IV. Summary

A new configuration of vortex generator has been proposed. This vortex generator, referred to as vane-type tab, can freely rotate around the jet axis. The effects of rotation on flow and acoustic fields, as well as thrust penalty, were investigated. A higher jet-spreading rate for the decay of the centerline velocity can be achieved compared with the corresponding stationary vanes. The jet plume cross section maintains an axisymmetric shape for the rotating case, whereas it is often nonaxisymmetric for the stationary case, depending on the number of vanes and their azimuthal locations. The rotation does not increase the noise level, and it does not impose larger thrust penalty either, compared with the stationary case. The vanes can reduce the overall SPL by as much as 10 dB in both cases, whereas the thrust penalty is about 1.5–2% per vane.

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Multiple Sensor Control of Vortex Shedding

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Introduction

MANY wake flows exhibit self-excited flow oscillations that are sustained by the flow itself and are not caused by amplification of external noise. The archetypal example of a self-excited wake flow is the unsteady flow past a circular cylinder. This flow exhibits self-sustained periodic vortex shedding above a critical Reynolds number. Suppression of vortex shedding, by flow control, is desirable to mitigate flow-induced structural vibrations and reduce drag and aerodynamic noise. However, controlling any fluid flowfield is a difficult task—the governing Navier–Stokes equations are nonlinear and have infinite degrees of freedom. The control problem is further complicated by the fact that fluid flows often evolve spatially and incorporate inherent time delays between control actuation and response. In this Note control is taken to mean complete suppression of flow oscillations.

In an actual cylinder wake the flow is three dimensional. However, it is reasonable to assert that control of the idealized two-dimensional wake must be demonstrated before associated three-dimensional instabilities are addressed. (Vortex shedding at start up is always two dimensional.[1,2]) This Note only considers feedback stabilization of the idealized two-dimensional cylinder wake and is only applicable to the very low-Reynolds-number range (<190) where the wake is two-dimensional, and also for cylinders of short span. Roussopoulos and Monkewitz[3] showed that two-dimensional models of vortex shedding with single sensor feedback are only appropriate for short spans ($<30D$) such that the span between the feedback sensor and either end is less than a critical length; otherwise, shedding is reestablished at other spanwise locations as a result of end effects.

The appropriate control strategy for any fluid flow depends on the nature of the fluid flow instability. In the low-Reynolds-number flow past a two-dimensional circular cylinder, the mean flow velocity profiles in the near wake are absolutely unstable, and this entire region acts as a "wavemaker" for the vortex street.[4] Absolutely unstable flows are intrinsically unstable and demonstrate self-excited oscillations even when all sources of noise are removed. These absolutely unstable flows present difficulties for flow control as they are relatively insensitive to external forcing and often interact with the control in a nonlinear fashion.[1]

Because the flow is inherently unstable, the enhancement of vortex shedding using a single sensor-actuator feedback loop is relatively straightforward. However, the suppression of vortex shedding by active control is much more difficult. As the Reynolds number is increased, the region of absolute instability in the near wake grows, and more and more global modes can become unstable. Although the von Kármán mode is the first global mode to become unstable, a wake flow can possess multiple global modes. Control of the flow requires attenuation of all of these global modes.[2]

Complete suppression of vortex shedding is feasible using a single sensor at slightly supercritical Reynolds numbers ($Re < 60$ from tunnel experiments of Ref. 5 or $Re < 80$ in a numerical experiment of Ref. 6). Farther beyond the critical value, however, the forcing amplitude necessary to control the most unstable mode merely destabilizes the next most unstable mode.[2,5] Oscillations can be suppressed at the sensor location but are, in general, exacerbated elsewhere.[5] Single-sensor linear feedback control is not an appropriate control strategy for the two-dimensional circular cylinder wake.

Wake Model

A numerical model of the circular cylinder wake with control feedback was required to investigate various alternative control strategies. An appropriate flow model is the one-dimensional, complex Ginzburg–Landau (G–L) equation,[2,7] which contains all of the stability features of the two-dimensional cylinder wake pertinent to control.[2,7] This wake model has been used frequently in the literature for wake control studies and has been shown to allow semiqualitative predictions of the wake with feedback.[2] Significantly, the G–L model demonstrates the ineffectiveness of single-sensor feedback in controlling the wake past a critical Reynolds number[7]: like the cylinder wake it has many unstable global modes. The G–L model is, however, relatively straightforward to integrate numerically and allows rapid prototyping of control strategies.

The wake model chosen for the study was of the following form[7]:

$$\frac{\partial A}{\partial t} + U\frac{\partial A}{\partial x} = \mu(x)A + (1 + jc_d)\frac{\partial^2 A}{\partial x^2} - (1 + jc_n)|A|^2 A$$

where $A(x, t)$ is the complex amplitude and U, c_d, c_n, and $\mu(x)$ are real. With fixed advection speed U and fixed parameter c_d the stability of the G–L wake is defined by the growth rate parameter $\mu(x) = \mu_0 + \mu' x$, where μ_0 is similar to a Reynolds number based on the cylinder diameter.[7] For $\mu' < 0$ the stability features of this prototype wake are similar to the stability features of a two-dimensional cylinder wake. Like a low-Reynolds-number cylinder wake, the G–L wake is absolutely unstable near the origin [where $\mu(x) > U^2/4(1 + c_d^2)$], convectively unstable further downstream [where $0 < \mu(x) < U^2/4(1 + c_d^2)$], and ultimately stable far downstream. Like the cylinder wake, the G–L model becomes globally unstable and oscillates with a coherent frequency when the region of absolute instability reaches a critical size.

The G–L model was solved numerically on a domain with $0 < x < 120$ using 1000 grid points with boundary conditions $A(0, t) = 0$ (which simulates the cylinder body) and $A(120, t) = 0$. The local growth rate $\mu(x)$ varies linearly in the streamwise direction such that the flow becomes stable far downstream. For all of

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the values of μ_0 considered, the flow is stable at $x = 120$, and all wake oscillations have decayed to zero by this point. The boundary condition at $x = 120$ therefore did not affect the behavior of the solution.

Fixed parameters were $U = 5$, $\mu' = -0.0434$, $c_d = 1$, $c_n = 0$ to allow comparison with earlier wake control studies.[7] The advective part of the model was solved using a weighted average flux method, which resulted in minimum numerical dissipation. This method calculates the intercell flux at each cell interface, at each half time step, by spatially averaging the states generated by solving the Reimann problem.[8] Diffusive and source terms were given timesteps approximately 10% of the advective solution, which was chosen to have a Courant number of 0.9. Explicit integration was used for all terms except the diffusive part, for which an implicit scheme was used. To check the grid dependency of the solution, additional runs were made with 250, 500, 2000, and 4000 grid points; the results of the 1000, 2000, and 4000 grid point solutions were indistinguishable. To validate the present analysis, comparisons were made with existing results of Ref. 7. The present analysis demonstrated the same phenomena as earlier studies, exhibiting self-excited oscillations above $\mu_{\text{crit}} = 3.43$, and matched the theoretically predicted frequency[7]; the model oscillated at a coherent frequency of $\omega = 3.0881$ lying well within the range of the predicted frequency[7] of $\omega \approx U^2/4(1 + c_d^2) + \mathcal{O}(\mu') \approx 3.125 + \mathcal{O}(-0.0434)$]. The mode shape and maximum amplitude also matched those of the earlier study.[7]

Sensing and Actuation of the Wake Model

Previous studies have shown that multiple, distributed feedback sensor control holds more promise for alleviating vortex shedding wake oscillations than single-sensor feedback control.[2,3] Experimentation with sensor locations, together with experimental evidence,[5] showed that successful control could only be achieved (even at low Reynolds numbers or values of μ_0) when the feedback sensors were placed within the absolutely unstable region of the near wake.

For initial single-sensor feedback studies a localized actuation of $g\delta(x - x_f)A(x_s, t)$ was added to the right-hand side of the G–L equation. The coordinate x_f is the actuator location, taken to be $x_f = 0$, which models, crudely, actuation of the body in a fashion similar to that of Park et al.[7] and Roussopoulos and Monkewitz.[3] The feedback gain g is complex. This gain is multiplied by the wake signal at the sensor location x_s. δ is the spatial delta function. Although it is difficult to relate this perturbation of the G–L wake directly to a physical control actuation of a cylinder wake, this simple actuation has been shown[6,7] to produce behaviors of the G–L wake similar to the cylinder wake in response to asymmetric suction and blowing at the separation points and also transverse cylinder oscillations or acoustic forcing.[3] Schumm et al.[1] have shown that injection of circulation into the cylinder wake is a common mechanism for control of the wake and that the wake response is similar for each of these different actuation methods. Experimental actuators generate a complex disturbance of the cylinder near wake; however, the much simpler delta function perturbation of the G–L wake produces a response qualitatively similar to the forced cylinder flow.[3] Schumm et al.[1] also pointed out that promotion of subcritical oscillations was a desired ability of any proposed flow control actuator: it was verified that the proposed actuation of the G–L wake succeeded in promoting subcritical oscillations.

For dual-sensor control studies the form of the gain and feedback signal was slightly modified, and this is described later.

Single-Sensor Proportional Feedback

Control of the wake by using a single sensor and proportional feedback gain was investigated and the results compared to similar studies of the G–L wake[2] and of the low-Reynolds-number circular cylinder wake.

The gains were selected by trial and error (as in Ref. 3): there was no a priori method for selecting proportional gains for the nonlinear G–L wake. (Roussopoulos and Monkewitz[3] found that gains determined from linear stability were significantly different from those required by the nonlinear G–L model.) Small controller gains were required, as larger gains merely destabilized the flow, sometimes by destabilizing other global modes of the wake. For actual fluid flow control applications small gains are also required to avoid driving the flow into a higher dimensional state (turbulence for example).

Single-sensor, linear feedback control is only able to suppress the wake oscillations just above criticality; for the model in this study, single-sensor feedback fails at $\mu_1 \leq 3.62$ or $\approx$5% above μ_{crit}. Further away from criticality, the single-sensor feedback may suppress one global mode, but it destabilizes another: this compares qualitatively with experimental results of Ref. 5 and numerical, Navier–Stokes, results of Ref. 6.

Dual-Sensor Control Strategy

It was conjectured that the original single-sensor control could be augmented by superimposing a small feedback signal from another sensor downstream of the first. The control actuation was $g_1 A(x_{s1}, t) + g_2 A(x_{s2}, t)]\delta(x - x_f)$. The arrangement was applied to a control run at $\mu_0 = \mu_1$ or 5% above criticality (just past the level where single-sensor control fails) and a control run at $\mu_0 = 3.85$ or 12.5% above criticality (far past the level where single-sensor control would fail). For both of these control runs, the upstream sensor was $x_{s1} = 4.80$, and the downstream sensor was $x_{s2} = 9.36$. (These positions were chosen by trial and error; some combinations of positions offered no improvement over single-sensor control.)

The wake oscillation magnitude at the absolute–convective stability boundary for the control run at μ_1 is shown in Fig. 1. The best upstream sensor control gain was $g_1 = 0.05$, and the downstream sensor gain was $g_2 = -0.00005j$. These gains were again chosen by trial and error. The dual-sensor control rapidly achieves complete stabilization of the wake (the wake oscillations decay almost exponentially to a value $< 10^{-4}$ before $t = 65$), whereas the wake oscillations for control using only the single upstream sensor maintain a constant amplitude of 1.052 after $t = 175$.

Sample results much farther from criticality are shown in Fig. 2, showing the real part of the wake oscillations at two locations in the wake: an upstream sensor at $x = 9.6$ and a downstream sensor at $x = 16.8$. (The downstream sensor is located at the absolute–convective stability boundary.) Both signals are seen to decay during the control, but there is a significant delay between decay of oscillations upstream and downstream. The control actuation was provided by gain $g_1 = 0.05$ and gain $g_2 = -0.00006 - 0.0005j$.

Complete control of the supercritical wake above μ_1 was achieved with this modified control strategy. This represents a significant improvement over previous wake control strategies, which fail at μ_1. Spatially distributed sensing increases the controllable range for the wake, perhaps by increasing the observability of higher global modes.

The downstream sensor control gains, which achieve this stabilization, are explored in Fig. 3. With a fixed upstream sensor gain

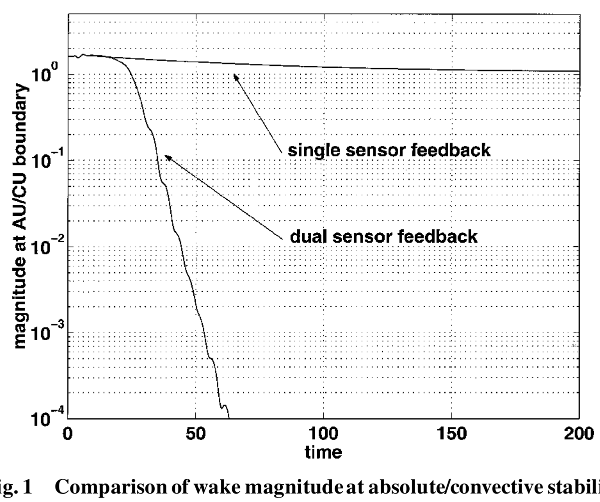

Fig. 1 Comparison of wake magnitude at absolute/convective stability boundary for single-sensor and dual-sensor control at 5% above critical.

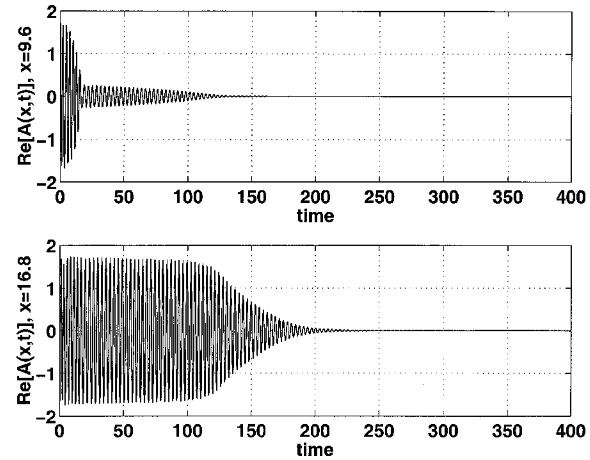

Fig. 2 Two-sensor feedback control at 12.5% above critical.

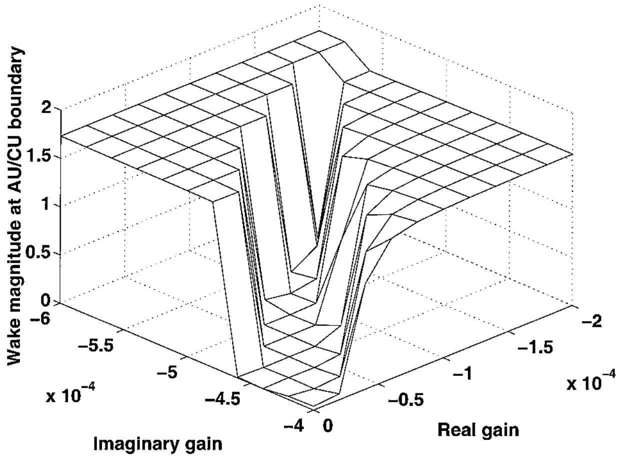

Fig. 3 Asymptotic wake magnitude for varying second sensor gain (12.5% above critical).

of 0.05, the figure shows which combinations of gain g_2 result in wake stabilization (corresponding to the zero asymptotic oscillation amplitude). This "window" of gains is quite small and shrinks with increasing μ_0. On either side of the gain window, there are plateaus: the left corresponding to oscillations in the original mode; the right to oscillations in another mode, destabilized by the control.

The dual-sensor control was found to be successful up to $\mu_2 = 3.876$ or 13% above criticality (compared to single sensor control, which fails at 5% above critical) even for a range of different sensor locations. It was conjectured that an increased number of distributed sensors might be able to extend this controllable range.

The feedback sensors employed in this study were at different streamwise locations, as this study is a preliminary investigation into stabilization of the two-dimensional cylinder wake. It is likely, however, that in a real wake, end effects will induce three-dimensional instabilities such that sensors placed at one spanwise location will fail to suppress vortex shedding at all spanwise locations.[3] For an actual wake sensors may need to be distributed in both spanwise and streamwise locations in the near wake.

Conclusions

Distributed sensing of the near wake of the globally unstable Ginzburg–Landau equation increases the controllable range of the wake. This was demonstrated by control of the wake further from criticality (13%) than possible before. This is a significant improvement in wake control, over single-sensor feedback schemes. It may be inferred that multiple, spatially distributed control schemes will increase the Reynolds number at which feedback control can stabilize the vortex shedding oscillations of the low-Reynolds-number cylinder wake.

There are large delays in the responses measured by the distributed sensors in the wake. Predictive controllers, rather than proportional feedback, may be a more appropriate strategy for future wake control strategies.

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Rapidly Growing Instability Mode in Trailing Multiple-Vortex Wakes

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I. Introduction

FOLLOWING Crow's[1] analytical study of the long-wave instability for a counter-rotating vortex pair, numerous wake-alleviation concepts have been tested in an effort to hasten this instability mechanism.[2–5] The hypothesis was that if this instability could be externally forced to grow, the linking of oppositely signed tip vortices would form Crow rings, hence, changing the two-dimensional nature of the wake into a three-dimensional one. The resulting incoherent wake would have an accelerated destruction, causing it to pose less of a threat to following aircraft. However, one drawback of the Crow instability is its slow growth rate. Typically, it requires a few hundred wingspans to develop, making it a less attractive candidate for rapid wake attenuation. The primary reason for this slow growth rate is that the equal-strength, oppositely signed vortices are too widely spaced for this cooperative instability to occur rapidly. To circumvent this impediment and increase the growth rate, it is necessary to redesign the trailing vortex wake.

One means of accomplishing this is to construct a vortex wake that contains multiple vortex pairs, each of which has vortices that are located close to one another. This allows the vortices to develop cooperative instabilities and interact strongly in a timescale much shorter than that for a single, widely spaced pair.[6] Recent towing tank experiments[7,8] have demonstrated this in the merger process of like-signed vortex pairs. By the mere reduction of the spacing between the flap and tip vortices from one-third of a span to one-sixth of a span, the vortices could interact more strongly

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