SEPARATED VORTICAL FLOW CONTROL BY IDEALIZED PARTIAL-SLIP BOUNDARY

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Summary A pilot numerical test for controlling airfoil separated flow by a local segment of idealized partial slip boundary near the leading edge shows that a reduction of lifting-producing favorable vorticity by partial slip can keep the flow perfectly attached even at the stall angle of attack of uncontrolled flow.

For large-Re viscous flow over a wing, the highly vortical boundary layer is an inevitable existence and a sword of double edges. While it provides entire desired wing lift, its side effects include friction drag, induced drag, early separation and stall at large angles of attack α, and transition to turbulence. Minimizing these side effects are the central task of the entire field of flow control. Owing to the rapid progresses of smart deformable and/or superhydrophobic (used in water only) materials, a new flow control strategy is emerging: to modify the wing boundary from no-slip to effectively partial slip (EPS for short) at some key local regions. This could radically alter the global flow property and prevent separation and stall. Although not yet realizable by current technique, pilot studies with idealized wall materials should be done in advance to guide future development of innovative materials. For example, analytical and numerical studies on several typical configurations have confirmed that a flexible wall making proper normal oscillations may generate a "fluid roller bearing" sheath to cover the body, so that the external global flow becomes shear free and even keep attached behind a buff body[1-5]. Similar spanwise tangential traveling waves by flexible wall was also found able to significantly reduce the turbulent friction drag.[6]

For a viscous incompressible flow over a curved EPS wall, the kinematic boundary condition reads[7]

$$\boldsymbol{n}\cdot\boldsymbol{u} = 0, \quad \boldsymbol{n}\times\boldsymbol{u} = 2\lambda\boldsymbol{n}\times(\mathbf{S}\cdot\boldsymbol{n}), \tag{1}$$

where $\mathbf{S}$ is the strain rate tensor and λ the slip length. For neatness we assume the flow is two-dimensional on an (x, y) plane. Let s be the coordinate along the wall, $\kappa(s)$ be the wall curvature, $(\boldsymbol{t}, \boldsymbol{n})$ be the unit tangential and normal vectors with $\boldsymbol{t}\times\boldsymbol{n} = \boldsymbol{e}_z$, and $u(s)$ be the slip velocity which we assume is . Then (1) is reduced to

$$u = \lambda\left(\frac{\partial u}{\partial n} - \kappa u\right) = -\lambda\omega \quad \text{on wall or} = \frac{\lambda}{1+\lambda\kappa}\frac{\partial u}{\partial n}, \tag{2}$$

which depends on not only λ and shear rate but also the wall curvature. However, while (2) is directly useful for reducing friction drag by slip, it alone is insufficient for flow-separation control which is our concern. The latter requires more dynamics based on the Navier-Stokes equation. Assume the flow has large Re with negligible $O(Re^{-1/2})$ effect, and $u(s)$ is time-independent. Then the tangential component of the NS equation applied to the wall yields the boundary vorticity flux (BVF) given by

$$\sigma = -\nu\frac{\partial \omega}{\partial n} = \frac{\partial}{\partial s}\left(\frac{1}{2}u^2\right) + \frac{1}{\rho}\frac{\partial p}{\partial s}. \tag{3}$$

Thus, the dynamic evolution of a boundary layer on an EPS wall should be managed by not the slip velocity u itself but its variation along the wall. An extremely idealized but trivial case would be a perfectly slippery wing surface with $\sigma \equiv 0$ and the flow is fully potential. But our interest is to minimize the EPS segment with finite λ.

As a first step toward this goal, a numerical experiment was conducted for flow over a NACA 0012 airfoil at $Re = 10^5$ by embedding a segment of idealized EPS wall on the upper surface that can have arbitrary $u(s) \geq 0$. Here s is the normalized wall coordinate around the airfoil in clockwise way, increasing from $s = 0$ at the "lower" trailing edge, passing the leading edge at $s = 1$, and reaching $s = 2$ at the "upper" traling edge. We used a vorticity-based fractional-step numerical scheme with no turbulence model, in which the BVF defines the Neumann condition for solving the viscous vorticity transport equation [2], which is just based on (3). Because for $1 \leq s \leq 2$ the boundary-layer separation is caused by adverse pressure gradient ($\partial p/\partial s > 0$) which on a no-slip wall generates $\omega > 0$, intuitively one should try to cut off the positive BVF by imposing a negative $\partial u/\partial s$ to cancel the pressure gradient. The EPS segment was correspondingly located right after the favorable pressure-gradient zone. But, the test showed that even at $\alpha = 6°$ (the maximum α for NACA-0012 below which the potential-flow theory is sufficiently accurate) such a "positive BVF cutting" made the flow even worse: it massively separated and strongly fluctuated (data not shown).

This being the case, we turned to an opposite strategy: a "negative BVF cutting" at a segment right downstream of the front stagnation point. The cutting was activated once $\sigma < -20$ (for uncontrolled flow the negative BVF peak reached -83 at $s = 0$). This strategy was found very successful. Not only at $\alpha = 6°$ the controlled flow was more strongly

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Case		$\overline{C}_l$	C_{lv}	$\overline{C}_d$	C_{dv}	$\overline{C}_m$	C_{mv}	L/D
$\alpha = 6°$	Uncontrolled	0.61	0.21	0.02	0.021	-0.005	0.12	30.5
	Controlled	0.61	0.11	0.005	0.012	-0.005	0.075	122
	Increased (%)	0	-47.6	-75	-42.9	0	-37.5	300
$\alpha = 12°$	Uncontrolled	0.9	0.6	0.12	0.1	0.01	0.24	7.5
	Controlled	1.25	0.2	0.005	0.04	-0.02	0.12	250
	Increased (%)	38.9	-66.7	-95.8	-60	-300	-50	3233

Table 1: Aerodynamic performances of controlled ($\sigma_{\text{limit}} = -20$) and uncontrolled flow at $\alpha = 6°$ and $12°$. Here subscripts l, d, m, and v stand for lift, drag, moment coefficients, and the maximal fluctuation amplitude, respectively. An overline denotes time average.

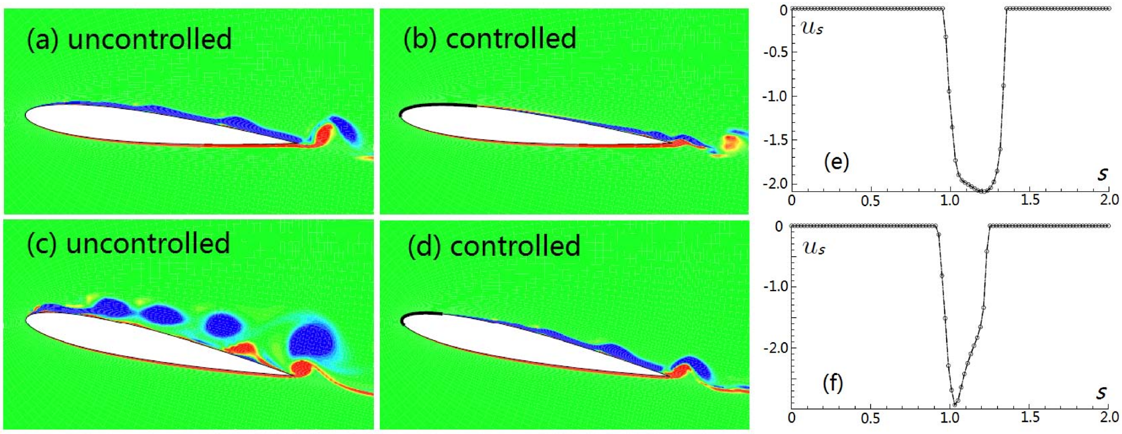

Figure 1: Uncontrolled (left) and controlled (middle) vorticity fields and slip velocity distributions (right) at $Re = 10^5$ and $t = 7.0$, $\alpha = 6°$ (upper) and $12°$ (lower). The thick line on the upper front airfoil marks EPS segment.

attached (Figs. 1a, 1b) but also at the stall angle $\alpha = 12°$ the flow pattern became even slightly better than uncontrolled flow at $\alpha = 6°$ (Figs. 1c, 1d). The airfoil performance benefit of the control is listed in Tables 1. A detailed physical explanation for the success of negative BVF cutting will be presented elsewhere.

The slip velocity distributions of EPS segment calculated under this control rule are shown in Figs. 1(e) and 1(f), which is time-independent since the flow there is locally steady. Note that such distributions can hardly be figured out by using (1) alone. Unfortunately, the very strong external flow acceleration around the leading edge of large κ requires a very large local peak partial-slip velocity (Figs. 1e, 1f), although the peak region is quite narrow. This is certainly far beyond today's technology. More comprehensive studies are necessary to optimize all relevant parameters.

We conclude this short paper by two remarks.

1. There seems to be an upper bound for the total vorticity that can be carried along by a moving body, beyond which (e.g., as α increases) the body-generated vorticity would be over-saturated and part of it has to be shed off by separation and left into the wake. A theory to fully explain the underlying physics and quantitize the saturated carrying-along vorticity for a given configuration would be highly desired.

2. The use of various EPS boundaries, with fluid roller bearing and superhydrophobic wall being just two possible examples, would represent a higher stage of bionics (to mimic moving animals in air and water from rigid to more complex boundary materials). The development along this line might lead to a return of dominant aerodynamic flows from complex vortical ones back to clean potential flow in the future, but in a spiral manner. The latter must grow from modern viscous vortical aerodynamic theory.

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