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Effect of Momentum Injection on Drag Reduction of a Barge-like Structure

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ABSTRACT

Using a rectangular prism with a square cross-section and an aspect ratio of 2, this paper studies the effect of the Moving Surface Boundary-layer Control (MSBC) on the fluid dynamics of a barge-like structure. Two rotating cylinders forming vertical edges of the upstream square face provided the momentum injection. Wind tunnel results at a subcritical Reynolds number of 5×10^5 are complemented by the tow-tank experiments. Results suggest a significant effect of the MSBC on both pressure distribution and forces acting on the barge. In general, the momentum injection leads to a delay in the boundary-layer separation, hence a reduction in the pressure drag. For the present case, wind tunnel results showed a reduction in the drag coefficient of around 24%, while the tow-tank study suggested a decrease of up to 28% for a Froude number of 0.18. It is important to point out that the MSBC is essentially a semipassive process. The rotating elements are hollow cylinders, and the power required in overcoming the bearing friction as well as fluid resistance is rather small. Results suggest that for an input of 1 W, there is at least an 8 W reduction in power due to the decrease in drag. A brief video is available.

NOMENCLATURE

A	: ref. area, $W \times W$ for wind tunnel tests; $W \times T$ for tow-tank data
$A.R.$	: aspect ratio, L/W, two in present case (Fig. 2)
C_D	: total drag coefficient, $D/(1/2)\rho U^2 A$
C_S	: side force coefficient, $S/(1/2)\rho U^2 A$
D	: drag
Fr	: Froude number, U^2/gL
g	: acceleration due to gravity
H	: height of top surface of model from ground
L	: length of model, $2W$ (Fig. 1)
P	: static pressure at model's surface
P_∞	: free-stream pressure
Re	: Reynolds number, $\rho UL/\mu$
S	: side force
T	: draft (Fig. 2)
U	: free-stream velocity
Uc	: surface speed of rotating cylinder
Uc/U	: momentum injection parameter
W	: length of one side of model's square cross-section
μ	: dynamic viscosity
ρ	: fluid density

INTRODUCTION

Ever since the introduction of Prandtl's boundary-layer concept, scientists and engineers have faced a constant challenge 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 varying degrees of success. A vast body of literature accumulated over years has been reviewed rather effectively by several authors, including Lachmann (1961), Rosenhead (1966), Schlichting (1968) and Chang (1970). However, the use of a moving wall for boundary-layer control has received relatively less attention. This is indeed surprising, as the Associate Committee on Aerodynamics (1966), appointed by the National Research Council, specifically recommended more attention in this area.

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 2 ways: It prevents the initial growth of boundary-layer by minimizing relative motion between the surface and the free stream; and it injects momentum into the existing boundary-layer. The injection of momentum helps in keeping the flow attached to the surface in the region of adverse pressure gradient, thus delaying its separation.

Of some interest is North American Rockwell's OV-10A, which was flight-tested by NASA's Ames Research Center (Cichy, Harris and Mackay, 1972). Cylinders, located at the flaps' leading edge, were made to rotate at high speed with the flaps in a lowered position. The main objective of the test program was to assess the 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 $-8°$, which corresponded to the lift coefficient of about 4.3.

This was the state of development with respect to the moving surface boundary-layer control when Modi (Modi, Lake, Mcmillan, Mullins, Swinton and Akutsu, 1981) entered the field. The subsequent contributions to the literature are essentially from Modi and his colleagues. They undertook comprehensive investigations with 2-dimensional airfoils (Mokhtarian, Modi and Yokomizo, 1988; Modi, Mokhtarian, Fernando and Yokomizo, 1991; Modi, Munshi, Bandyopadhayay and Yokomizo, 1998) as well as 2- and 3-dimensional bluff bodies involving a flat plate (2-D), rectangular prisms and tractor-trailer truck configurations (Modi, Ying and Yokomizo, 1990; Modi, Fernando and

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KEY WORDS: Moving Surface Boundary-layer Control (MSBC), momentum injection, boundary-layer, drag reduction.