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Flow Control for an Airfoil with Leading-Edge Rotation: An Experimental Study

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An experimental investigation has been conducted on a two-dimensional NACA 0024 airfoil equipped with a leading-edge rotating cylinder. The airfoil was tested for different values of leading-edge rotations and flap deflection angles. The effects of the angle of attack α, the cylinder surface velocity ratio U_c/U, and the flap deflection angle δ on lift and drag coefficients, the size of the separated flow region, and the stall angle of attack are included. The effect of U_c/U on the boundary-layer growth and turbulence intensity are also shown. Experimental results, for example, showed that the leading-edge rotating cylinder increases the lift coefficient of a NACA 0024 airfoil from 0.85 at $U_c/U = 0$ to 1.63 at $U_c/U = 4$ and delays the stall angle of attack by about 160%. Smoke-wire flow visualization results were also used to demonstrate the strong effect of the leading-edge rotating cylinder on the size of the recirculation region.

Nomenclature

C_D = drag coefficient
C_L = lift coefficient
L/D = lift-to-drag ratio
U = freestream mean velocity, m/s
U_c = cylinder tangential velocity, m/s
U_c/U = cylinder surface velocity ratio
u = mean velocity inside the boundary layer at a specific location, m/s
u' = root mean square values of velocity fluctuations along x, m/s
u'/U = turbulence intensity
α = angle of attack, deg
δ = flap deflection angle, deg

Subscripts

c = cylinder
max = maximum
R = required for flow reattachment

Introduction

THE problem of boundary-layer control is very important in the field of aerodynamics and hydrodynamics. Boundary-layer control is essential for current wing design technology to increase lift, lift-to-drag ratio, and stall angle of attack. Several methods, such as suction and blowing, have been developed and reported for controlling boundary-layer flow. Although interest in boundary-layer control has increased, little is known about the use of a moving surface to control the boundary layer. Several authors, including Schlichting[1] and Chang,[2] have reviewed a vast body of literature pertaining to boundary-layer control. The effects of a rotating cylinder in a water channel at various cylinder peripheral speeds was investigated by Prandtl and Tietjens.[3]

The application of a clockwise rotating cylinder on the upper surface of an airfoil wing was investigated by Alvarez-Calderon and Arnold.[4] Their investigation covers a vertical takeoff and landing configuration and a short takeoff and landing (STOL) configuration. Results showed that the angle-of-attack range, with attached flows, was substantially doubled and that large flap deflections on the order of 90 deg, with attached flows, were possible. Of the same interest is the flight tests of a flap with a rotating leading edge on a North American Rockwell YOV-10A twin-engine aircraft,[5,6] where the rotating cylinder flap was used to control boundary-layer flow and to improve aerodynamic performance for STOL-type aircraft. The flight test was conducted at speeds of 29–31 m/s and angles of attack up to −8-deg landing approaches that corresponded to a lift coefficient of about 4.3.

Tennant[7] applied the moving wall to an airflow through a diffuser with a step change in area. The diffuser incorporated rotating cylinders to form a part of its wall at the station where the area change took place. Experimental results showed no separation for the appropriate ratio of the moving surface to the diffuser inlet velocity, and the moving surface provided a high area ratio diffuser with a short overall length.

Johnson et al.[8] conducted tests on a symmetrical lifting body with a leading-edge rotating cylinder. The angle of attack, in their study, was limited to 15 deg, and the cylinder speed necessary to reattach the flow was determined. Their study included the effect of the gap between the rotating and fixed surfaces on the effectiveness of the boundary-layer control technique. They concluded that the gap should be kept at its minimum value to minimize the cylinder speed required for effective boundary-layer control.

Circulation control for a symmetrical airfoil with a rotating cylinder forming its trailing edge was presented by Tennant et al.[9] The lift coefficient reached 1.2 with $U_c/U = 3$ at $\alpha = 0$ deg. The lift coefficient and the stagnation point location were found to be linear functions of the cylinder surface velocity ratio U_c/U. In Refs. 10 and 11, the region of transition from a fixed wall to a moving wall was analyzed, and the physical gap between surfaces was ignored by assuming all of the acceleration effects of the wall occurred in a fixed streamwise span.

Sayers[12] presented lift coefficients and stall angles of a rudder with a leading-edge rotating cylinder. Results of the study showed that the leading-edge rotating cylinder increases the lift coefficient and stall angle and, thus, increases the maneuverability of a vessel fitted with such a rudder.

Hassan and Sankar[13] conducted a numerical and experimental study to investigate the effects of forebody boundary-induced vorticity on the development of the laminar/turbulent boundary layers over modified NACA 0012 and NACA 63-218 airfoils with leading-edge rotation. They utilized an implicit finite difference procedure to solve the two-dimensional compressible full Reynolds-averaged Navier–Stokes equations on a body-fitted curvilinear coordinate system. The study presented the effects of varying the circumferential

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