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Moving-Surface Boundary-Layer Control for Aircraft Operation at High Incidence

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The paper studies effectiveness of the moving-surface boundary-layer control on a NACA 63-218 (modified) two-dimensional wing used in the Canadair CL-84, a twin-propeller V/STOL design. Tests with rotating cylinder(s) at the leading edge of the airfoil and/or of the flap show the former to have a significant effect on the maximum lift, stall characteristics, and lift/drag ratio. On the other hand, the advantage gained by the presence of the rear cylinder is relatively small for the slotted flap configuration. The availability of a high value of lift suggests the approach velocity with this form of boundary-layer control is likely to be limited only by the lateral-directional stability characteristics. The concept presents several possible applications including a mechanism for delaying the vortex-induced resonance of bluff bodies.

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 to control it to advantage. Methods such as suction, blowing, vortex generators, turbulence promotors, etc., have been investigated at length and employed in practice with a varying degree of success. A vast body of literature accumulated over the 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 moving walls for boundary-layer control has received relatively little attention. This is indeed surprising as the Associate Committee on Aerodynamics appointed by the National Research Council specifically recommended more attention in this area.[6]

Regardless 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 surface. A moving surface attempts to accomplish this in two ways: it prevents the initial growth of the boundary layer by minimizing relative motion between the surfaces and the freestream, and it injects momentum into the existing boundary layer.

Newton was probably the first one to observe the effect of moving-wall boundary-layer control on the trajectory of a spinning ball,[7] without any appreciation as to the basis of the effect. Almost 200 years later, Magnus[8] studied lift generated by circulation and utilized the effect to construct a ship with a vertical rotating cylinder replacing the sail. Swanson[9] and Iverson[10] have presented excellent reviews of literature on the Magnus effect. As early as in 1910, Prandtl[11] himself demonstrated his "ship of zero resistance" through flow around two counter-rotating cylinders, while Flettner[12] applied the principle to ship propulsion in 1924 when he fitted large vertical rotating cylinders on the deck of the *Buchau*. A little later, in 1934, Goldstein[1] illustrated the principle of boundary-layer control using a rotating cylinder at the leading edge of a flat plate. However, the most practical application of the moving wall for boundary-layer control was demonstrated by Favre.[13] Using an airfoil with an upper surface formed by a belt moving over two rollers, he was able to delay separation until the angle of attack α reached 55 deg where the maximum lift coefficient of 3.5 was realized.

After a lull of more than 20 years (1938-1960), during which the tempo of research activity as indicated by important contributions in the field remained dormant, there appears to be some signs of renewed interest in this form of boundary-layer control. Alverez-Calderon and Arnold[14] carried out tests on a rotating cylinder flap to evolve a high-lift airfoil for STOL-type aircrafts. The system was flight tested on a single-engine, high-wing research aircraft designed by Aeronautics Division of the Universidad Nacional de Ingenieria in Lima, Peru.[15] Around the same time Brooks[16] presented his preliminary results of tests on a hydrofoil with a rotating cylinder at the leading or trailing edge. For the leading-edge configuration only a small increase in lift was observed; however, for the latter case a substantial gain in lift resulted. Motivation for the test program was to assess improvement in the fin performance for torpedo control. Along the same line, Steele and Harding[17] studied the application of rotating cylinders to improve ship maneuverability. Extensive force measurements and flow visualization experiments were conducted using a water tunnel and a large circulating water channel. Three different configurations of rudder were used with the rotating cylinder: 1) in isolation; 2) at the leading edge of a rudder; and 3) combined with a flap-rudder, the cylinder being at the leading edge of the flap.

From the overall consideration of hydrodynamic performance, mechanical complexity, and power consumption, configuration 2 was preferred. An application to a 250,000 ton tanker showed the power requirement for a 1 m diam cylinder rotating at 350 rpm to be around 400 kW.

Of some interest is the North American Rockwell OV-10A which was flight tested by NASA Ames Research Center.[17-19] Cylinders, located at the leading edge of the flaps, are made to rotate at high speed with the flaps in a 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 correspond 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. Excellent photographs of the airplane on the ground (showing the cylinders in position and in flight) have been published in *Aviation Week and Space Technology*.[20]

Efforts so far, although useful to an extent, were generally aimed at specific configurations, scattered, and lacked approach to the problem at a fundamental level in an organized

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fashion. From this point of view Tennant's contribution to the field is significant. In 1971 Tennant presented an interesting analysis for the two-dimensional, moving-wall diffuser with a step change in area.[21,22] The diffuser incorporated rotating cylinders to form a part of its wall at the station of the area change. Preliminary experiments were also conducted for area ratios up to 1/2.5, which showed no separation for the appropriate ratio of the moving surface to the diffuser inlet velocity. Tennant et al.[23] have also 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 effects of the increase in gap size (between the cylinder and the flap surface) were also assessed. No effort was made to observe the influence of the increase in cylinder surface velocity beyond $U_c/U=1.2$ (U_c = cylinder surface velocity, U = freestream velocity). More recently, Tennant et al.[24] have reported circulation control for a symmetrical airfoil with a rotating cylinder forming its trailing edge. For zero angle of attack, a lift coefficient C_L of 1.2 was attained with $U_c/U=3$. Also of interest is their study concerning boundary-layer growth on moving surfaces accounting for the gap effects.[25,26]

This paper describes results of an extensive test program of boundary-layer control for lifting bodies through moving surfaces which has been in progress for the past four years. In contrast to previous investigations, it studies the aerodynamics of an airfoil, NACA 63-218 (modified), used in the Canadair CL-84, a twin-propeller V/STOL design. The test program was divided into three stages as follows:

1) The airfoil with its leading edge formed by a circular cylinder (Fig. 1a).

2) The airfoil with its leading edge formed by a rotating cylinder and provided with a plain unslotted flap (Fig. 1b).

3) The airfoil with a slotted flap, leading edges of both formed by circular cylinders (Fig. 1c).

Model 3 is indeed quite versatile in that it provides flexibility not only in the airfoil angle of attack but also in the flap deflection and the rotation of one or both cylinders. Thus considerable information can be obtained pertaining to the separation conditions as affected by the wing angle of attack α, flap deflection β, and surface velocity ratios for the wing $(U_c/U)_f$ and the flap $(U_c/U)_r$ cylinders (f = front, r = rear). The project aims at obtaining this information through an organized variation in the system parameters.

In the next section the models, their support system, and test arrangement are described. This is followed by a brief account of the flow visualization procedure used to obtain some qualitative appreciation as to the character of the fluid field and the relative importance of the governing parameters of the problem. Finally, attention is directed toward pressure distribution and force data.

Experimental Program and Test Arrangement

Before embarking upon an extensive wind-tunnel test program, it was thought appropriate to undertake a preliminary flow visualization study to obtain some appreciation as to the character of the flow and to help establish, qualitatively, the relative merit of the system parameters involved (such as gap size, velocity ratio, cylinder surface roughness, etc.). This in turn helped to design the models and plan the aerodynamic tests. The flow visualization experiments were carried out in a glycerol-water solution tunnel having a test section of 20.32 cm × 20.32 cm × 2.44 m and capable of producing a Reynolds number in the range of 60-10,000 (Fig. 2). Deflection annular vanes—together with several sections of honeycombs, brass screens, and nylon wool—gave exceptionally flat velocity profiles, which were recorded using a quartz-coated, wedge-shaped platinum hot-film probe (DISA 55A83). The tunnel is powered by a centrifugal pump (Aurora type GAPB, 200 gal/min, 7.6 m head, 1750 rpm) driven by a 3 hp, variable-speed dc motor. A heat exchanger in the return circuit maintained the temperature of the working fluid within ±0.2°C. The dyed solution, of the same density as the working fluid, was injected upstream of

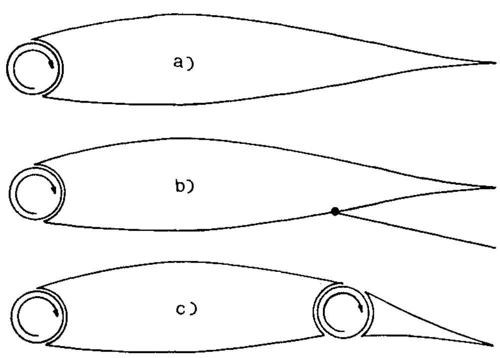

Fig. 1 Family of three models forming the test program.

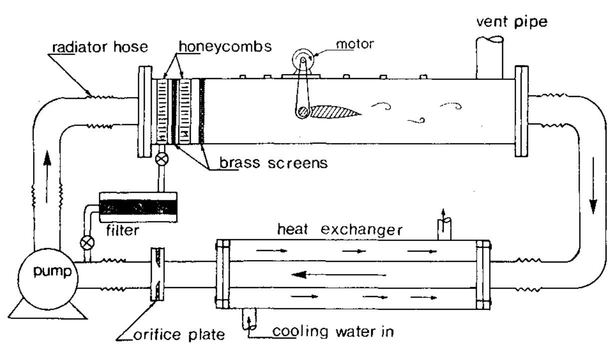

Fig. 2 Glycerol-water solution tunnel used in the flow visualization study to establish important system parameters.

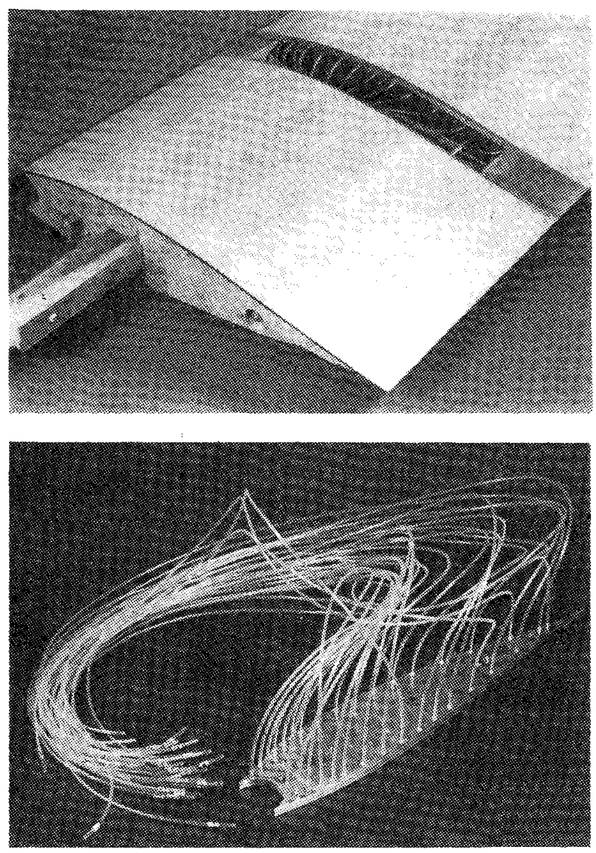

Fig. 3 Typical wind-tunnel model (leading-edge cylinder removed) with details of the central pressure ring.

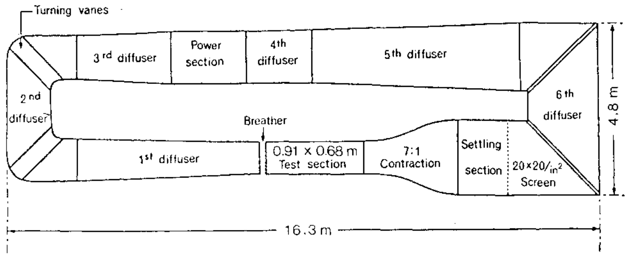

Fig. 4 Low-speed wind tunnel used in the test program.

the specially constructed models with rotating cylinders powered by an externally located drive system. The dye injection probe consisted of seven No. 23 syringe needles (0.38 mm diam) placed 0.5-1 cm apart on a streamlined support. The rate of injection was controlled with brass needle valves.

For the wind-tunnel tests, three models, 0.41 m chord and 0.675 m long, with the configurations described in Fig. 1 were constructed. Radius of the cylinder was so selected as to match average curvature of the leading edge. The models spanned the tunnel test section, $0.9 \times 0.68 \times 2.6$ m, to create essentially a two-dimensional condition. Primarily made of wood, each of the models carried a central aluminum pressure ring provided with 32 pressure taps, suitably distributed over the circumference, to yield detailed information concerning the surface loading (Fig. 3). A given model was supported by an Aerolab six-component strain gage balance and tested in a low-speed, low-turbulence, return-type wind tunnel where the air speed could be varied between 1-50 m/s with a turbulence level of less than 0.1%. A Betz micromanometer with an accuracy of 0.2 mm of water was used to measure the pressure differential across the contraction section of 7/1 ratio. The rectangular test section (0.9×0.68 m) is provided with 45 deg corner fillets which vary from 15.25×15.25 cm to 12×12 cm to partly compensate for the boundary-layer growth. The spatial variation of velocity in the test section is less than 0.25%. A schematic diagram of the tunnel is shown in Fig. 4.

Results and Discussion

The amount of information obtained through a systematic variation of important system variables is rather extensive; however, for conciseness, only a few of the typical results, sufficient to establish the trends, are recorded here.

The qualitative flow visualization study showed that in the absence of any rotation of the leading-edge cylinder the flow separates rather early, resulting in a wide wake for $\alpha \doteq 14$ deg. However, the streamline pattern changed substantially with $U_c/U = 2$, resulting in the delayed separation and drastically reduced wake width. An increase in cylinder velocity beyond $U_c/U = 4$ improved the situation only marginally, suggesting the existence of a critical speed ratio beyond which momentum injection through a moving surface appears to have little effect. Wind-tunnel tests confirmed this observation. These preliminary tests also provided useful information concerning the importance of the gap size between the cylinder and the airfoil. In general, an increase in the gap size affected the flow adversely and, for a gap size greater than 4.5 mm, the beneficial effects of cylinder rotation tended to be negligible. This information proved quite useful in design of the wind-tunnel models where an average gap size of 1.5 mm was maintained.

Wind-tunnel experiments with nonrotating cylinder(s) showed the aerodynamic coefficients to be essentially independent of the Reynolds number in the range of $R = 10^5 - 2.5 \times 10^5$. In general, the results were obtained for five values of the speed ratio ($U_c/U = 0,1,2,3,4$) and over a range of the angle of attack extending beyond the stall value. However, in presenting the data, certain test runs are purposely omitted for clarity.

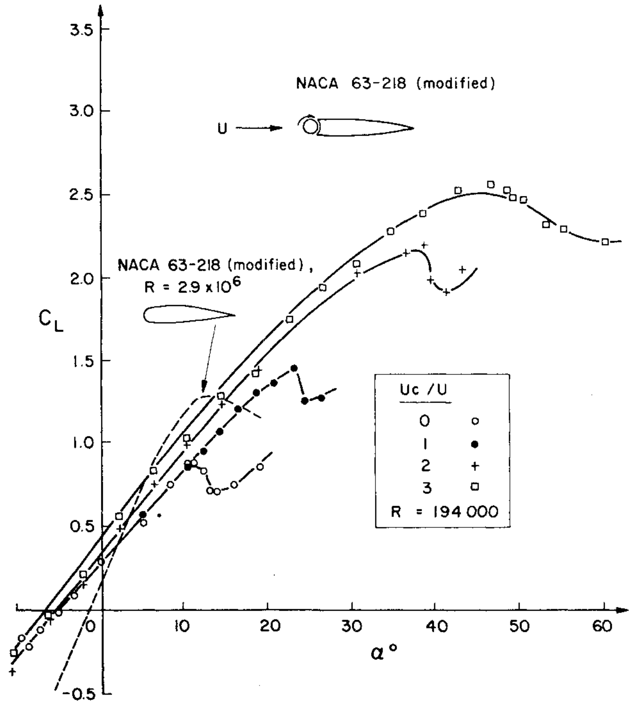

Fig. 5 Typical plots showing variation in the lift coefficient with angle of attack as affected by leading-edge cylinder velocity.

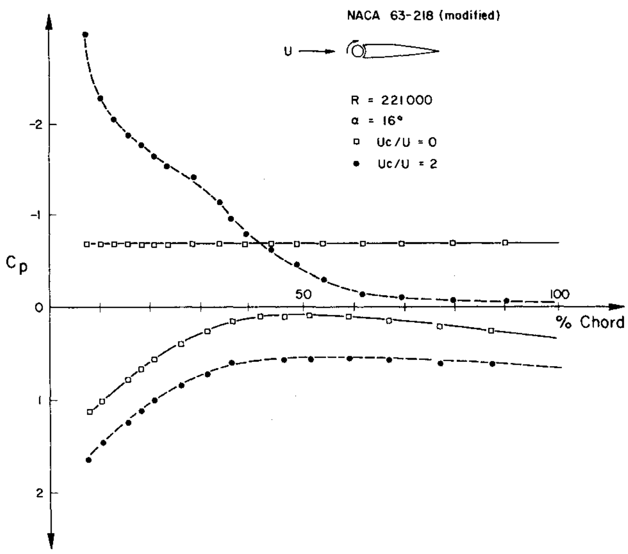

Fig. 6 Representative surface pressure distribution plots showing a delay in stall caused by the moving-surface boundary-layer control.

The first logical step would be to record the aerodynamic characteristics of the basic airfoil to assess the deterioration in performance caused by a bluff cylinder, with a gap, replacing its nose. One can then evaluate the influence of the rotating cylinder as reflected on the boundary-layer control. This is shown in Figs. 5 and 6. The basic airfoil (without cylinder) has a maximum lift L coefficient of around 1.3; however, the bluffness of the cylinder and the associated gap cause the slope of the lift curve as well as $C_{L,\max}$ to diminish. In the absence of the cylinder rotation, the airfoil stalled at around 12 deg, giving a uniform pressure distribution on the top surface. The stall was found to set in rather abruptly, as shown by a sudden drop in the lift. However, with cylinder rotation a large, well-developed suction peak was observed at the leading edge of the wing, suggesting a delay in the stall. In fact, the balance data showed the stall to occur around 45 deg ($U_c/U = 3$) with an increase in the lift coefficient of about

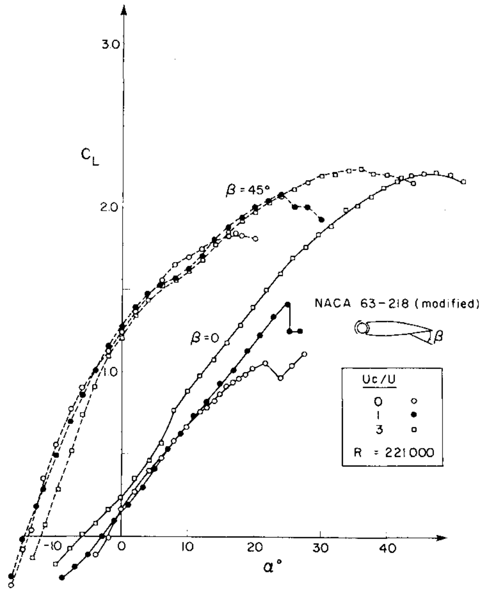

Fig. 7 Effect of the leading-edge cylinder rotation on the lift coefficient in presence of plain unslotted flap deflection.

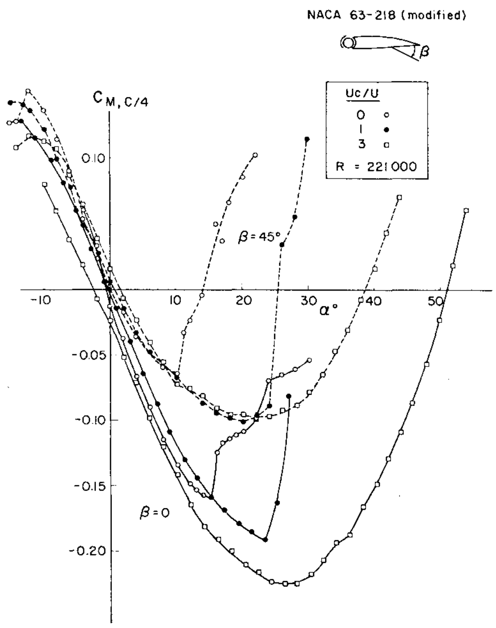

Fig. 8 Variation of the pitching moment coefficient with the angle of attack as affected by the cylinder rotation and flap deflection.

200%. Note also that the effect of rotation is to extend the lift curve without affecting its slope and to flatten the stall peak. The drag D data showed a substantial increase in the L/D at virtually all angles of attack. The availability of such a high value of lift suggests that the approach velocity of a V/STOL type of airplane using this form of boundary-layer control could be drastically reduced and perhaps would be limited only by the lateral-directional stability and control characteristics.

With an additional circulation introduced by the flap deflection, one would expect a reduction in the relative velocity of the cylinder. Tests with the model having a plain unslotted flap (Fig. 1b) were aimed at assessing this effect. Figure 7 presents the results of the lift variation with the angle of attack in the presence of flap deflection and cylinder rotation. As can be expected, the effect of flap deflection is to shift the plots to the left and, in general, to increase the $C_{L,\max}$ value. However, note a drastic reduction in the percentage

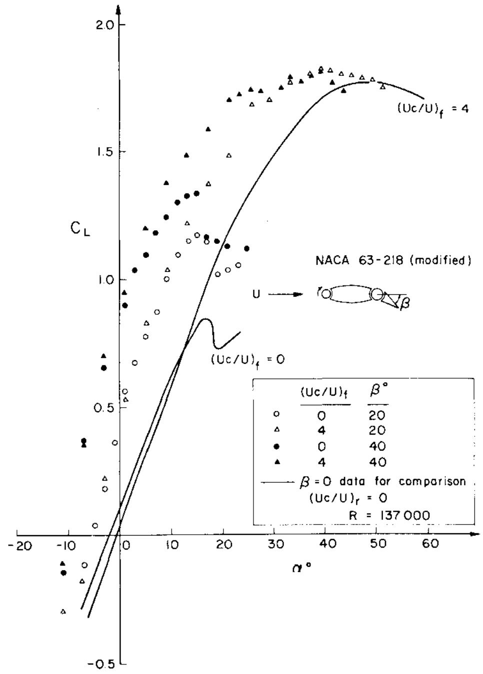

Fig. 9 Variation of the lift coefficient with the angle of attack as affected by the front cylinder rotation and flap deflection.

increase in $C_{L,\max}$ due to cylinder rotation in the presence of flap deflection. It is only 30% at $\beta = 45$ deg compared to around 130% in absence of the flap deflection, with U_c/U ranging over 0-3. Furthermore, note that for $U_c/U = 3$, $C_{L,\max}$ remains virtually unchanged even for α as large as 45 deg.

A remark concerning the small variation in $\beta = 0$ data as given in Figs. 5 and 7 is appropriate. This may be attributed to several factors including the following:

1) Models used in the two tests, although theoretically of the same geometry (NASA 63-218 modified), are two distinct units constructed from wood in our machine shop. It is possible that there were minor variations in the geometry, i.e., the two models may not be precisely identical.

2) Although ideally one would like to have the same gap size between the cylinder and the model, in practice it is extremely difficult—if not impossible—to achieve over the entire span of the model.

3) Even when undeflected the flap, because of its finite thickness (1.6 mm), alters the geometry of the lower surface of the model.

The minor differences in the results given by the two models for $\beta = 0$ are of no consequence here. What is important is the influence of different parameters, such as the flap deflection and speed ratio, which is effectively brought out by Figs. 5 and 7.

Figure 8 summarizes the effect of cylinder rotation on the pitching moment coefficient about the quarter chord ($C_{M,c/4}$). It is of interest to recognize that in spite of a large change in lift due to the momentum injection and boundary-layer separation control, the corresponding change in $C_{M,c/4}$ is essentially negligible in the region of practical interest, except for an expected delay in the stall and a corresponding increase in the maximum value of the moment. Minor variations are probably due to the reaction moment at the bearings. The same behavior persists in presence of the flap deflection. Note that the cylinder rotation does not seem to affect the slope of the curves (both C_L vs α as well as $C_{M,c/4}$ vs α), which is a distinct advantage in terms of stability and handling quality from a pilot's standpoint.

The next step was to attempt to overcome this reduction in the effectiveness of the front cylinder by further injection of momentum through the addition of a rotating cylinder at the leading edge of the flap, as shown in Fig. 1c. Some of the

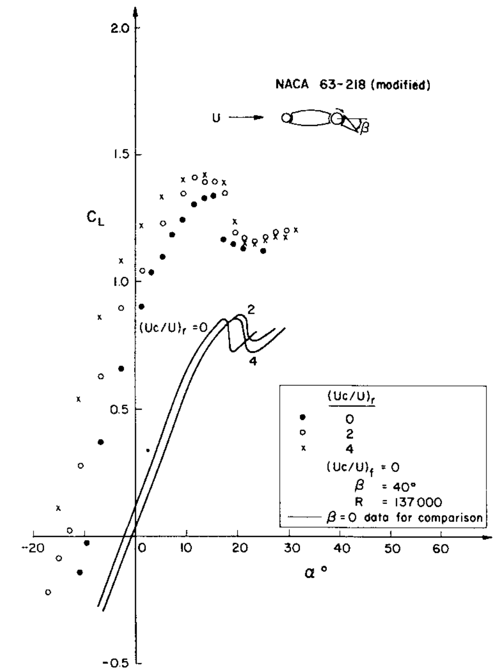

Fig. 10 Effect of rear cylinder rotation on lifting characteristics in the presence of flap deflection.

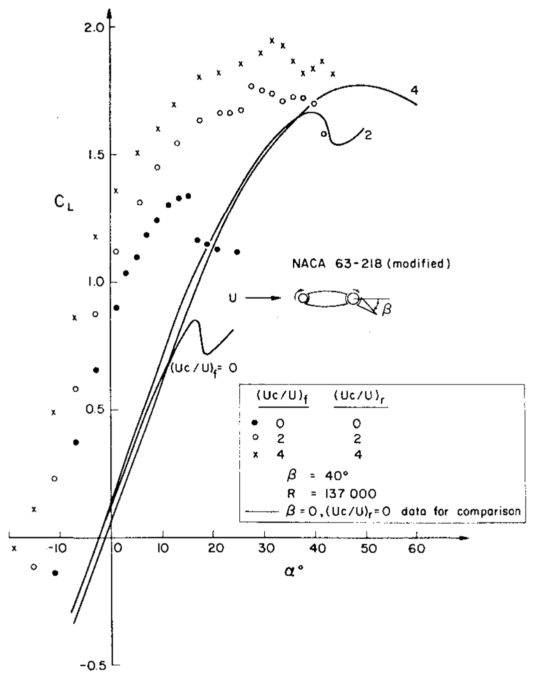

Fig. 11 Lifting characteristics as affected by rotation of both the cylinders and flap deflection.

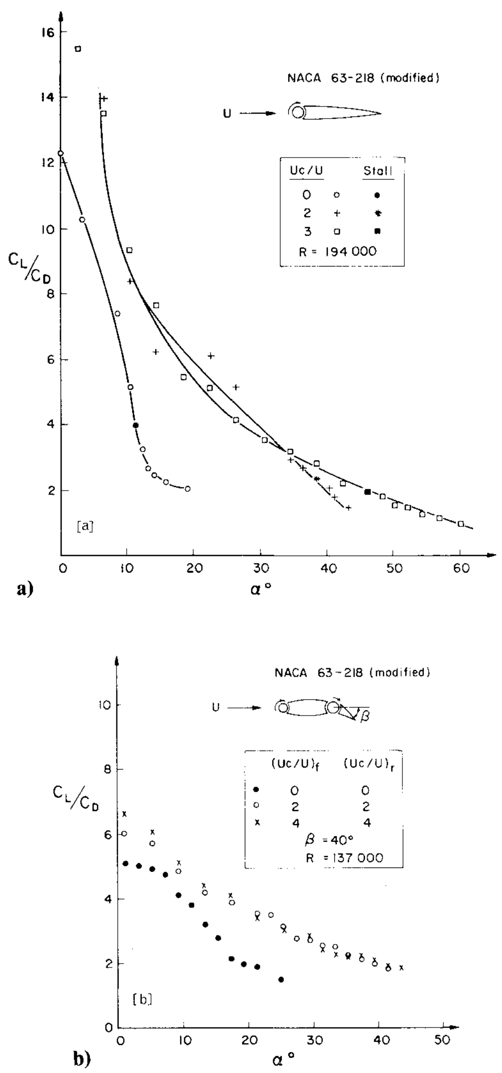

Fig. 12 Effect of cylinder rotation on lift to drag ratio: a) single-cylinder case; b) cylinders at leading edge of the airfoil and its slotted flap.

results of this two-cylinder case are presented in Figs. 9-11. Figure 9 summarizes a considerable amount of information concerning the effect of the front cylinder rotation and flap deflection in a single diagram for convenient comparison. In the absence of any rotation and flap deflection, the wing stalled at about 14 deg, with a further drop in $C_{L,\max}$ due to the additional gap at the rear cylinder. However, the stall is delayed to about 45 deg with an increase in $C_{L,\max}$ by around 100% when the nondimensional speed ratio $(U_c/U)_f$ reaches a value of 4. It must be recognized, however, that this still represents a substantial reduction in both $C_{L,\max}$ and the stall angle due to a gap at the rear cylinder location (Figs. 5 and 9). As before, the effect of the flap deflection is to shift the curves to the left and the influence of the front cylinder rotation maintains the same trend.

The fact that the rear cylinder rotation in the present configuration does not affect the wing performance substantially is suggested by Fig. 10. Note that here the front cylinder is stationary. Solid lines represent the results for $\beta = 0$ and are included to facilitate comparison. It is apparent that a rear cylinder velocity ratio $(U_c/U)_r$ as high as 4 has an insignificant effect on the C_L vs α plot. Essentially, the same trend continues at a flap deflection of 40 deg. With an increase in the rear cylinder rotational rate the plots slightly shift to the left and there is a small increase in $C_{L,\max}$. In this sense, the rear cylinder rotation is equivalent to a small amount of flap deflection. The main reason for this relative ineffectiveness of the rear cylinder may be attributed to the communication between the high- and low-pressure regions brought about by the gap at the rear cylinder. Recent tests with a new configuration, which completely eliminates this communication, showed a significant improvement in performance.

The same point is further emphasized by the results in Fig. 11. It shows the cumulative effect of both the cylinders rotating together with the flap deflected. Thus it gives some idea as to the highest value of $C_{L,\max}$ that one can hope to attain with this configuration. At the outset, it is apparent that the presence of the rear cylinder considerably degenerates the performance as compared to the single-cylinder case considered in Fig. 5. The zero-flap deflection data are indicated by solid lines. As can be expected, in absence of cylinder rotation, the effect of flap deflection is to decrease the zero-lift angle with an increase in $C_{L,\max}$ and lowering of the stall angle. The effect of cylinder rotation, however, is to further increase $C_{L,\max}$ and the stall angle. It is interesting to recognize that the effect of flap deflection on $C_{L,\max}$ in the presence of rotation continues to be quite small, with usual leftward shift of the plot.

From the design consideration and for a better indication as to the overall effectiveness of this concept, one should also look at an increase in the associated drag penalty, i.e., the ratio of lift to drag. This is shown in Fig. 12 for both single- and two-cylinder cases. Substantial improvement at all angles of attack is quite evident. However, for $U_c/U>2$, any additional gain appears to be only marginal. Note, for a speed ratio of 4, the increase in C_L/C_D can be as large as 90% (Fig. 12b).

A comment concerning the power required to rotate the cylinders would be appropriate. Each cylinder was powered by a ⅛ hp (93 W) variable speed dc motor. In steady state, the power demanded is primarily governed by the bearing losses. During the tests, the power required was always below 0.07 hp ($\doteqdot$50 W).

Conclusion

The results suggest that the concept of a moving surface can serve effectively as a boundary-layer control. It can provide a significant increase in the maximum lift coefficient and stall angle. It appears that a rotating cylinder at the leading edge of an airfoil is likely to provide the maximum benefit. In general, a rear cylinder does not contribute substantially in improving the performance, at least in the configuration tested here. In fact, in certain situations due to presence of an additional gap, it affected the performance adversely. Tests aimed at assessing the effect of gap size for the configurations studied here are in the planning stage. However, on the whole, the concept appears to be quite promising and has applications in areas other than aeronautical. Several variations in geometry are being tested currently which promise further improvement in performance.

Acknowledgment

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References

[1] Goldstein, S., *Modern Developments in Fluid Mechanics,* Oxford University Press, Oxford, England, 1938, Vols. I and II.

[2] Lachmann, G.V., *Boundary Layer and Flow Control,* Pergamon Press, London, 1961, Vols. I and II.

[3] Rosenhead, L., *Laminar Boundary Layers,* Oxford University Press, Oxford, England, 1966.

[4] Schlichting, H., *Boundary-Layer Theory,* McGraw-Hill Book Co., New York, 1968.

[5] Chang, P.K., *Separation of Flow,* Pergamon Press, 1970.

[6] Report of the Research Co-ordination Group on Boundary Layer Control to Suppress Separation, Associate Committee on Aerodynamics, National Research Council, Sept. 1966.

[7] Thwaites, B., *Incompressible Aerodynamics,* Clardon Press, London, 1960, p. 215.

[8] Magnus, G., "Ueber die Verdichtung der Gase an der Oberflache glatter Korper," *Poggendorfs Annalen der Physik und Chemie,* Vol. 88, No. 1, 1853, pp. 604-610.

[9] Swanson, W.M., "The Magnus Effect: A Summary of Investigation to Date," *Transactions of ASME, Journal of Basic Engineering,* Vol. 83, Sept. 1961, pp. 461-470.

[10] Iverson, J.D., "Correlation of Magnus Force Data for Slender Spinning Cylinders," Paper 72-966 presented at AIAA 2nd Atmospheric Flight Mechanics Conference, Palo Alto, Calif., Sept. 1972.

[11] Betz, A., "History of Boundary Layer Control in Germany," *Boundary Layer and Flow Control,* edited by G.V. Lachmann, Pergamon Press, London Vol. I, pp. 1-20.

[12] Flettner, A., "The Flettner Rotor Ship," *Engineering,* Vol. 19, Jan. 1925, pp. 117-120.

[13] Favre, A., "Contribution a L'étude Experimentale des Mouvement Hydrodynamiques a Deux Dimensions," Thesis, University of Paris, 1938.

[14] Alvarez-Calderon, A. and Arnold, F.R., "A Study of the Aerodynamic Characteristics of a High Lift Device Based on Rotating Cylinder Flap," Stanford University Technical Rept. RCF-1, 1961.

[15] Brown, D.A., "Peruvians Study Rotating-Cylinder Flap," *Aviation Week and Space Technology,* Vol. 88, No. 23, Dec. 1964, pp. 70-76.

[16] Brooks, J.D., "Effect of a Rotating Cylinder at the Leading and Trailing Edges of a Hydrofoil," U.S. Naval Ordnance Test Station, Department of the Navy, NAVWEPS Rept. 8042, April 1963.

[17] Cichy, D.R., Harris, J.W., and MacKay, J.K., "Flight Tests of a Rotating Cylinder Flap on a North American Rockwell YOV-10A Aircraft," NASA CR-2135, Nov. 1972.

[18] Weiberg, J.A., Giulianetti, D., Gambucci, B., and Innis, R.C., "Takeoff and Landing Performance and Noise Characteristics of a Deflected STOL Airplane with Interconnected Propellers and Rotating Cylinder Flaps," NASA TM X-62, 320, Dec. 1973.

[19] Cook, W.L., Mickey, D.M., and Quigley, H.G., "Aerodynamics of Jet Flap and Rotating Cylinder Flap STOL Concepts," Paper 10 presented at AGARD Fluid Dynamics Panel Symposium on V/STOL Aerodynamics, Delft, the Netherlands, April 1974.

[20] "Rotating Cylinder Flaps Tested on OV-10A," *Aviation Week and Space Technology,* Vol. 95, No. 16, Oct. 1971, p. 19; and Vol. 95, No. 24, Dec. 1971, cover page.

[21] Tennant, J.S., "The Theory of Moving Wall Boundary Layer Control and its Experimental Application to Subsonic Diffusers," Ph.D. Dissertation, Clemson University, Clemson, S.C., May 1971.

[22] Tennant, J.S., "A Subsonic Diffuser with Moving Walls for Boundary-Layer Control," *AIAA Journal,* Vol. 11, Feb. 1973, pp. 240-242.

[23] Johnson, W.S., Tennant, J.S., and Stamps, R.E., "Leading Edge Rotating Cylinder for Boundary-Layer Control on Lifting Surfaces," *Journal of Hydronautics,* Vol. 9, April-June 1975, pp. 76-78.

[24] Tennant, J.S., Johnson, W.S., and Krothapalli, A., "Rotating Cylinder for Circulation Control on an Airfoil," *Journal of Hydronautics,* Vol. 10, July-Sept. 1976, pp. 102-105.

[25] Tennant, J.S., Johnson, W.S., and Keaton, D.D., "On the Calculation of Boundary Layers Along Rotating Cylinders," *Journal of Hydronautics,* Vol. 11, April-June 1977, pp. 61-63.

[26] Tennant, J.S., Johnson, W.S., and Keaton, D.D., "Boundary Layer Flow from Fixed to Moving Surfaces Including Gap Effects," *Journal of Hydronautics,* Vol. 12, April-June 1978, pp. 81-84.