Rotating Cylinder for Circulation Control on an Airfoil

J.S. Tennant*
Florida Atlantic University, Boca Raton, Fla.
and
W.S. Johnson† and A. Krothapalli‡
University of Tennessee, Knoxville, Tenn.

The lift augmentation effect of a rotating cylinder located at the truncated trailing edge of a body is presented. A symmetrical airfoil model with a trailing-edge cylinder was tested in a low-speed wind tunnel, and the lift produced as a function of cylinder speed was determined for cylinder speeds up to three times the freestream velocity. Since the lift was attained at a 0° geometric angle of attack, the lift-producing phenomenon is called circulation control, which results from the alteration of the wake region by the spinning cylinder. The lift coefficient was found to be a linear function of the ratio of cylinder speed to freestream velocity and reached a value of 1.20 at a speed ratio of 3.0. A comparison is made with a lone spinning cylinder in a crossflow (magnus effect) and the cylinder-forebody combination reported herein. The cylinder-forebody pair produces higher values of lift at a given cylinder speed and a linear response in contrast to the nonlinear response of the lone cylinder at low cylinder speeds.

Nomenclature

C_L = lift coefficient
C_p = surface pressure coefficient
U = local velocity in the boundary layer
U_{cyl} = cylinder surface speed
U_e = velocity at the edge of the boundary layer
U_∞ = undisturbed freestream velocity
Y = distance from wall
δ = local boundary-layer thickness
β = speed ratio (U_{cyl}/U_∞)

Introduction

CIRCULATION control by the use of a rotating cylinder as the trailing element in a cylinder-forebody pair (Fig. 1) produces, in effect, an augmentation of the well-known magnus effect for rotating cylinders alone. Lift is achieved on the body combination by an adjustment of the trailing wake which is initiated at the location of the separation points on the upper and lower surfaces of the body. By means of boundary-layer control, these separation points are moved, and the wake takes on a new trailing direction. Although the boundary-layer control described herein is by moving wall, it could be achieved by other means, such as tangential slot blowing or area suction. The unique aspect of this cylinder-forebody lifting device is that lift may be produced by a symmetrical body at zero angle of attack, and the amount of lift can be controlled by variation in the amount of boundary-layer control applied. In the case of moving wall boundary-layer control, the amount of lift is related directly to cylinder rotational speed.

An alteration of the wake flow greatly changes the effective body shape as "seen" by the potential flowfield surrounding the body and its viscous surface boundary layer. In order to cause the potential flow best to describe the external flow with the altered wake, it is necessary to add circulation to the noncirculatory solution. Of course, lift then can be calculated by the Kutta-Joukowski theorem, and thus we have the name circulation control.

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*Associate Professor of Ocean Engineering. Member AIAA.

†Associate Professor of Mechanical and Aerospace Engineering. Member AIAA.

‡Graduate Research Assistant. Student Member AIAA.

Trailing-edge blowing for circulation control with bluff bodies has been reported by several investigators, including Neumann[1] and Kind.[2] More recently, Ambrosiani[3] presented an analysis of an elliptical airfoil with circulation control by blowing based on modern computational techniques. Walters[4] reported a series of wind-tunnel tests of cambered elliptical airfoils with circulation control by blowing and reported relatively high lift coefficients at low blowing rates. Loth[5] reported the successful application of the concept of circulation control to a small STOL aircraft. A study by Wagner[1] combined both area suction and tangential blowing on a single model and found the effects of both to be additive. His measurements indicated that significant increases in lift could be obtained.

Only limited work on circulation control by moving wall has been reported in the literature. For example, Brooks[6] performed an experimental study of circulation control due to a rotating cylinder at the trailing edge of a hydrofoil in a water tunnel. He employed a 1.9-cm-diam cylinder with a symmetrical hydrofoil having a chord of 14 cm and a span of 6.35 cm and measured lift coefficients at speed ratios up to 1.64, where he obtained a value of 0.22 at zero angle of attack. The model had a large gap (about 0.15 cm) between the fixed and moving surfaces and was operated at a Reynolds number of about 1.3×10^6 based on model chord.

Lee[7] performed wind-tunnel studies of a submarine sail plane model with a rotating cylinder at the trailing edge for circulation control. This model had a cylinder diameter of 16.2 cm, an overall chord of 165 cm, and a span of 117 cm. Results included overall measurements of lift, pitching moment, and yawing moment as a function of cylinder speed and geometric angle of attack. The gap between fixed and moving surfaces was around 0.17 cm, and tests were undertaken at a Reynolds number of 3×10^6.

The specific objective of this study was to determine the lift produced by moving wall circulation control on a two-dimensional model as a function of the wall velocity and to examine the flowfield around the model by flow visualization and by the measurement of surface pressures and boundary-layer profiles.

Approach

Test Apparatus

Wind-tunnel tests were undertaken on a circulation control model in the University of Tennessee subsonic wind tunnel, which is an open-circuit suction tunnel having a test section size of 50.8×71 cm and a top speed of 90 m/sec. The model was a combined NACA-EPH symmetrical section fitted with

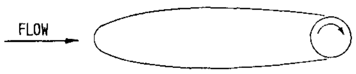

Fig. 1 Model cross section.

a trailing-edge cylinder, as shown approximately to scale in Fig. 1. The model had a 47-cm chord, a maximum thickness of 11.4 cm, a nose radius of 3.2 cm, and was mounted at zero angle of attack between the top and bottom walls of the test section to simulate two-dimensional conditions. Thin steel strips were used at the rear of the model so that the resulting gap at the point of tangency between the fixed and moving wall would be small and could be adjusted over a narrow range. The 7.6-cm-diam hollow aluminum cylinder was mounted on a center steel shaft and was rotated by a 1-hp variable-speed electric motor, which was capable of speeds up to 25,000 rpm. A total of 40 static pressure taps were spaced around the midspan of the body except, of course, on the moving surface.

Lift Determination

The lift force produced by cylinder rotation was determined by the integration of measured static pressures over the fixed wall portion of the model. A suitable extrapolation was made for the moving wall portion, which constituted only a small fraction of the model chord. All data were taken at a freestream velocity of 20 m/sec, which produced a Reynolds number of 6.4×10^5 based on the model chord. The wall velocity was varied up to around three times the freestream value, and the gap between fixed and moving surfaces was varied from 0.04 to 0.12 cm.

Flowfield Examination

In order to obtain a better understanding of the flow phenomena involved, the flowfield around the body was examined by three different procedures. These were: 1) visualization of the wake region using a smoke probe, 2) measurement of boundary-layer velocity profiles on the moving surface, and 3) determination of the shift in forward stagnation point caused by the cylinder rotation.

The smoke probe was used in order to correlate wake behavior with cylinder speed. Extensive photographs of this region were taken, and the streamline pattern was evident in virtually every case. The smoke probe also was used to examine the region of intersection between the model and tunnel wall for secondary flows, which could destroy the two-dimensional nature of the results. These studies led to the inclusion of a fillet around the model-wall intersection which virtually eliminated secondary flow in this region.

A 0.04-cm-diam boundary-layer total pressure tube was used to determine velocity profiles on the moving surface approximately 2 cm downstream of the fixed forebody. These measurements were undertaken to demonstrate how the boundary layer is energized by momentum transport from the moving wall.

The displacement of the forward stagnation point as a function of cylinder speed illustrated the relationship between the rotating cylinder and the circulation about the entire body. A unique procedure involving a moving tuft was employed to determine the stagnation-point location. This procedure involves the attachment of a single tuft of very fine thread to a flat ribbon, which was guided chordwise around the body to eyelets near the trailing edge, and then both ends were routed outside the tunnel to an operator. The operator could translate the tuft along the body by pulling on the ribbon and viewed the tuft location and deflection relative to a grid attached to the model through a surveyors' transit located upstream of the tunnel inlet. When the tuft was at the stagnation point, it did not respond, but, as it was moved away, a slight movement could be detected, allowing the stagnation point to be bracketed.

Results and Discussion

Figure 2 gives a typical static pressure distribution along the body surface from which the lift coefficient was determined by integration. The lift coefficient produced by the model as a function of cylinder speed is given in Fig. 3 for each of the three gaps tested. It generally is assumed that an increase in the gap between fixed and moving walls should decrease the effectiveness of moving wall boundary-layer control by removing the high-speed fluid at the moving wall farther from the low-velocity region in the boundary layer where control is desired. In fact, for the case of a cylinder at the leading edge, Johnson and Tennant[8] measured a significant gap effect.

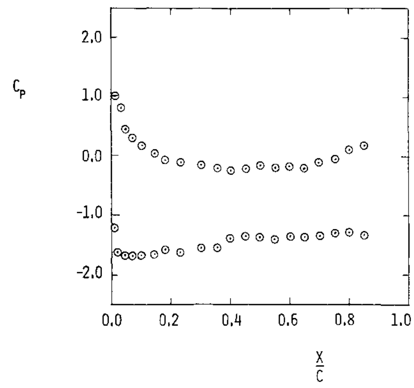

Fig. 2 A typical surface pressure distribution ($\beta = 3.11$, gap = 0.04 cm).

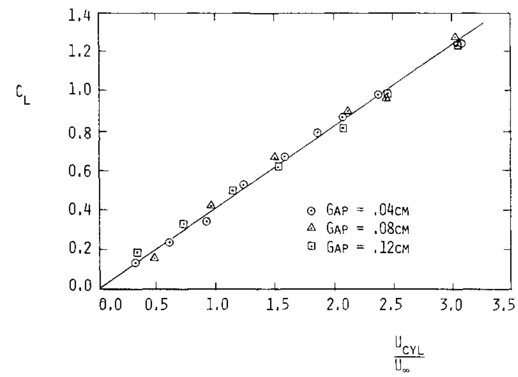

Fig. 3 Lift coefficient vs the ratio of cylinder speed to freestream velocity.

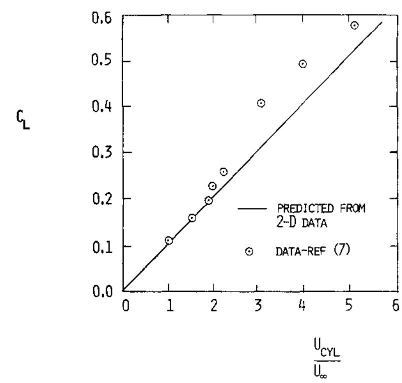

Fig. 4 Comparison with data from Ref. 7.

It should be noted that the model produced relatively high wind-tunnel blockage (16%) and, consequently, the experimental data have been corrected as suggested by Pope,[9] to approximate a body in a freestream. Since the model used in this study was quite similar in cross section to the model used by Lee,[7] a finite wing analysis was applied to the results in Fig. 3 to predict the lift coefficient for a model having an aspect ratio of 0.71, which was the value for Lee's model. These results are shown, along with Lee'e measured lift coefficients, in Fig. 4. For this particular case, the results compare quite favorably. A discussion of the application of finite wing theory to obtain the foregoing prediction is given in the Appendix.

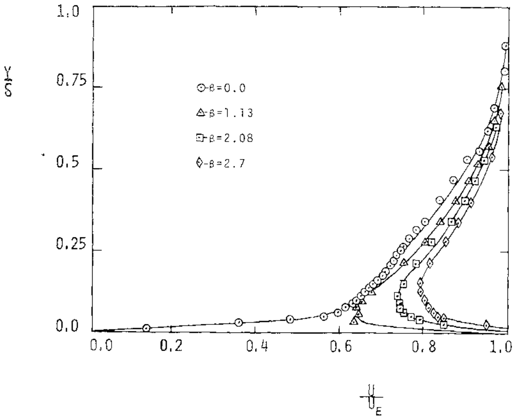

Fig. 5 Moving wall boundary-layer velocity profiles.

Fig. 6 Smoke photography of wake region ($\beta = 2.14$).

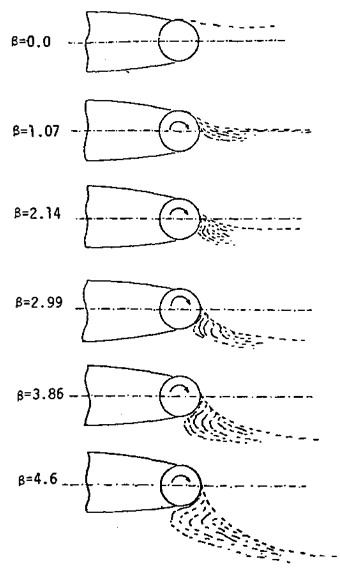

Fig. 7 Schematic representation of wake region for various cylinder speeds.

A comparison also can be made with the data of Brooks,[6] who reported a lift coefficient of 0.22 at a speed ratio of 1.64. The corresponding value at the same speed ratio from the data in Fig. 3 appropriately adjusted to the same aspect ratio is 0.16, which is reasonably close, considering that the models were not very similar in design.

Boundary-Layer Measurements

The effect of wall motion on the boundary layer is presented clearly in Fig. 5, which shows boundary-layer velocity profiles on the cylinder 2.1 cm downstream of the gap for various cylinder speeds. It is seen that the effect of wall speed is felt farther away from the wall as the wall speed is increased and, in particular, the minimum velocity in the layer is increased. The minimum velocity is a critical parameter since, for a moving surface boundary layer, it is the streamline with minimum velocity which would be the first to undergo flow reversal in the presence of an adverse pressure

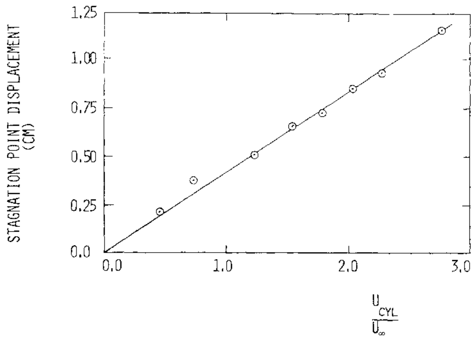

Fig. 8 Measured displacement in forward stagnation point.

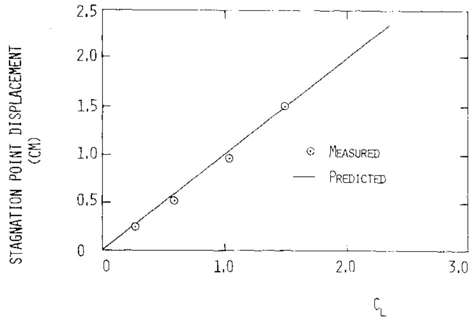

Fig. 9 Forward stagnation-point displacement vs lift coefficient (by Douglas-Neumann method).

gradient. It has been shown by several investigators[10-12] that such a flow reversal near a moving wall is, in effect, boundary layer separation.

Wake Observations

Numerous observations and photographs of the wake region were made with a smoke probe located just upstream of the moving wall adjacent to the fixed surface. A typical photograph is shown in Fig. 6 for a speed ratio of 2.14. Figure 7 represents an attempt to characterize the wake region for various values of the ratio of cylinder surface speed to freestream velocity. It is observed that flow separation occurs near the intersection of the fixed and moving walls when the cylinder is not rotating. This point of separation shifts as the cylinder speed is increased until it reaches the model centerline at a speed ratio of around 4.0.

Stagnation-Point Location

The lateral displacement of the forward stagnation point as measured by the moving tuft technique is shown in Fig. 8 as a function of the ratio of moving wall velocity to freestream velocity. The relationship is linear over the range of the data, with some scatter at low speed ratios, where the shift was difficult to read precisely. Figure 9 presents a prediction of the stagnation point location as obtained from a potential flow analysis. The body configuration was input to the Douglas-Neumann potential flow program,[13] and the effect of the cylinder was simulated by the imposition of various amounts of circulation on the solution. The varied circulation produced a correlation between lift coefficient and stagnation-point displacement, as shown. The corresponding experimentally determined correlation also is shown in Fig. 9, and the close agreement between predicted and measured stagnation-point location indicates that the primary effect of the trailing-edge rotating cylinder is to develop circulation about the body.

Comparison with Lift from Lone Cylinder

An interesting comparison can be made by examining the lifting performance of a lone rotating cylinder in crossflow and comparing the result with the lift on the same cylinder with an attached forebody. A comprehensive study of the "pure" magnus effect is reported by Swangon,[14] who presented lift coefficient as a function of the ratio of cylinder surface

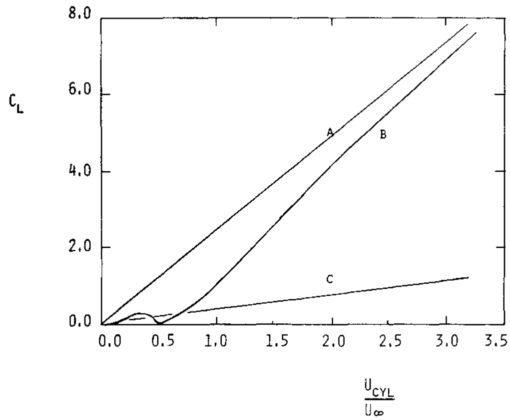

Fig. 10 Comparison of cylinder forebody configuration with lone cylinder. (Curve A: cylinder-forebody based on cylinder diameter; curve B: lone cylinder; curve C: cylinder-forebody based on chord).

velocity to freestream velocity and the Reynolds number based on cylinder diameter. Curve A in Fig. 10 represents the lift coefficient obtained in this study based on cylinder diameter. Curve B shows Swanson's results for a lone cylinder at the same Reynolds number based on cylinder diameter (1×10^5). The lift for the cylinder-forebody pair is seen to be a linear function of speed ratio, whereas the lift produced by the lone cylinder is characterized by a sharp dip at low speed ratios. This dip, according to Swanson, results from asymmetrical boundary-layer transition and, consequently, varies significantly with Reynolds number. In addition to somewhat higher values of lift coefficient, the linear response of the cylinder-forebody pair represents a considerable advantage over the nonlinear response of a lone cylinder in most applications.

The curve labeled C in Fig. 10 is the lift coefficient for the cylinder-forebody pair based on the model chord. It should be noted that the lift for this model can be augmented significantly by operation at an angle of attack.

Conclusions

A rotating cylinder at the trailing edge of a truncated streamined body is an effective means of developing lift by circulation control, and the lift produced is greater than that for a cylinder alone. The relationship between lift and cylinder speed is linear for the cylinder-forebody pair which is normally a considerable advantage in a control function over the nonlinear response of a lone cylinder. The experimental evaluation of lift coefficient by means of measuring the displacement of the forward stagnation point relative to its position when there is no lift (i.e., zero circulation) is an adequate alternative to integration of the pressure distribution over the entire lifting body.

Appendix: Finite Wing Calculations

The method of DeYoung and Harper[15] was employed to modify the two-dimensional results for finite aspect ratios. This is a modified lifting surface theory in which the wing is replaced by a plate of zero thickness and the condition of zero velocity normal to the plate is applied at four locations across the semispan at the three-quarter chord line. This procedure has been found to be quite accurate, both for highly swept wings and low aspect ratios.

The absolute angle of attack was defined as the ratio of measured two-dimensional lift coefficient to the theoretical lift curve slope, 2π. The angle then was multiplied by the "finite wing" lift curve slope obtained from Ref. 15 to get the lift coefficient corresponding to a particular aspect ratio. Normally, finite wing calculations are applied only to bodies having a sharp trailing edge where the theoretical lift curve slope is known to be 2π. In the present case, the bluff trailing edge made the application of this procedure questionable. However, comparison of the results from this prediction procedure with lift coefficient as a function of angle of attack obtained on a blunt trailing edge model by Lee[7] indicates that the procedure is accurate for the cases reported herein.

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