the gap between the cylinder and the main body was around 1 mm. Preliminary tests suggested a significant reduction in effectiveness of the MSBC for a gap size >3 mm.

Of course, surface characteristics of the moving element can display infinite variety. Only five different roughness features are considered here to have some appreciation as to their relative effectiveness in the momentum injection process. Once the potential of the MSBC is established, one may try to determine an optimum roughness configuration through a separate project.

The flat plate model, 9 × 40.5 cm, was also constructed from Plexiglas. The model was equipped with either one or two MSBC elements (rotating cylinders). The cylinders were driven by variac controlled ac motors through flexible belt drives. The motor speed was monitored using a strobe light. In the present test program, the ratio U_c/U was varied from 0–4. This corresponded to a maximum cylinder speed of around 11,000 rpm at a freestream speed of 5 m/s. To ensure two dimensionality of the flow, the models were fitted with end plates. In general, the tunnel speed was kept constant at 5 m/s, which corresponds to a Reynolds number of 3×10^4 based on the freestream velocity and the model width. The lift and drag forces as well as pressure data were recorded over a range of the angle of attack at 5-deg increments. The force could be measured with a sensitivity of 0.5 gm/mV and an accuracy of 1 mV.

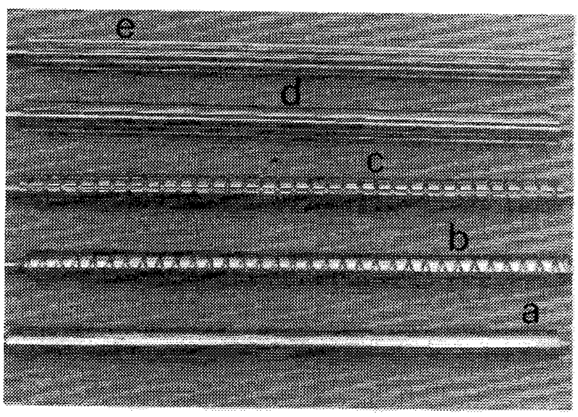
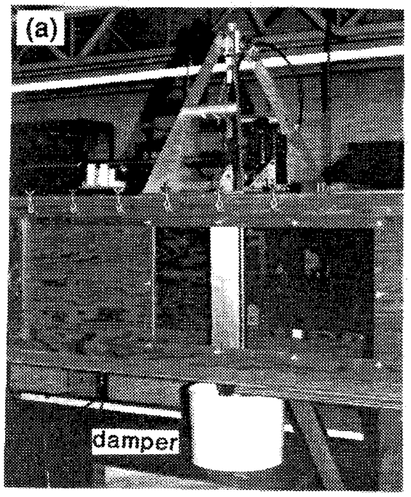


Fig. 2 Photograph showing the cylinders with different surface roughnesses used in the test-program: a) smooth; b) helical groves; c) roughness squares; d) spline-1; e) spline-2.



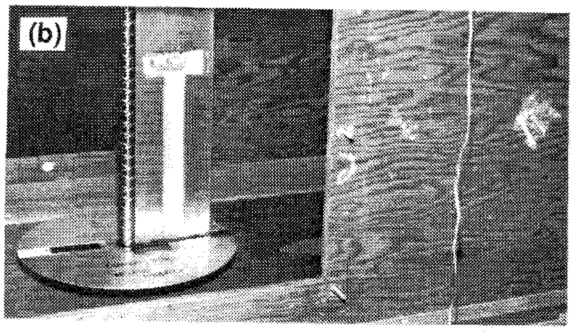


Fig. 3 Photographs of the wind-tunnel test arrangement: a) model supported by the lift-drag strain-gauge balance; b) close-up of the model showing the rough surface cylinder (helical groves).

The models were susceptible to vibration, particularly at high angles of attack, due to the turbulent wake created by the shedding vorticity. This was minimized by a nutation damper, which is essentially a hollow ring partially filled with liquid. Occasionally, an externally located viscous oil damper was used to achieve the same end. The test arrangement is shown in Fig. 3.

The wind-tunnel test results were complemented by an extensive flow visualization study. This was carried out in a closed-circuit water channel facility. The models were constructed from Plexiglas and fitted with one or more cylinders driven by a compressed-air motor. A suspension of fine polyvinyl chloride powder was used as tracer in conjunction with slit lighting to visualize streak lines. Both the angle of attack and the cylinder speed were systematically changed, and still photographs as well as videos were taken.

Results and Discussion

The lift and drag characteristics of an airfoil are significantly affected by the airfoil's geometry, i.e., thickness and camber distribution. To help isolate the effect of momentum injection, the models selected for study were taken to be simple: a wedge-shaped airfoil and a flat plate. Note that both of them are free of camber (symmetrical about the chord line) and two dimensional. The amount of information obtained through a systematic variation of the Reynolds number, angle of attack, cylinder's surface condition, and speed of rotation is literally enormous. For conciseness, only a few of the typical results useful in establishing trends are presented here. As the influence of the Reynolds number in the subcritical range 10^4–5×10^5 was found to be negligible, the results for both the wind-tunnel tests and the flow visualization studies are at $R_n = 4 \times 10^4$.

The relatively large angles of attack used in the experiments result in a considerable blockage of the wind tunnel (≈20% at $\alpha = 55$ 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 mostly applicable to streamlined bodies with attached flow. A satisfactory procedure applicable to a bluff body offering a large blockage in a flow, with separating shear layers, is still not available.

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 absence of any reliable procedure to account for wall confinement effects in the present situation, the results are purposely presented in the uncorrected form.

Perhaps, to evaluate effectiveness of the concept, it is more important to ensure essentially similar conditions of two dimensionality and blockage with and without the MSBC. The experimental setup attempts to provide that.

Wedge Airfoil

To establish a reference that can be used to assess the influence of cylinder rotation and surface condition, the first step was to obtain lift and drag characteristics of the wedge airfoil, with the smooth stationary cylinder forming its nose ($U_c/U = 0$) and the gap between the cylinder and rest of the wedge sealed. The results are presented in Fig. 4, which also shows effects of the cylinder rotation. The force coefficients are defined in the conventional fashion, i.e., based on the freestream velocity and planform area of the model. The reference configuration gave a maximum lift coefficient of around 1.5 at $\alpha = 55$ deg (Fig. 4a). However, with the cylinder rotating at $U_c/U = 4$, the peak C_L reaches a value of 4, an increase of around 170%! The corresponding results for drag are presented in Fig. 4b. It is of interest to recognize that, in general, the drag coefficient also shows a favorable trend, decreasing by about 36% at $\alpha = 55$ deg and $U_c/U = 4$.

Of course, one way to assess effectiveness of the momentum injection in controlling the boundary-layer separation would be to study a variation of C_L/C_D with α as affected by the cylinder rotation. This is shown in Fig. 4c. Note, in absence of the cylinder rotation ($U_c/U = 0$, reference case), the peak C_L/C_D is around 1.5, which attains a value of ≈10.5 at $\alpha = 15$ deg and $U_c/U = 3$, an increase of around 600%!

It seemed logical that the character of the cylinder surface roughness should improve efficiency of the process of momentum injection. Hence, as mentioned earlier, experiments were carried out with four distinctly different rough surfaces (Fig. 2). The lift and drag data for the helical surface (not shown here) gave a $C_{L,\max}$ of 4.6 at $\alpha = 55$ deg and $U_c/U = 4$, and the drag reduction amounted to around 30% under the same condition. The maximum C_L/C_D was observed to be ≈16 ($\alpha = 15$ deg and $U_C/U = 2$), an increase by a factor of ≈11. This suggested that an optimum choice of cylinder surface can improve the momentum injection and, hence, delay the boundary-layer separation.

To that end, the cylinder surface characterized by slotted squares (roughness squares) and splines running parallel to the cylinder axis appeared promising. Figures 5 and 6 show some typical results for two more promising surface characteristics (roughness squares and spline-2). The mechanism of momentum injection in the two cases appears to be fundamentally different. Square projections serve as large-scale

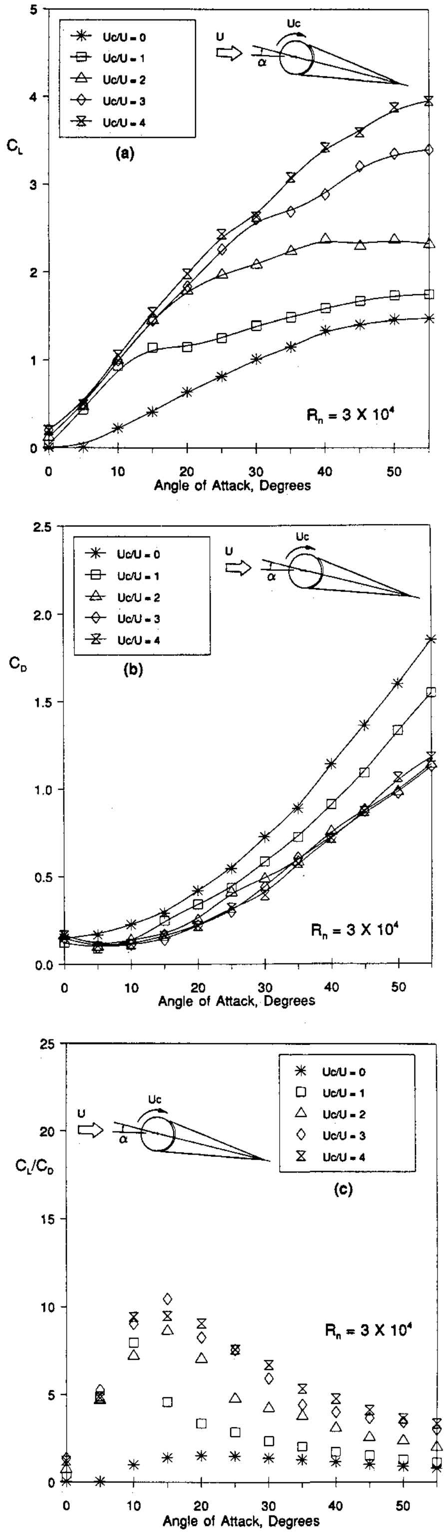


Fig. 4 Effect of the moving surface boundary-layer control on several aerodynamic parameters. Note, the $U_c/U = 0$ case serves as reference: a) lift coefficient C_L; b) drag coefficient C_D; c) C_L/C_D.

roughness elements rendering the flow turbulent. Splines, on the other hand, act like turbine blades, thus injecting momentum in a more direct way. With the roughness squares case, the peak lift coefficient attained a value of 4.15 at $\alpha = 50$ deg and $U_c/U = 4$ (compared to $C_{L,\max}$ of 1.5 for the reference case), as shown in Fig. 5a. In general, the drag coefficient also reduced as expected (Fig. 5b). However, as before, the optimum performance appears to occur at a lower angle of attack of $\alpha = 15$ deg where C_L/C_D of around 22 is realized (Fig. 5c), an increase by a factor of 13!

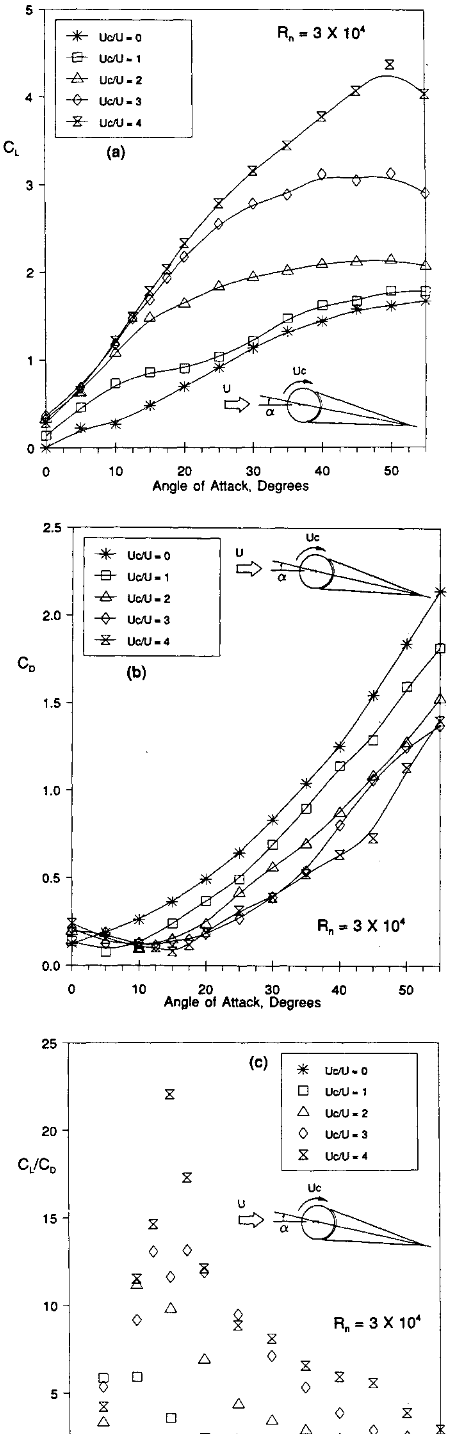


Fig. 5 Plots showing the effect of surface roughness (roughness squares) on the variation of aerodynamic coefficients with the angle of attack in the presence of MSBC: a) C_L; b) C_D; c) C_L/C_D.

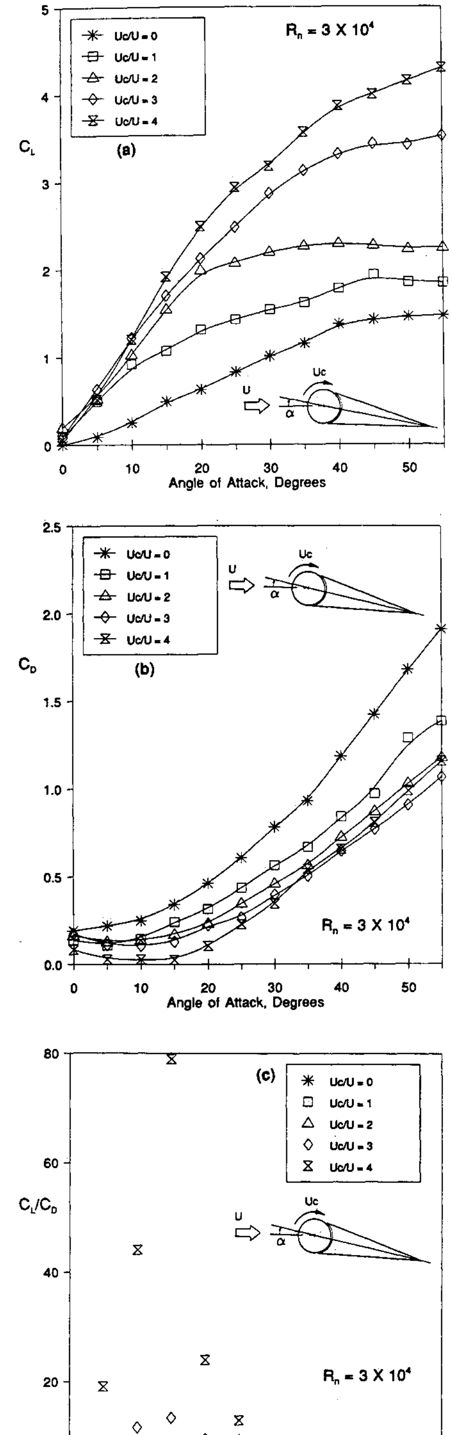


Fig. 6 Effect of spline cylinder-2, acting as a rotating element, on lift and drag characteristics of the wedge-airfoil.

Effectiveness of the spline-2 cylinder was found to be indeed dramatic (Fig. 6). Although the lift plots show small local variations compared to the previous cases, the reduction in drag is rather spectacular, particularly at U_c/U = 4 (Fig. 6a and 6b). This results in a peak C_L/C_D of 80 at α = 15 deg and U_c/U = 4 (Fig. 6c). Such an increase in C_L/C_D by a factor of at least 40 (compared to the reference case) can help improve performance of the next generation of highly maneuverable airplanes.

Figure 7 summarize the results concerning $C_{L,\max}$, $C_{D,\min}$, and $(C_L/C_D)_{\max}$ as affected by the cylinder surface. The numbers at the top of the arrows correspond to the U_c/U value and the angle of attack. For example, the model with a rotating cylinder having helical groves on its surface has the minimum drag coefficient of 0.108 (Fig. 7b) at U_c/U = 2 and α = 15 deg. It is interesting to note that although the maximum lift coefficient is associated with higher α (α = 50 or 55 deg, Fig. 7a) the peak C_L/C_D corresponds to α in the range

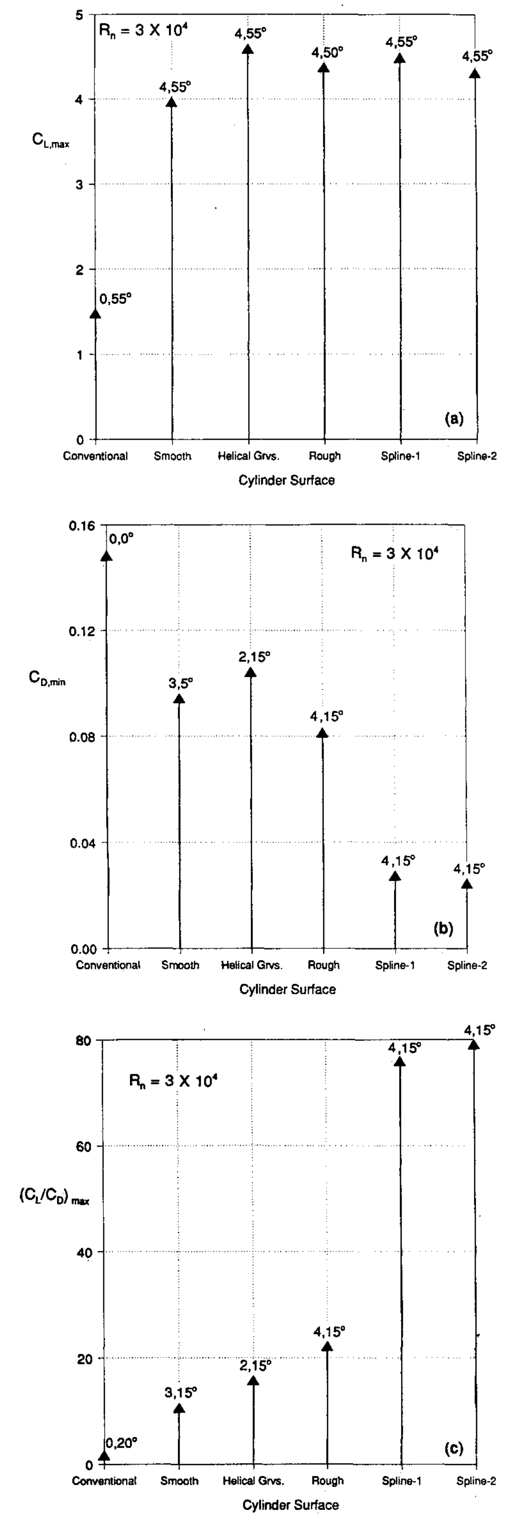


Fig. 7 Results obtained using a family of rotating cylinders, with different surface roughness, during the test-program (the conventional wedge airfoil (U_c/U = 0) serves as reference): a) maximum lift $C_{L,\max}$; b) minimum drag $C_{D,\min}$; c) maximum lift/drag ratio $(C_L/C_D)_{\max}$.

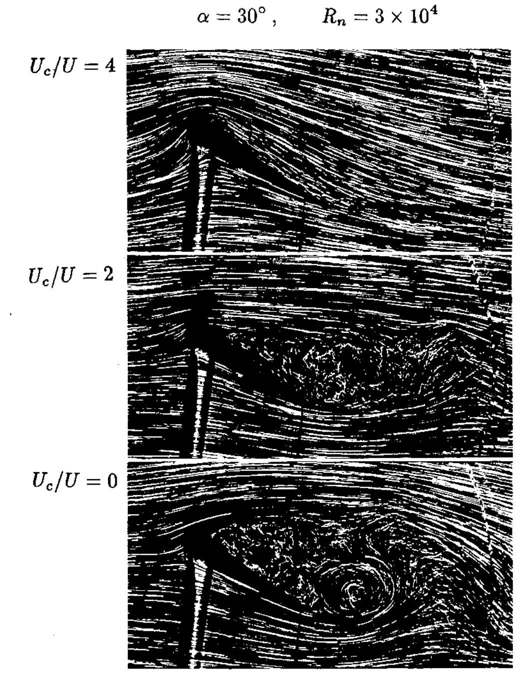


Fig. 8 Typical flow visualization photographs for a wedge-shaped airfoil, with a smooth surface cylinder, showing remarkable effectiveness of the MSBC concept. Note the progressive downstream shift of the separation point as the U_c/U increases. Eventually the flow appears to approach the potential character.

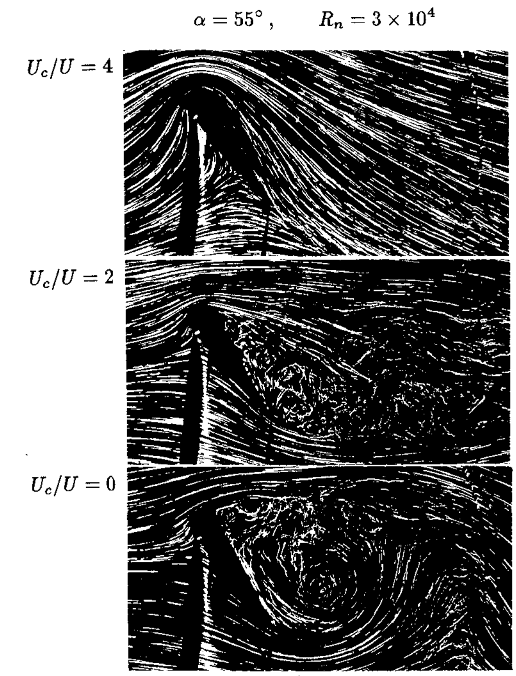


Fig. 9 Concept of moving surface boundary-layer control continues to be effective even at a high angle of attack of 55 deg.

of 15–20 deg (Fig. 7c). Of course, this is because of the drag characteristics as shown in Fig. 7b. It is interesting that differences in number and shape of splines, as with the spline-1 and spline-2 cases, has relatively little effect on $C_{L,\max}$, $C_{D,\min}$, and $(C_L/C_D)_{\max}$.

Figure 8 shows representative flow visualization pictures for the wedge airfoil, with a smooth surface cylinder forming its nose, at α = 30 deg and U_c/U varying from 0 to 4. The effectiveness of MSBC in controlling separation is spectacularly evident. Note, even at α as high as 55 deg, the momentum injection concept through a rotating cylinder continues to be quite effective (Fig. 9).

Flat Plate

Experiments with a flat plate involved introduction of a second rotating cylinder, as shown in Fig. 1. Now it was possible to inject momentum at the leading (upstream), trailing (downstream), or both of the edges of the plate.

Figure 10 shows variation of the lift and drag coefficients, C_L and C_D, with the angle of attack at four different speed

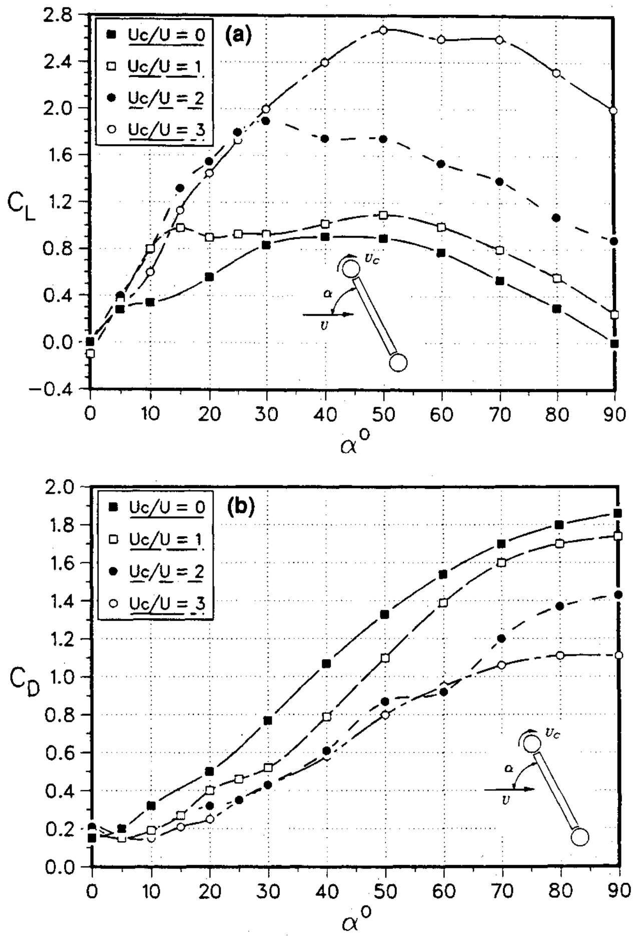


Fig. 10 Variation of the lift and drag coefficients for a two-dimensional flat plate when the moving surface boundary-layer control is applied at the upstream edge.

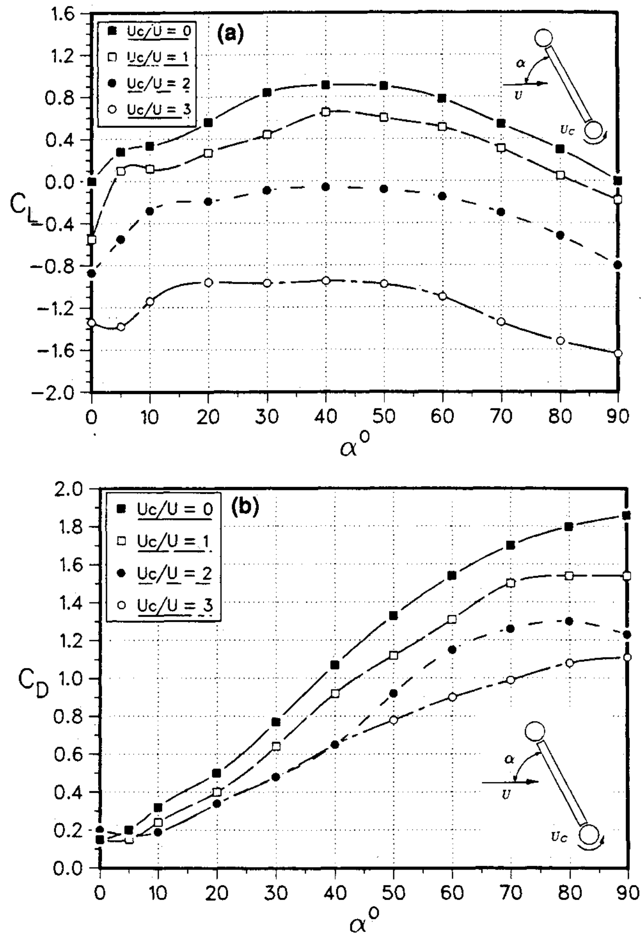


Fig. 11 Effect of rotation of the downstream cylinder on lift and drag characteristics of a flat plate. Note a significant reduction in lift, particularly at $U_c/U = 3$.

ratios ($U_c/U = 0, 1, 2, 3$) of the upstream (upper) cylinder when the downstream cylinder is at rest. With both of the cylinders at rest, the plate stalls at around 10 deg (Fig. 10a); however, with the upstream cylinder rotation, the stall is delayed and there is substantial increase in lift. The $C_{L,\max}$ of 2.7 at $U_c/U = 3$ represents an increase of 200% compared to the nonrotating cylinder case. However, the focus here is on the drag, which for $\alpha = 90$ deg and $U_c/U = 3$ corresponds to $C_D = 1.1$, a reduction of around 40% (Fig. 10b, $C_D = 1.85$ at $U_c/U = 0$).

The corresponding results for the downstream rotating cylinder with the top cylinder held stationary are presented in Fig. 11. As can be expected, injection of momentum on the top surface, near the trailing edge, opposing the flow results in a significant reduction in lift (Fig. 11a). In fact, the lift can become negative under a certain combination of the angle of attack and cylinder rotation. On the other hand, suction created on the front surface and injection of momentum in the wake does reduce its width, thus decreasing the pressure drag (Fig. 11b).

The effects of momentum injection at both of the edges are shown in Fig. 12. As can be expected, the adverse effect of the trailing edge cylinder rotation continues to be felt. Of course, the maximum reduction in wake and, hence, the corresponding decrease in the drag coefficient can be expected when both of the cylinders are rotating, as shown in Fig. 12b. For $\alpha = 90$ deg, a decrease in the drag coefficient from 1.85 at $U_c/U = 0$ to 0.47 at $U_c/U = 3$ represents a reduction of around 75%! The flow visualization photographs also showed a remarkable reduction in the wake width, thus qualitatively substantiating the trend suggested by the wind-tunnel test results (Fig. 13). Even for the bluff geometry represented by the plate at $\alpha = 60$ deg, the flow tends to be potential with the wake bubble gradually diminishing in size as U_c/U is increased. The MSBC continues to be effective in the extreme situation of the plate normal to the flow ($\alpha = 90$ deg, $U_c/U = 2$).

Flow visualization tests were also carried out to qualitatively assess the effect of the size of the cylinder. Though present, it did not seem to be a dominant parameter. The rotating element behaves more like a bound vortex. Its strength, as reflected in U_c, in relation to the freestream velocity U, appears to have the major influence.

A comment concerning power requirement and practical application of the concept at the full-scale level would be appropriate. At the outset, it should be pointed out that the concept presents exciting possibilities for application in a variety of situations ranging from high-performance airplanes and fuel efficient ground transportation vehicles to effective diffuser design, pulp separation in paper industry, and control of fluid-structure interaction instabilities. Investigations in these areas are in progress. Obviously, the power expended would depend on the situation in hand and the manner in which the concept is implemented. Hence, evolution of the concept to the prototype will have to be studied at length in the intended application. In the present study, a $\frac{1}{8}$-hp motor was sufficient to drive the cylinder(s) at a speed corresponding to $U_c/U = 4$. As pointed out in the introductory section, the OV-10A aircraft tested by NASA[8-10] involved flaps with leading-edge cylinders, the configuration similar to the wedge airfoil studied here.

It is important to recognize that the concept not only results in a reduction of drag but also leads to an increase in lift and a delay in stall. Thus, possible power conservation is only one

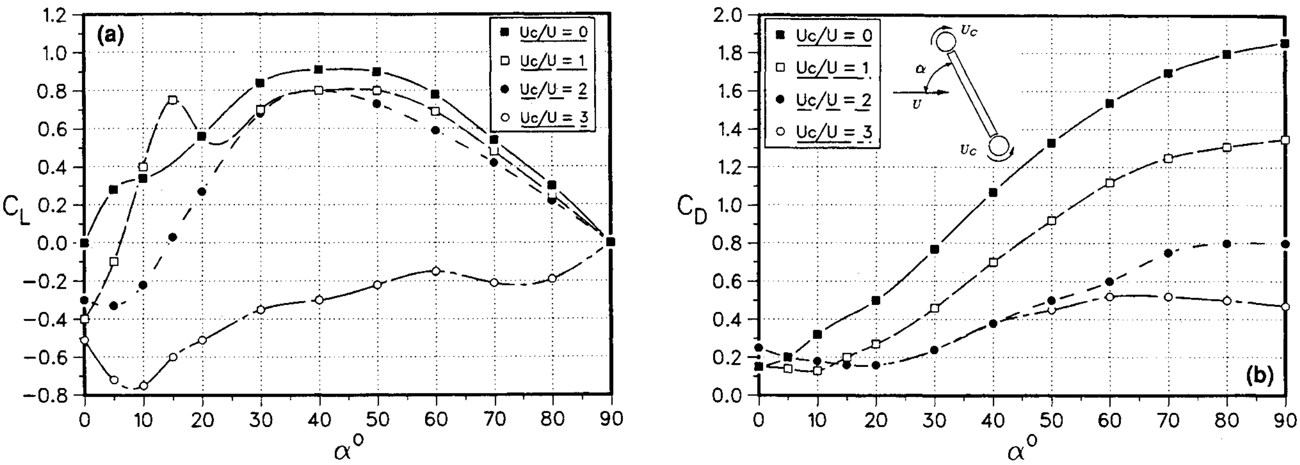


Fig. 12 Plots showing the effect of momentum injection, at both the edges of a two dimensional flat plate, on its lift and drag characteristics. Note, the lift is affected adversely; however, there is a remarkable reduction in drag.

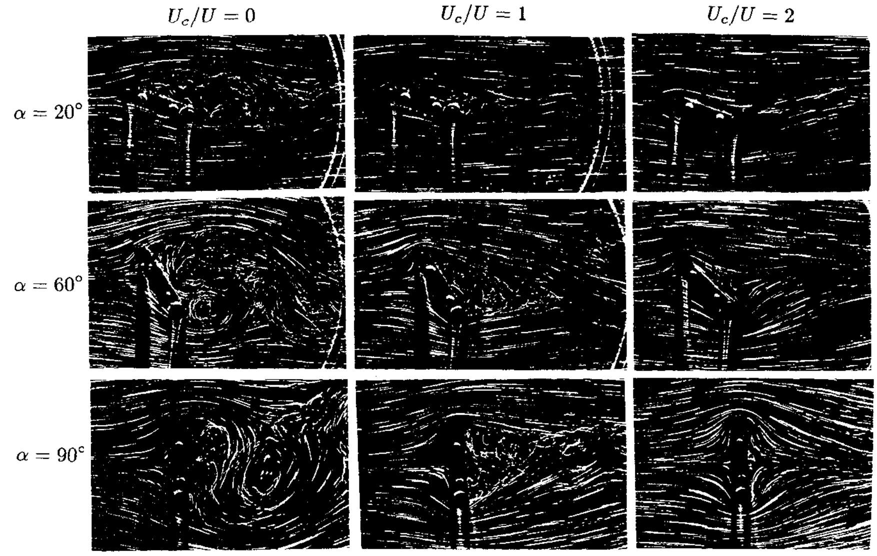


Fig. 13 Typical flow visualization photographs for a flat plate at α = 90 deg, showing, in a spectacular fashion, effectiveness of the moving surface boundary-layer control applied at top and bottom edges. The cylinders had smooth surface finish (R_n = 3 × 10^4).

aspect of its merit. The boundary-layer control on high-performance airplanes through suction or blowing can amount to as much as 14–18% of the engine power. Yet it is considered acceptable because of the nature of the mission, which demands a certain level of performance. In the application to a tractor-trailer truck configuration under study, <1% of the truck horse power was needed for the boundary-layer control. It promised to result in a savings of around $500/year in the fuel cost.

It should be emphasized that such idealized laboratory scale experiments represent only a small yet necessary first step in evaluating the potential of any new concept. Its practical realization would require considerable amount of tests with models as well as prototypes. Furthermore, possible practical problems pertaining to dynamic balancing of high-speed cylinders, gyroscopic effects, and the shroud design for the U_c/U = 0 condition, icing, mechanical failure, etc., will have to be addressed.

In any case, the small-scale experiments do suggest effectiveness of the MSBC in delaying the boundary-layer separation with associated improvement in lift, delay in stall, and reduction in the pressure drag.

Concluding Remarks

Based on a rather fundamental study of moving surface boundary-layer control with two-dimensional wedge and flat plate models, conducted at a subcritical Reynolds number of 3 × 10^4, the following general conclusions can be made.

1) For the wedge-shaped airfoil, rotation of the leading-edge cylinder results in increased suction over the nose. It is the propagation of the lower pressure downstream that determines effectiveness of the rotation. This depends mainly on the speed of rotation, surface roughness, and smoothness of transition from the cylinder to the airfoil surface. A large gap (>3 mm) substantially decreases the beneficial effect of the cylinder rotation.

2) The increased momentum injection into the boundary layer, with an increase in speed and appropriate surface roughness, delays separation of the flow from the upper surface, resulting in higher lift and reduced drag. The existence of a critical speed is also evident beyond which momentum injection through a moving surface appears to have relatively less effect.

3) With the rotation of the cylinder, the onset of flow separation occurs at higher angles of attack. The upper surface flow remains attached up to a distance downstream of the leading edge at which point it separates followed by, at times, reattachment downstream.

4) In the present study with a wedge airfoil, rotation of the smooth cylinder resulted in the increase of $C_{L,\max}$ by 170%. The corresponding decrease in drag was by about 36%.

5) Among the cylinder surfaces tested, the splined configuration proved to be the most successful in increasing lift as

well as reducing drag. It raised the $C_{L,\max}$ from 1.5 (reference case) to 4.3 (spline-2 case), an increase of 197%! The reduction in drag was also quite impressive. In fact, the maximum C_L/C_D increased from 2 to around 80. Although the splined cylinder proved to be the best, the results showed that an increase in roughness of the cylinder surface, in general, improves the boundary-layer control.

6) The large C_L/C_D attained here through MSBC may find application in design of the next generation of high-performance airplanes.

7) The concept appears equally promising in reducing drag of bluff bodies. For the flat plate at $\alpha = 90$ deg, it reduced the drag coefficient by 75%. This can have a far-reaching consequence in reducing aerodynamic resistance of ground vehicles such as trucks and buses. Furthermore, as the separation of shear layers is delayed, or even suppressed, the process of vorticity generation and its shedding in the wake is affected. Hence, the moving surface boundary-layer control may prove effective in suppressing vortex induced and galloping-type of instabilities. Investigations in these areas are in progress.

8) The concept of MSBC is essentially semipassive in character, requiring negligible amounts of power for its implementation. In the present set of model tests, a $\frac{1}{8}$-hp ($\approx$90 W) motor was more than adequate to obtain $U_c/U = 4$. However, it should be emphasized that practical realization of the concept at the industrial scale will require resolution of several challenging problems normally encountered in implementation of any new idea.

Acknowledgment

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