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Technical Notes

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Separation Control by Alternating Tangential Blowing/Suction at Multiple Slots

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Introduction

BOUNDARY-LAYER separation entails great losses and limits the performance of many flow-related devices. Through separation control, a flow pattern close to that given by inviscid flow theory can be obtained, leading to large lift and small drag. Much research has been done on this area (e.g., Ref. 1). Recently, Wang and Sun[2] showed that, for a thick airfoil, using multiple slots blowing tangentially at low speeds, boundary-layer separation can be suppressed effectively and that the method has the advantage of small power expenditure (because the kinetic energy of the blowing jet is proportional to the third power of the blowing speed). In the present study, we extend the work in Ref. 2 by replacing the tangential blowing with alternating tangential blowing/suction (ATBS). At each slot exit, the blowing/suction velocity is in the tangential direction of the airfoil surface, and its magnitude varies periodically with a zero mean. A thick airfoil with multiple slots is shown in Fig. 1. The idea of ATBS comes from the following considerations. In the blowing phase, the boundary layer downstream of a slot will be energized, and the separation delayed. What will happen in the suction phase? It is known that, when a sink is put into a freestream, a layer of fluid particles that is upstream of the sink is sucked into the sink, and the fluid particles above (and below) this layer move to the region that is near the line of symmetry and downstream of the sink. During suction, a slot exit might be taken as a small sink panel. The fluid in the boundary layer flows over the sink panel. It is expected that the retarded fluid particles in the near-wall region of the boundary layer upstream of the slot exit would be sucked into the slot, and the fluid particles in the region farther from the wall, which are momentum rich, would pass over the slot exit and flow to the near-wall region of the boundary layer downstream of the slot, making the velocity profile there more separation resistant. Because both the blowing and suction would make the boundary layer more separation resistant, ATBS might lead to a steady global flow that is without separation. ATBS with low speeds at multiple slots can be implemented by microfabricated electromechanical systems (using an array of zero-mass jet to replace a slot; Fig. 1). In this Note, numerical simulations based on the Navier–Stokes equations are conducted to study the effectiveness of controlling boundary-layer separation on a thick airfoil by ATBS with low speeds at multiple slots.

Computational Method

The Reynolds-averaged Navier–Stokes equations were solved using the implicit, approximate factorization algorithm of Beam and Warming.[3] The Baldwin–Lomax[4] turbulence model was used in the calculation. The interaction between the flow of blowing/suction at a slot exit and the surrounding fluid is simulated using a time-dependent boundary condition at the slot exit. At grid points located at the slot exit, harmonically varying velocities were prescribed, and caution was exercised to ensure that the calculated pressures and, hence, densities on these grid points were consistent with the prescribed time-dependent blowing/suction velocities.

Results and Discussion

The airfoil considered in this Note was of 40% thickness, the upper and lower surfaces of which were semi-ellipses of 32 and 8% thickness, respectively. On the upper surface of the airfoil, 10 slots were equally spaced (from $0.6c$ to $0.97c$) and the slot heights were $0.002c$. The flow conditions were $M_\infty = 0.15$, $\alpha = 0$, and $Re = 10^6$. A grid resolution study was conducted, and the 480×131 grid was chosen for the present study. The grid spacing in the normal direction varied from $0.0005c$ at the wall to $0.3c$ at the outer boundary, and about 35 points were submerged in the boundary layer. On the airfoil surface, about 25 points were distributed on each slot exit and in its neighborhood. The blowing/suction velocity at a slot exit is prescribed using a sinusoidal function of the form $V = V_a \sin(2\pi f \tau)$, where V, V_a, f, and τ are the nondimensional instantaneous velocity, peak velocity, frequency, and time, respectively (in the nondimensionalization, U_∞, c, and c/U_∞ are used as reference velocity, length, and time, respectively). The sinusoidal boundary condition was enforced at each grid point on a slot exit. All 10 slots were assumed to operate in unison with no phase shift.

The case of $V_a = 1.5$ and $f = 2.5$ (hereafter referred to as case 1) is chosen for detailed discussion. The calculated lift and drag coefficients, C_L and C_D, respectively, vary with time periodically with the same period as that of V. The time averages of C_L and C_D, that is, $\bar{C}_L$ and $\bar{C}_D$, respectively, are 1.44 and 0.09, respectively (C_L oscillates between 1.2 and 1.6 and C_D between −0.1 and 0.3). Figure 2a shows the global pictures of the flow at two time instants (instant C, maximum suction and instant G, maximum blowing). It is seen that the global flowfield almost does not vary with time. The time variation of the aerodynamic forces is due to the variation of the flow inside the upper-surface boundary layer. For comparison, the flow around the airfoil without flow control was calculated, and the flow is shown in Fig. 2b. It is seen that, without flow control, massive separation occurs, and with the flow control, separation is almost suppressed. To examine the interaction between the blowing/suction and the fluid particles surrounding a slot exit, the flow near one of the slots (the second slot) is plotted in Fig. 3 for seven equally spaced time instants in one period. At instant A, when the blowing phase is just finished and the suction phase is about to start, there is a separation bubble

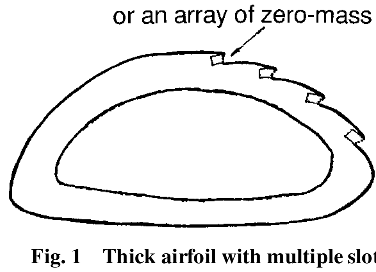

Fig. 1 Thick airfoil with multiple slots.

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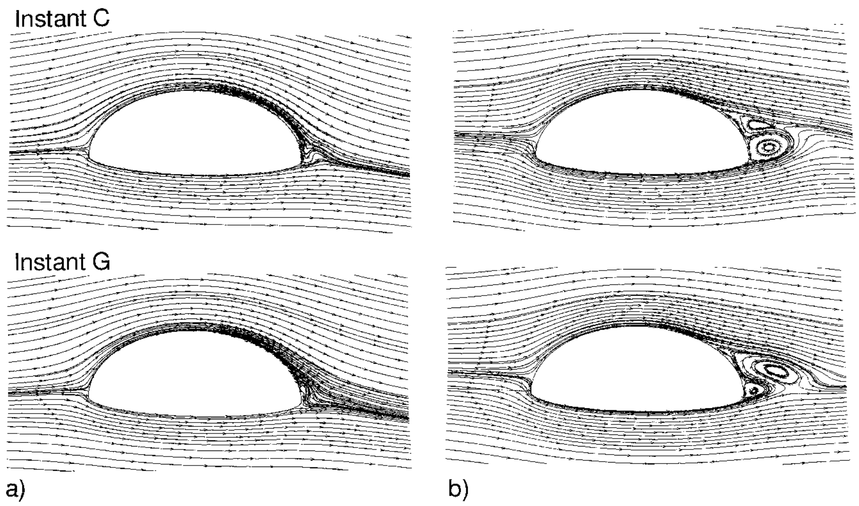

Fig. 2 Streamline plots at various instants: a) with flow control ($V_a = 1.5$, $f = 2.5$, and $\alpha = 0$ deg) and b) without flow control ($V_a = 0.0$ and $\alpha = 0$ deg).

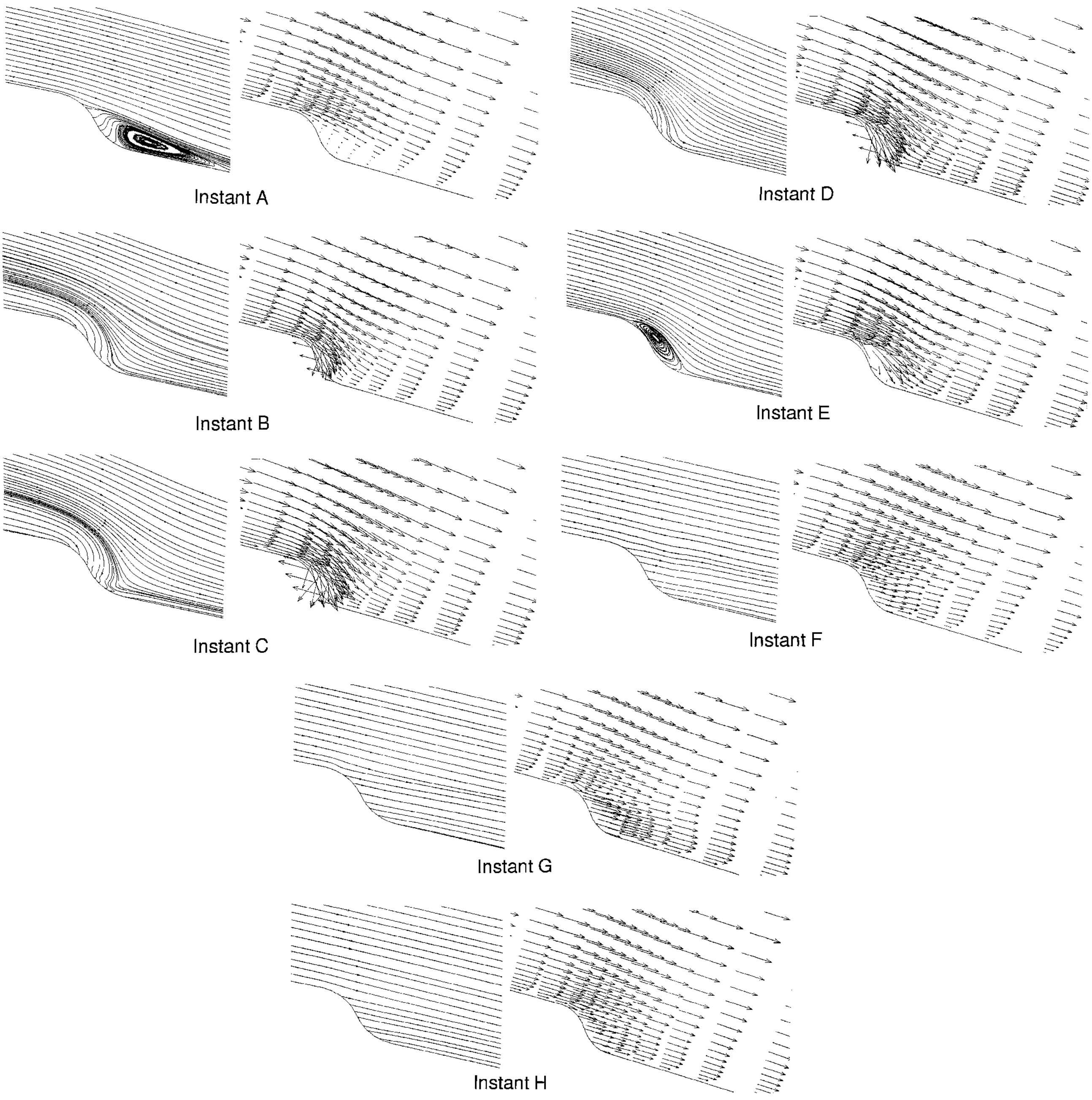

Fig. 3 Streamline and velocity-vector plots around the second slot at various instants: $V_a = 1.5$, $f = 2.5$, and $\alpha = 0$ deg.

near the slot exit. During the suction phase (instants B, C, and D), the fluid particles in the near-wall region of the boundary layer upstream of the slot exit flow into the slot. The fluid particles in the region farther from the wall, which are momentum rich, pass over the slot exit and move down to the near-wall region of the boundary layer downstream of the slot exit. As a result, the boundary-layer velocity profiles downstream of the slot exit become fuller and more separation resistant. During the blowing phase (instants F, G, and H), the major effect of the blowing is to make the boundary-layer velocity profile downstream of the slot exit fuller. When the velocity-vector plots at instants F, G, and H (blowing phase) are compared with that at instants B, C, and D (suction phase), it is clearly seen that the boundary-layer velocity profiles during the suction phase are fuller than that during the blowing phase. The reason for this is that the suction not only removes the near-wall retarded fluid particles but also brings fluid particles that are momentum rich to the near-wall region.

The effect of varying V_a while keeping f the same as that of case 1 was studied. When V_a is decreased to 1, the separation is delayed, but it is not suppressed. As a result, $\bar{C}_L$ is only 0.72. When V_a is increased to 2, separation is completely suppressed, and $\bar{C}_L$ is as large as 2.2. From these results, it is seen that for the present airfoil at this f, at least a value of 1.5 is needed for V_a to suppress the flow separation.

The effect of varying f while keeping V_a as in case 1 was also studied. When f is increased to 10, similar to case 1, the global flowfield almost does not vary with time, and the separation is suppressed to almost the same extent as in case 1. The amplitudes of C_L and C_D, and also $\bar{C}_L$ and $\bar{C}_D$, are very close to that of case 1. When f is decreased to 1, the global flowfield becomes slightly unsteady. When f is further decreased to 0.25, the global flowfield is noticeably unsteady, varying with time periodically with the same period as that of the V. In part of the cycle, the flow is separated, and in another part of the cycle, the flow is well controlled. The amplitudes of the C_L and C_D variations are much larger than that of case 1 (C_L varies between 0.73 and 1.63). The described flow behavior is because, for the same mass flux, suction is more effective than blowing in controlling boundary-layer separation. When suction and blowing are applied alternatively at very low frequency and the blowing is not strong enough for suppressing the separation, alternating attached and separated flows would occur.

Conclusions

1) By the use of ATBS, in both the blowing and suction phases, the boundary-layer velocity profiles downstream of the slot are made fuller and more separation resistant.

2) For the airfoil considered in the Note, when the frequency and amplitude of the blowing/suction are above 1 and 1.5, respectively, the flow separation is suppressed. The global flowfield does not vary with time. The flow in the neighborhood of the slots varies with time, and as a result, the aerodynamic forces oscillate with small amplitudes.

3) The suction is more effective than the blowing in controlling the boundary-layer separation, and as a result, when the frequency of the blowing/suction is low, the global flowfield would vary with time periodically with the same period as that of the blowing/suction and the aerodynamic forces would oscillate with large amplitudes.

References

[1]Gad-el-Hak, M., and Bushnell, D. M., "Separation Control: Review," *Journal of Fluid Engineerings*, Vol. 113, No. 3, 1991, pp. 5–29.

[2]Wang, C. Y., and Sun, M., "Separation Control on a Thick Airfoil with Multiple Slots Blowing at Small Speeds," *Acta Mechanica*, Vol. 143, No. 3–4, 2000, pp. 215–227.

[3]Beam, R. M., and Warming, R. F., "An Implicit Factored Scheme for the Compressible Navier–Stokes Equations," *AIAA Journal*, Vol. 16, No. 4, 1978, pp. 393–402.

[4]Baldwin, B., and Lomax, H., "Thin-Layer Approximation and Algebraic Model for Separated Turbulent Flows," AIAA Paper 78-0257, Jan. 1978.

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Effect of Wall Shear Stress on Structural Vibration

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Nomenclature

D	=	beam stiffness given by $D = E_p h^3/12(1-\nu^2)$
E_p	=	modulus of elasticity
h	=	beam thickness
L	=	beam length
M_∞	=	freestream Mach number
P	=	total mean pressure
P^a	=	acoustic pressure
P^{bl}	=	turbulent boundary-layer pressure
Re_L	=	freestream Reynolds number
t	=	time
U	=	nondimensional mean velocity
x	=	downstream coordinate direction
z	=	vertical coordinate direction
Γ	=	structural damping
ΔP	=	pressure difference across the beam
ε	=	amplitude of the inflow excitation
η	=	out-of-plane beam displacement
μ	=	molecular viscosity of the fluid
ν	=	Poisson's ratio of the beam material
ξ	=	in-plane beam displacement
ρ_p	=	beam density
τ_w	=	fluid wall shear stress
ω_0	=	frequency of the inflow excitation

Introduction

FLUID wall shear stress has not been included in most structural vibration models.[1–7] In this Note, a fully coupled model that accounts for all fluid–structure interactions is presented. The system of equations describing the motion of a beam is derived from the fundamental principles and shows explicitly the fluid wall shear stress. In addition, a simple beam equation that takes into account the wall shear stress is derived using an integrated value of the tension over the beam.

Full coupling of structural vibration to the surrounding fluid has been shown to be critical in several earlier studies. Frendi and Robinson[8] showed that for large-amplitude harmonic or random excitations, a fully coupled model was able to explain some of the results obtained in an earlier experimental study.[9] An attempt at explaining the same experimental results using a decoupled structural vibration model failed. In another experimental and numerical study, Maestrello et al.[10] showed that, when a flat panel was excited by plane acoustic waves having a frequency that corresponds to one of the panel's natural frequencies, its response became nonlinear as the amplitude of the excitation was increased. Similar results were later obtained by Frendi et al.[11] using a two-dimensional fully coupled model. The fluid was modeled using the nonlinear Euler equations, whereas the structure was modeled using a nonlinear beam equation. Wall shear stress was not needed in the model because the experiment was carried out in a transmission loss facility (no flow).

In more recent studies, Frendi[12,13] used the fully coupled model to study the noise transmission from a supersonic turbulent boundary layer to an interior cavity through a flexible structure. The model did not include the effects of the fluid wall shear stress on the structural

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