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Feedback control of vortex shedding at low Reynolds numbers

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This paper describes experiments undertaken to study in detail the control of vortex shedding from circular cylinders at low Reynolds numbers by using feedback to stabilize the wake instability. Experiments have been performed both in a wind tunnel and in an open water channel with flow visualization. It has been found that feedback control is able to delay the onset of the wake instability, rendering the wake stable at Reynolds numbers about 20% higher than otherwise. At higher flow rates, however, it was not possible to use single-channel feedback to stabilize the wake – although, deceptively, it was possible to reduce the unsteadiness recorded by a near-wake sensor. When control is applied to a long span only the region near the control sensor is controlled. The results presented in this paper generally support the analytical results of other researchers.

1. Introduction

The phenomenon of vortex shedding from bluff bodies is of interest because of its practical importance and because, although it is regular and apparently simple in behaviour, it still defies complete analytic understanding. The Kármán vortex street in the wake of a circular cylinder has been widely studied during this century, and many of these studies have considered methods of altering the wake structure. This problem is of practical as well as academic importance because, particularly at higher Reynolds numbers, the shedding of vortices from alternate sides of bluff bodies is associated with strong periodic transverse forces that can damage structures. It was shown early that relatively small changes to the geometry such as adding a splitter plate in the near wake or surrounding the cylinder with a shroud reduce the transverse forcing significantly (e.g. Price 1956). More recently, other methods of preventing or affecting vortex shedding have been demonstrated: steady or periodic suction or bleeding from the recirculation zone can prevent the vortex street from forming, as in various Reynolds number ranges can heating the cylinder, locating a small secondary cylinder in the near wake, imparting a large-amplitude transverse oscillation to the cylinder at an appropriate frequency or imparting a constant or periodically varying angular rotation to the cylinder (Wood 1964; Bearman 1966; Berger 1967; Strykowski & Sreenivasan 1989; Williams & Amato 1989; Tokumaru & Dimotakis 1990; Lecordier, Hamma & Paranthoen 1991; and the review in Huerre & Monkewitz 1990). All of these are open-loop control methods, control being achieved without the use of a sensor.

The understanding of vortex shedding from bluff bodies has advanced greatly in recent years. Provansal, Mathis & Boyer (1987) and others showed experimentally

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that vortex shedding was the result of an initially linear wake instability. The current interest in considering the absolute and convective nature of instabilities in wakes followed from concepts developed in the field of plasma physics, and has been applied to free shear flows by Huerre & Monkewitz (1985) and others; for a recent review with 175 references see Huerre & Monkewitz (1990). It is now widely accepted that the observed Kármán vortex street is the nonlinear limit cycle of a self-excited global instability – the behaviour has been related to the existence of a finite region of absolute instability in the near wake. Schumm (1991) has presented experimental support for this by showing that transient behaviour follows very closely that predicted by the Landau equation.

Recent years have seen the active control of various unstable fluid mechanical and other systems. The approach is generally to introduce feedback into the system with one or more sensors and actuators so that the combined system is stable. Instabilities that have been stabilized using active control include aerofoil flutter (Huang 1987), compressor surge (Ffowcs Williams & Huang 1989), reheat buzz (Langhorne, Dowling & Hooper 1990), the Rijke tube (Dines 1983; Heckl 1985), and flow over cavities (Huang & Weaver 1991).

The earliest experiments using a sensor and electronic feedback to control vortex shedding were probably carried out by Berger (1964, 1967). He used an oval-shaped body (a 'Bimorph transducer') of width 0.69 mm and chord 1.68 mm, located in a low-turbulence air jet with the major axis aligned with the flow. The body moved transverse to the flow in response to an applied voltage. A hot-wire sensor was located in the far wake. Natural vortex shedding occurred at Reynolds numbers above 77, but feedback was able to prevent vortex shedding at Reynolds numbers up to 80. Wehrmann (1965) performed the same experiment with very similar equipment and also observed suppression of vortex shedding.

The possibility for feedback control of global oscillations was investigated analytically by Monkewitz (1989), with reference to Berger's earlier experiments. The conclusion was that stable flows could readily be destabilized by feedback, but that self-excited systems might only be able to be stabilized over a small range of Reynolds numbers above the onset of vortex shedding, because at higher Reynolds numbers the feedback necessary to stabilize the most unstable mode would destabilize higher modes. Monkewitz, Berger & Schumm (1991) repeated Berger's original experiment and confirmed that the variation of response at the sensor location with gain in the feedback loop agreed with their theoretical predictions.

Ffowcs Williams & Zhao (1989) considered independently the potential for suppressing vortex shedding using active control. They suggested that if vortex shedding was the limit cycle of an initially linear instability then active control, suppressing instability, should prevent vortex shedding. They performed experiments to test this hypothesis, also using a hot-wire sensor and a single actuator, but their sensor was located in the near wake; their actuator was a loudspeaker in the wind tunnel wall. They observed that at Reynolds numbers between 400 and 10^4 control significantly reduced the vortex shedding frequency component of the hot-wire signal. In addition they presented results indicating that the vortex street was suppressed significantly throughout the wake. Their results were preliminary and they did not claim to understand the control mechanism. Monkewitz *et al.* (1991), who were only able to achieve control at Reynolds numbers 5% above the onset of shedding, drew attention to the difference between their results and those of Ffowcs Williams & Zhao.

Lewit (1988, 1992) obtained interesting results using a different approach at

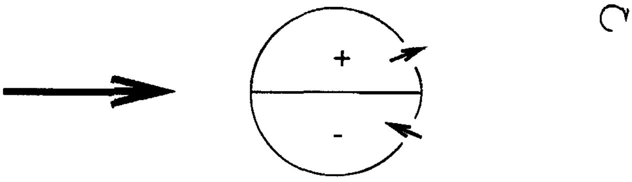

FIGURE 1. Actuation method used by Lewit (1988, 1992) and Williams & Amato (1989).

Reynolds numbers of around 2×10^4. He used a cylinder with a series of holes along the downstream side to either side of the centreline of flow, as shown in figure 1. Flow in an out of the holes on either side of the body was driven in opposite phase as actuation. He used both a hot-wire sensor in the near wake and a microphone in the far field (located at 90° from the cylinder relative to the oncoming flow). By feeding back the signal from the hot wire to the loudspeakers with appropriate gain and phase adjustment he was able to reduce the vortex shedding frequency velocity fluctuations at the hot-wire location to the background noise level (or even below) – the radiated sound detected in the far field was also reduced by around 6 dB. He was also able to use the microphone as the sensor for the feedback; this enabled the sound field to be even further reduced, although the vortex street as detected by the hot wire was less attenuated than before. (Williams & Amato 1989 used similar actuation at a Reynolds number of 370 to reduce the wake momentum deficit and also observed that the vortex street was suppressed; their control was open loop in that they did not use feedback.)

This paper describes experiments performed both in air and water. Our experiments have used a more convenient actuation method to achieve the suppression described by Berger and Monkewitz at transition Reynolds numbers, and the suppression mechanism has been investigated in more detail. In addition we have duplicated the experiments described by Ffowcs Williams & Zhao with their original and other equipment, but we find that they are mistaken in implying a control of vortex shedding. Their technique merely protects the sensor from unsteadiness induced by the persistent vortices.

2. Experimental details

2.1. *Wind tunnel experiments*

Aeronautics laboratory wind tunnel

Most experiments were performed in a 30 × 30 cm working section open-return wind tunnel in the Aeronautics Laboratory of Cambridge University Engineering Department. This wind tunnel has a series of screens and a 9:1 contraction ratio at the inlet to reduce turbulence. Experiments were performed at flow rates in the range 0.5–1.2 m/s. The mean velocity uniformity across the region of the working section used for experiments was better than 0.1%, and r.m.s. turbulence levels were less than 0.1%.

Cylinders used as bluff bodies

Three different circular cylinders were used for the experiments. A stainless steel 'piano' wire sample of diameter 0.775 mm and aspect ratio 130 was used for experiments on long spans at low Reynolds numbers. A cylinder of diameter 1.59 mm with a section of aspect ratio 19 isolated by concentrically mounted spheres of

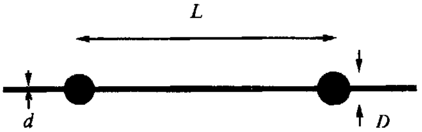

FIGURE 2. Geometry of short span used to investigate shedding in a single cell (originally used by Papangelou 1991, 1992*a*). $L/d = 19$, $D/d = 4$.

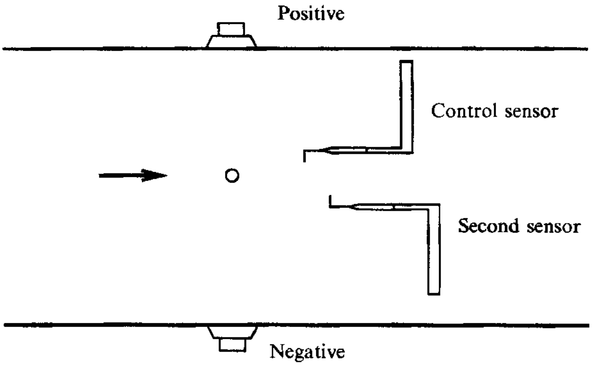

FIGURE 3. Arrangement of cylinder, hot-wire sensors and loudspeakers in wind tunnel (not to scale).

diameter 6.35 mm, illustrated in figure 2, was used to perform experiments on a short span. Papangelou (1991, 1992*a*) investigated the behaviour of this device at low Reynolds numbers. A solid brass cylinder of diameter 6.3 mm and aspect ratio 50 was used for experiments at higher Reynolds numbers. The brass cylinder was bolted directly to the tunnel wall; the other bodies were rigidly mounted to lengths of studding bolted to the tunnel walls. There was no discernible vibration of the samples, and no tendency for vortex shedding to 'stick' at preferred frequencies (which might have betrayed a mechanical resonance); at the low Reynolds numbers and flow velocities of the experiments the fluid mechanical forcing is tiny, and the fan was structurally isolated from the working section by a tunnel section made of flexible PVC.

Sensors and actuation

Velocity measurements were made with two Dantek miniature hot-wire probes and constant-temperature anemometry equipment. The hot wires were of type 55P14, of nominal wire length 1.25 mm, and were mounted as illustrated in figure 3; it was found that this configuration minimized the interference of the probes with each other and with the wake. Each hot wire was generally positioned near the edge of opposite sides of the wake. The wires were aligned with the axis of the test cylinder. One hot wire (the 'control sensor') was used as the actuator for the control loop; the other (the 'second sensor') was used for investigating the wake at other locations. The hot wires were conditioned with Dantek 55M01 constant-temperature anemometer bridges.

Actuation was by means of an identical pair of 10 W, 14 × 5 cm elliptical loudspeakers – one mounted at the top of the tunnel working section and one on the bottom, as illustrated in figure 3, and with the major axes of the ellipses aligned with the test cylinder axis. The speakers were driven in opposite phase (unless otherwise stated), so they moved up and down together. The cylinders were mounted centrally in the tunnel so the velocity flux due to actuation could be assumed by symmetry to

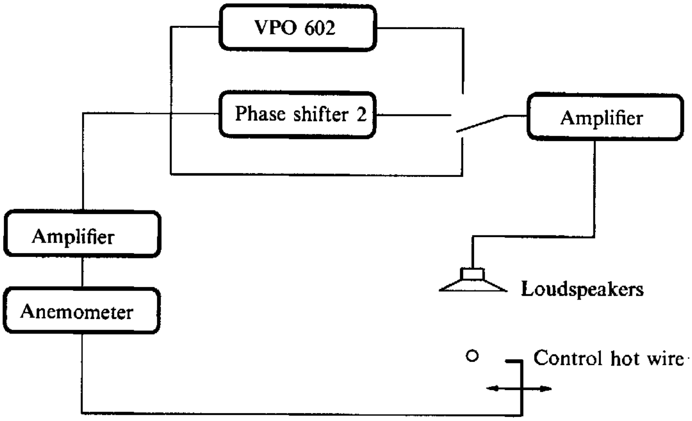

FIGURE 4. Schematic diagram of control loop.

be normal to the tunnel flow. Since the mean flow in the wake region is substantially parallel to the main flow, the hot wire sensors, which measure the vector total velocity, were very insensitive to the normal velocity flux due to the speakers: a hot wire located in the free stream was completely unable to detect any flow variations with the speakers driven at their maximum amplitude.

Flow measurement calibration

The velocity in the tunnel was generally deduced from the vortex shedding frequency of the test cylinder. It is evident from Williamson (1989, figure 12) that at Reynolds numbers (Re) just above the onset of shedding for a long span the Roshko number $Ro = fd^2/\nu$ is naturally almost the same as that observed with induced parallel shedding. In this regime, therefore, William's formula for the Re/Ro relationship,

$$Ro = -3.3265 + 0.1816Re + 0.00016Re^2, \tag{1}$$

was used to estimate the Reynolds number from the measured Roshko number. (The quadratic term is of particular significance at these low Reynolds numbers; using the best linear fit to Williamson's results gave results that differed by several units of Reynolds number.) For the short-span 'single cell' device, the linear Ro/Re relationship determined experimentally by Papangelou (1991, 1992*a*) was used:

$$Ro = -4.032 + 0.194Re. \tag{2}$$

The hot-wire sensors were calibrated against King's Law, using the long-span cylinder at higher Reynolds numbers or Papangelou's single cell. At these higher Reynolds numbers Roshko's (1954) Ro/Re relationship

$$Ro = -4.5 + 0.212Re \tag{3}$$

was used to deduce the flow velocity from the measured shedding frequency of a long span. In this paper values of Reynolds number are quoted to the nearest tenth; the absolute accuracy of the calibration is probably only unity, but the measurements are mutually consistent to about 0.2.

The actuation due to the loudspeakers at the cylinder location was determined by using a hot wire at 45° to the incident flow and to the velocity flux due to the speakers, and driving the speakers with a sinusoidal signal of known voltage. This was done with a range of voltages at all the frequencies of interest; the unsteady signal measured by the calibrated hot wire at the speaker frequency enabled the calculation of the velocity flux due to the speakers.

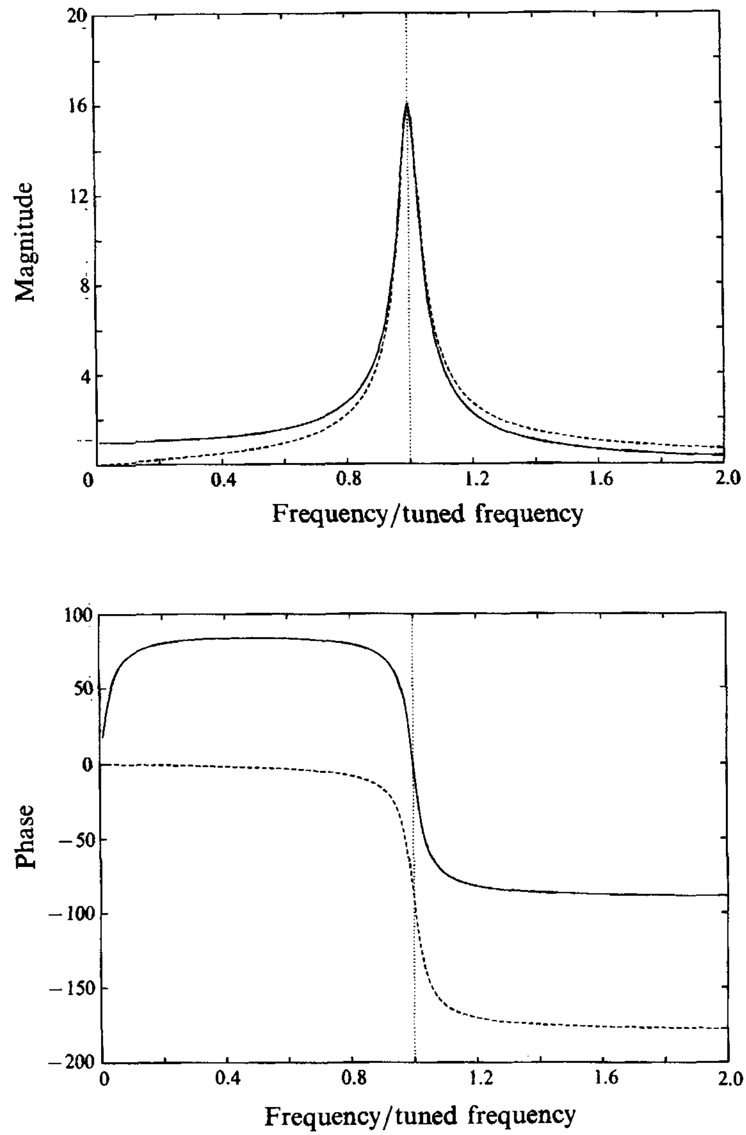

FIGURE 5. Magnitude and phase response of 'Feedback' VPO 602 tuned phase shifter in external excitation mode (——, tuned to 0°; ---, tuned to 90°).

Feedback loop

The control loop is illustrated schematically in figure 4. The signal from the anemometer is a.c. coupled and amplified. This amplified signal is then either phase-shifted with one of two devices, or fed straight to the power amplifier. The first phase-shifting device is a 'Feedback' VPO 602 variable-phase oscillator (used in 'externally excited mode'). This combines a tuned oscillator of Q-factor approximately 16 with a phase-shifting network, and its magnitude and phase response is illustrated for two phase settings in figure 5. The device is most easily characterized by its impulse response, which is of the form

$$g(t) = H(t)\,\mathrm{e}^{-at}\cos(\omega_0 t - \phi), \tag{4}$$

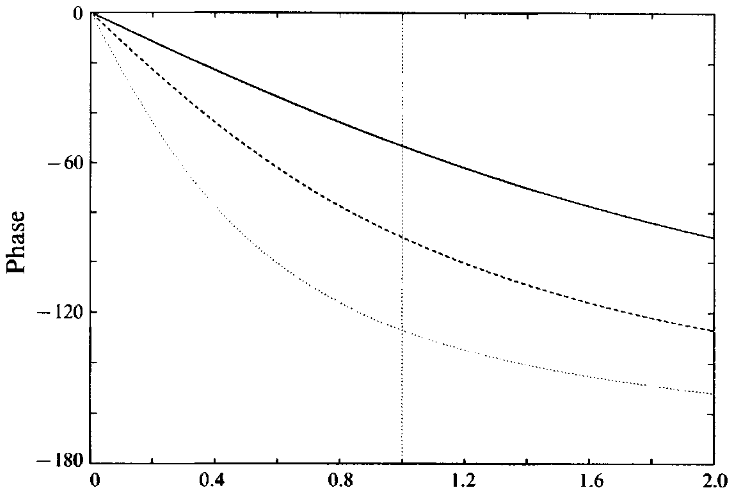

FIGURE 6. Phase response of untuned phase shifter (target frequency set to 45°, 90° and 135°, top to bottom curves, respectively).

with ω_0 the variable tuned frequency, ϕ the variable phase shift, $H(t)$ the unit step function and a a real constant. The phase shift at the tuned frequency can be set to any desired value, but the phase shift changes extremely rapidly with changes of frequency. The second ('untuned') phase shifter was made in-house: its magnitude response is completely flat, and its phase response is shown in figure 6: this is characterized by its complex frequency response

$$G(\omega) = \frac{1-\mathrm{j}k\omega}{1+\mathrm{j}k\omega}, \tag{5}$$

with j the imaginary operator and k variable. It can only vary the phase through 180°; an inverting amplifier was used to access the other 180° of phase shift. The power amplifier (a 'Quad' 303 conventional hi-fi amplifier with logarithmic gain control and an approximately flat frequency response in the operating frequency range) in turn drove the loudspeakers in parallel.

Data acquisition and processing

Data were acquired, analysed and processed using an 'Analogic Data' Data 6000A waveform analyser, and associated D681 disk storage device; further post processing was performed off-line on other computers.

Acoustics laboratory wind tunnel equipment

The experiments described by Ffowcs Williams & Zhao (1989) were also repeated using, as far as possible, the original equipment as described in their paper. The wind tunnel, that of the Acoustics Laboratory at Cambridge University Engineering Department, has a test section of 25 × 35 cm, and was run at an air speed of 1 m/s. A smooth brass cylinder, of diameter 6.3 mm, was rigidly fixed to the tunnel walls. The sensors are old DISA hot-wire probes of type 55F31, orientated with their wires parallel to the cylinder axis. One sensor detects the signal used in the control loop; this sensor was located in the upper shear layer of the cylinder, about 0.7 diameters behind and 0.6 diameters offset from the cylinder axis. The phase shifter in the feedback loop was the VPO 602 described above. A single loudspeaker fitted to the sidewall comprised the actuation.

2.2. *Water channel experiments*

Hydraulics laboratory water channel

Some experiments were performed in the small recirculating water channel of the Hydraulics Laboratory at Cambridge University Engineering Department. The working section is 10×10 cm, and of length 1 m. Flows in the range 10–50 mm/s were used in this study. Smooth brass cylinders of diameter 6.4 and 3.2 mm were orientated vertically in the middle of the working section and supported from above the free surface.

Sensors, actuation and processing

Nickel hot-wire probes and a Dantek hot-film probe type 55R13 were used as velocity sensors. Both gave usable signals at velocities above 5 mm/s, although calibration drift was evident; the hot film gave the best performance. Conventional tungsten hot-wire probes were insufficiently sensitive and prone to abrupt failure. The probes were operated with a Dantek 55M10 constant-temperature anemometer bridge.

The anemometer signals were digitized and processed by a fast microcomputer in place of the analogue variable gain and phase devices used with the wind tunnel. The result was converted to an analogue signal and used to drive a position actuator via a voltage-to-current amplifier. The position actuator was a 'Ling' 201 vibration generator: at frequencies around 1 Hz it functions as an actuator with position proportional to input current.

The computer used an infinite impulse response filter to bandpass and phase-shift the signal: the impulse response was a digital approximation to

$$g(t) = AH(t)\,\mathrm{e}^{-at}\cos(\omega_0 t - \phi), \tag{6}$$

with A the variable gain, ϕ the variable phase shift at the tuned frequency ω_0 and a a variable factor enabling the bandwidth/rise-time of the filter to be adjusted. During experiments ω_0 was set to the natural vortex shedding frequency, typically in the range 0.5–1 Hz. The digital sampling rate was typically 70 Hz, and time discretization effects were negligible. The computer also continuously logged data.

3. Experimental results

3.1. *Control at a single point in a long span*

General

The long-span cylinder was mounted in the centre of the 30×30 cm wind tunnel. The control sensor was located near midspan. It was found that at Reynolds numbers near to the onset of transition (about 48.4 in these experiments) the wake was readily controlled by feedback. It was possible to stabilize the wake completely at one spanwise location without the use of any phase shifter in the feedback loop, with phase adjusted by moving the control sensor along the wake in the flow direction. It was also possible to control the wake from any 'reasonable' sensor location by using the untuned phase shifter in the feedback loop. With the VPO 602 tuned phase shifter, however, it was never possible to stabilize the wake.

When the wake was stabilized, the signal from the control sensor typically fell to almost the background noise level – up to 40 dB below the natural signal. Figure 7

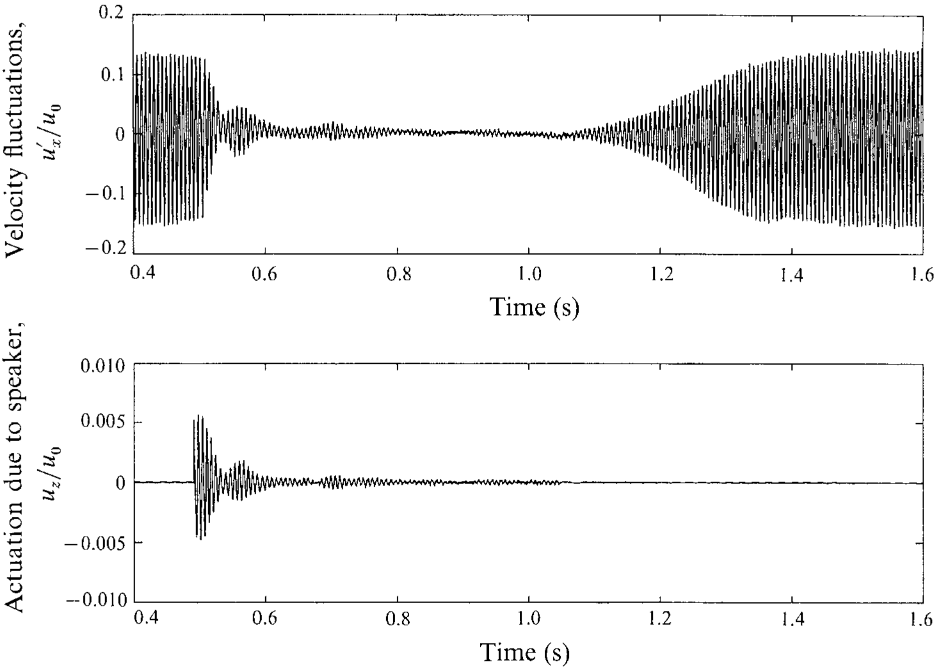

FIGURE 7. Illustration of vortex shedding suppression at one point in a long span at a Reynolds number of 48.9.

shows a typical record of the sensor signal and the actuation due to the loudspeaker when the controller is turned on and off again. In this figure and all other similar figures the only filtering of the hot-wire trace is a high-pass 'a.c. coupling' and a low-pass anti-aliasing filter in the data acquisition system; frequencies between 3 Hz and 30 kHz are passed with no attenuation or phase shift. The actuation due to the speaker is deduced from the speaker voltage. When the system is stabilized the actuation required to maintain stability is very small, being just that required to overcome the destabilizing effects of incident noise in the flow. This is a characteristic of the feedback stabilization of unstable systems.

It was found that one speaker alone was able to suppress the mode just as effectively as the two acting in anti-phase if the gain was doubled. If the speakers were coupled to act in-phase suppression could not be achieved, although the wake was slightly affected by very large signals.

Figure 8 shows the control attained at various Reynolds numbers above the onset of shedding. This figure shows two measurements; one is the attenuation of the signal measured by the sensor used for the feedback loop, and the other is the attenuation of the signal measured by a second sensor located behind the first sensor and on the other side of the wake (as illustrated in figure 3). The sensor offsets from the wake centreline were adjusted so that their output was essentially sinusoidal and of maximum amplitude when the controller was off. No phase shifter was used. The attenuation shown is the reduction in the standard deviation of the sensor signal, with no filtering to remove noise (noise levels being about 30 dB below typical uncontrolled signal levels); the r.m.s. was determined from data measurements over more than 500 shedding periods, and was statistically invariant (the scatter in the graphs arises from the feedback loop not always being optimally adjusted). It is seen that greater control is observed at the control sensor location than at the second

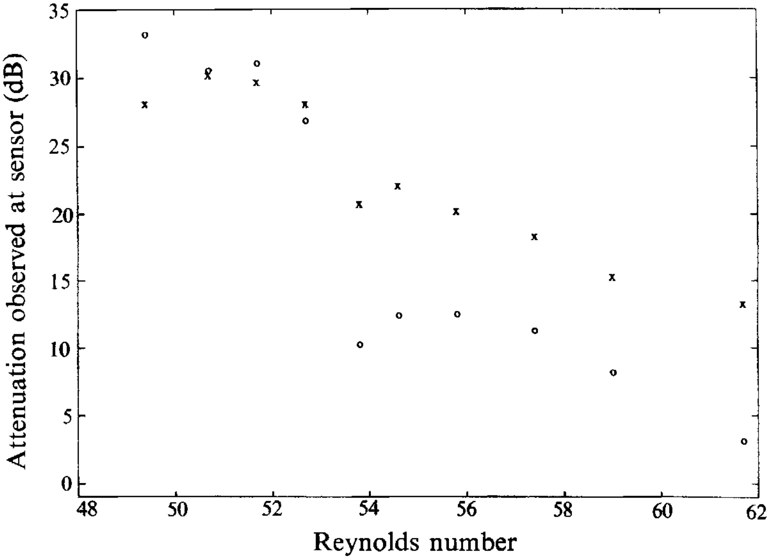

FIGURE 8. Control attainable at a range of Reynolds numbers, as measured at the control sensor (×) and at a co-located second sensor (○).

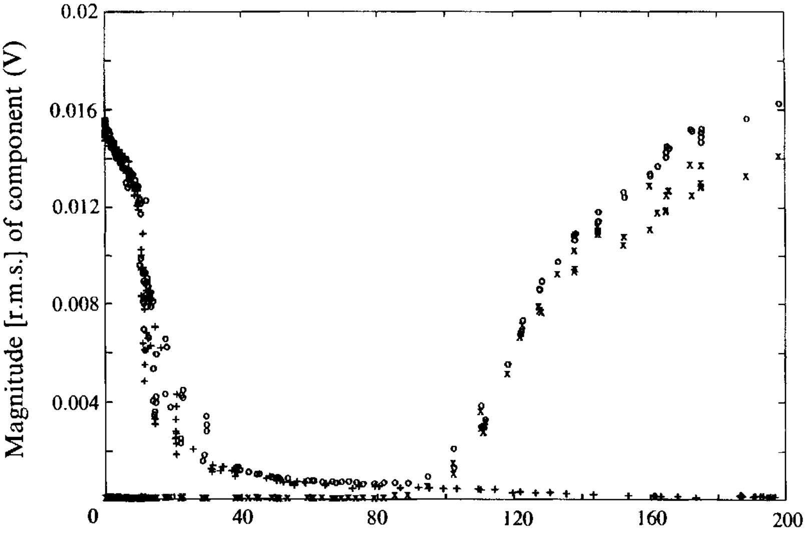

FIGURE 9. Response at control sensor as gain is increased at a Reynolds number of 52.8 (○, r.m.s. of whole signal; +, component in frequency range 156–171 Hz; ×, component in frequency range 136–150 Hz).

sensor location; the latter is obviously a better indication of the suppression of the shedding mode. At Reynolds numbers up to about 53 the shedding is completely suppressed, down to noise levels; between 53 and 58, the shedding is substantially suppressed, but the residual signal (presumably due to excitation by incident noise) becomes more significant. Complete control was not attainable at higher Reynolds numbers, although the wake was affected by feedback in an intermittent manner and the mean unsteadiness at the control sensor location could be reduced.

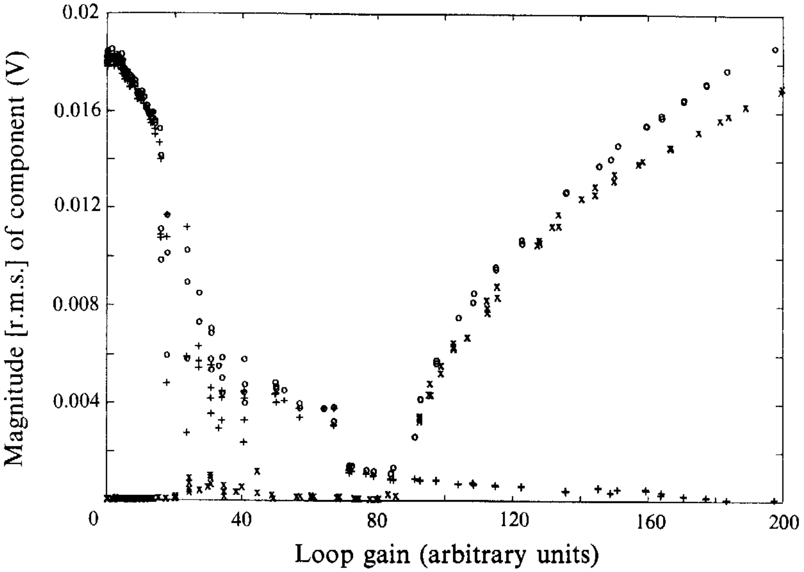

FIGURE 10. As figure 9 but at a Reynolds number of 54.8 (○, r.m.s. of whole signal; +, component in frequency range 170–185 Hz; ×, component in frequency range 147–163 Hz).

Variation of control with feedback gain

Monkewitz (1989) has suggested from theoretical arguments that wake stabilization might only be possible near the onset of shedding in a gain window between the suppression of the first mode and the destabilization of a higher mode; Monkewitz *et al.* (1991) presented experimental results illustrating this gain window at one Reynolds number. We observed the same phenomenon; shedding was stabilized with a particular range of gains, but when the gain is increased the wake becomes unstable again, with the instability at a different and slightly lower frequency. This is illustrated in figure 9, measured at a Reynolds number of 52.8. The gain is necessarily in arbitrary units, since the amplitude of the shedding mode as measured by the sensor depends on the location of the sensor. The amplitude of the primary shedding mode decreases continually as gain increases, while the next most unstable mode is very small until a particular gain, at which it starts to grow rapidly. Monkewitz *et al.* (1991) suggest that the continuation of the primary mode at higher gains can be explained by regarding it as being continually excited by incident noise in the tunnel. Figure 10 is the result of repeating the experiment of figure 9 at a Reynolds number of 54.8. It is clear that the window of control is reduced as predicted.

Variation of control in the rest of the wake

Vortex shedding is simply being controlled in one region of a long span. When the control essentially suppresses the mode at the control sensor location the excitation due to the loudspeakers is tiny, and it might be expected that at distant points in the span the controller would have no effect – this is indeed observed.

Experiments were performed with the control sensor located a third of the way along the span, while the second sensor traversed the span in the longest direction (so that the aspect ratio from the control sensor to the mounting point was about 80). At a range of spanwise locations the shedding amplitude was measured with the control loop on and off, and the attenuation at the second sensor location due to the

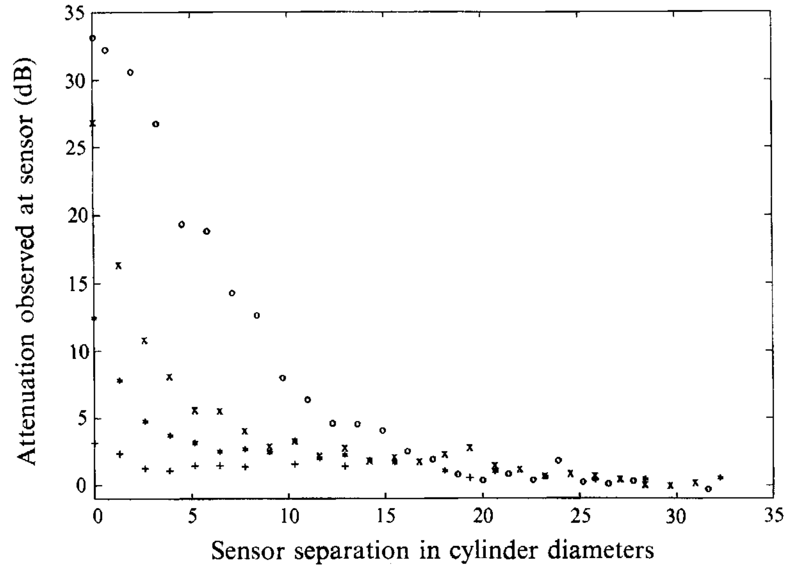

FIGURE 11. Attenuation of shedding mode due to controller action observed at various distances from the control sensor at four Reynolds numbers: ○, 49.4; ×, 52.7; *, 55.8; +, 61.7.

controller action computed. (The attenuation was measured in the same manner as described above for the suppression due to feedback at the sensor location.) Figure 11 shows the variation of control with spanwise location at four Reynolds numbers. It is clear that at some distance from the control location the actuation has negligible effect on the shedding.

Various recent papers have described the spanwise structure of the vortex street behind cylinders and cones using a transverse 'pseudo-viscosity' term (Noack, Ohle & Eckelmann 1991; Albarède & Monkewitz 1992; Papangelou 1991, 1992*b*), so that the amplitude of shedding is effectively controlled along the span by diffusion. The effect of control is to force a condition of zero amplitude at the location of the control sensor. Albarède & Monkewitz (1992), using a result from Nozaki & Bekki (1984), show that the Ginzburg–Landau equation model for three-dimensional vortex shedding has an exact solution for this situation, and it is shown in Roussopoulos (1992) that their solution is in reasonable agreement with these experimental data.

Cross-correlation analysis revealed that shedding was correlated along the whole span when the controller was off; i.e. no shedding 'cells' (Gaster 1971) were observed. This is to be expected at such low Reynolds numbers. The phase relationship between the signal detected by the control sensor and that detected by a second sensor located at a distant point in the span was monitored while the shedding was slowly suppressed at the control sensor by increasing the gain in the feedback loop. It was found that the phase relationship remained constant until the mode was attenuated at the control sensor by around 3 dB; thereafter, the signals became uncorrelated.

The effect of the controller on the flow unsteadiness was investigated with the second sensor at different locations in the region affected by the control. Traversing this sensor through the wake revealed that the wake was stabilized by the controller everywhere directly behind the control sensor, but that at fixed spanwise offsets from the control sensor the effect of the controller on the wake unsteadiness reduces as one moves away from the cylinder. Figure 12 shows the variation of sensor output with

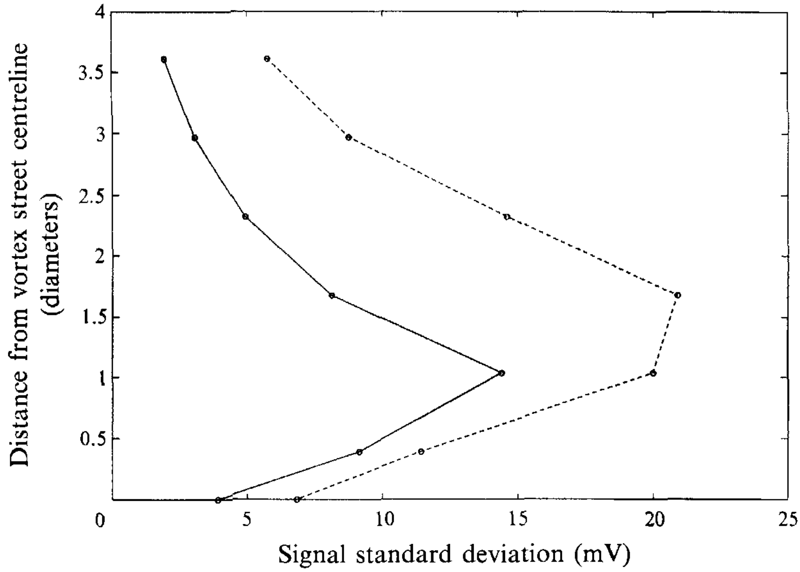

FIGURE 12. Standard deviation of hot-wire signal measured 3.8 diameters along span from control hot wire, 14 diameters behind cylinder, at various heights above the vortex street centreline, with controller on (——) and off (----).

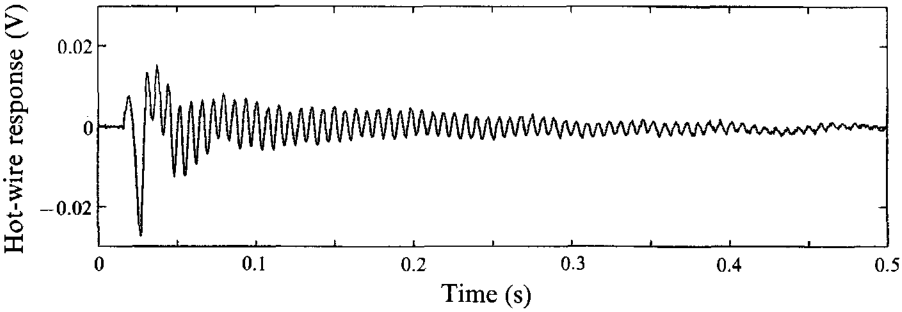

FIGURE 13. Response of subcritical wake to excitation, Reynolds number 46.8.

distance from the vortex street centreline at a typical location with the controller on and off. The attenuation due to the controller action is independent of the distance of the detecting sensor from the vortex street centreline as long as this distance is more than, say, 2 cylinder diameter; this corresponds to requiring the sensor signal to be essentially sinusoidal.

Growth and decay rates

Provansal *et al.* (1987) and others have measured the growth rate of the shedding mode following a step increase in the air speed in a wind tunnel. Schumm (1991) avoided the step increase by using control techniques such as base bleed and steady cylinder vibration (Berger 1967) to suppress vortex shedding, and then abruptly turning the controller off. With feedback control of vortex shedding it is also possible to turn the controller off abruptly and observe the natural growth of the instability; this is clearly visible in figure 7. Unfortunately the suppression thus achieved is only local, as discussed below.

At Reynolds numbers below the onset of shedding, the instability can be excited acoustically, and its decay observed. Provansal *et al.* (1987) achieved this with a brief

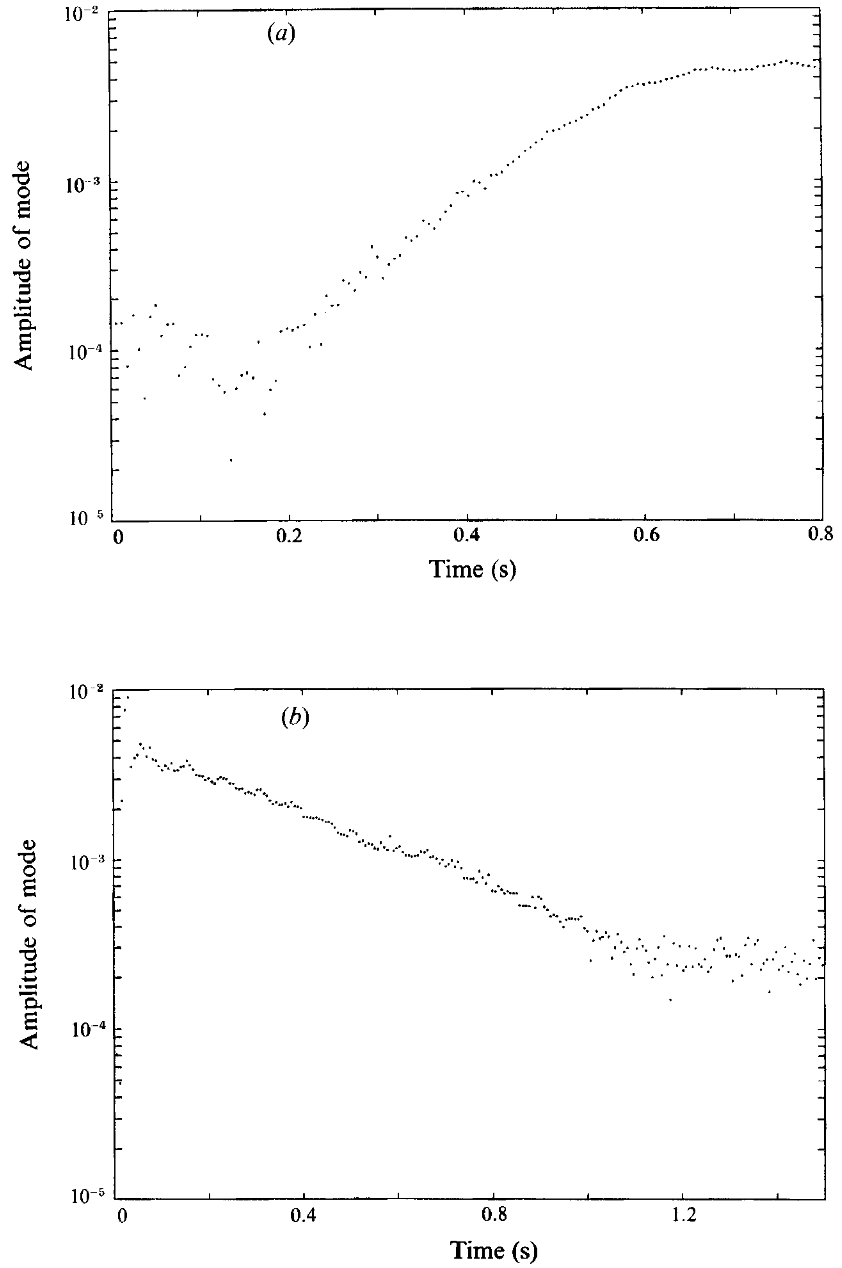

FIGURE 14. Supercritical growth rates and subcritical decay rates on a logarithmic axis: (*a*) Reynolds number 49.3; (*b*) 48.0.

sound generated by striking a membrane acoustically coupled to the tunnel; their excitation was aligned with the tunnel flow. Schumm (1991) artificially excited shedding at subcritical Reynolds numbers and then observed the decay. We achieved this by exciting the speakers in our experiment with a transient signal. Figure 13 shows the response at a sensor in the wake at a Reynolds number of 46.8. The excitation is normal to the tunnel flow; this is probably more effective than exciting the asymmetrical mode symmetrically. (Provansal *et al.* 1987 also showed that the

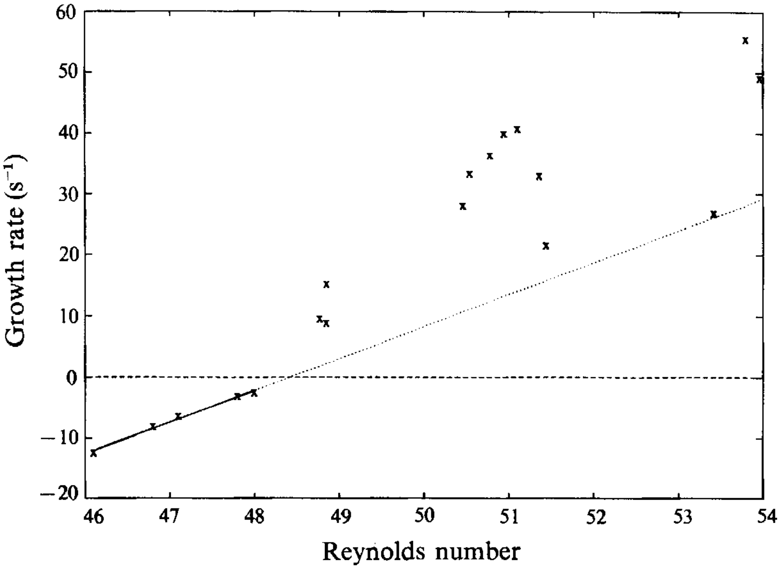

FIGURE 15. Growth rates measured at a number of Reynolds numbers.

Ro/*Re* relationship is continuous between supercritical and subcritical Reynolds numbers, so in this regime the Reynolds number has been calculated from the frequency of the instability.) In this case shedding is induced along the whole span simultaneously, so the decay rates are not affected by variations along the span.

The amplitude of the shedding mode can be estimated by numerically fitting a sine wave to each period of the growing or decaying signal. In figure 14 the amplitude per period is plotted on a logarithmic scale for a growing and decaying signal. There is very clearly a linear growth/decay region at low amplitudes, and linear regression over the appropriate points yields a growth rate estimate.

The variation of growth rate with Reynolds number is illustrated with a number of measurements in figure 15. It is clear that in the subcritical region there is a reasonably linear relationship between the growth rate and the Reynolds number, and the least-squares best fit line is shown. This enables the Reynolds number of the onset of shedding to be estimated by regression; it is approximately 48.4. There is considerably more scatter, however, on the measurements made at supercritical Reynolds numbers, and the growth rates are consistently higher than those predicted by regression from the subcritical measurements. This is in contrast to the results of Provansal *et al.* (1987) and Schumm (1991), who observed a smooth relationship between growth rate and Reynolds number from subcritical to supercritical Reynolds numbers. In our experiments, unlike theirs, shedding suppression is only local, and the measured growth rates are affected by shedding along the rest of the span; this induces unsteadiness at the formerly controlled region, causing growth rates to be higher than those of the natural two-dimensional instability. In addition the phase relationship between the modes on either side of the controlled region will vary at random; if they are nearly in phase when the controller is turned off, they will presumably reinforce to increase the growth rate observed at that location; if they are nearly out of phase, they will interfere to reduce the observed growth rate. This explains the scatter. In the experiments of Provansal *et al.* (1987) and Schumm (1991) the supercritical transients began from a condition of no shedding anywhere along the span.

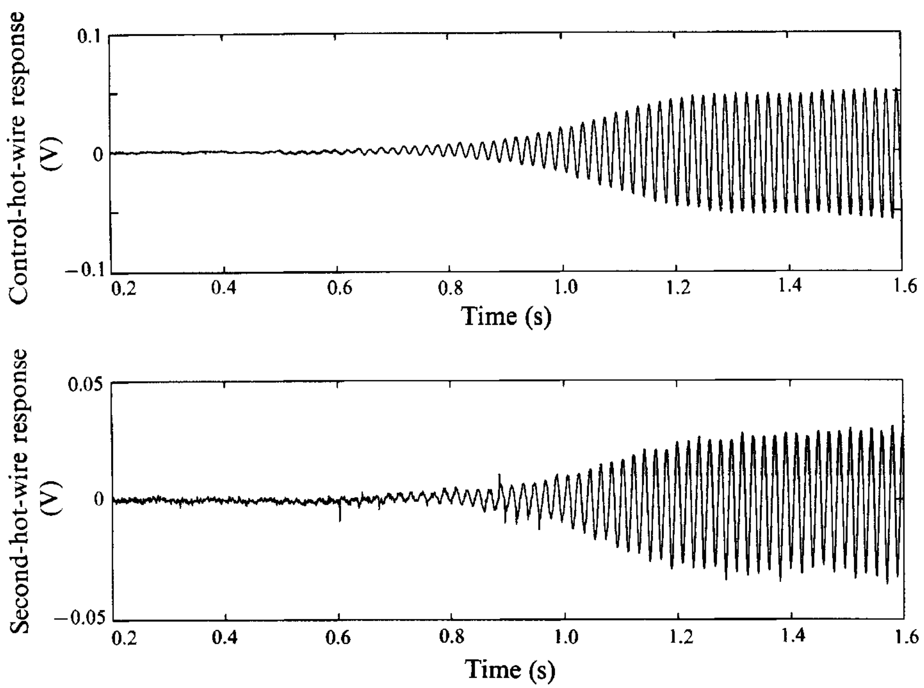

FIGURE 16. Illustration of control and growth of instability at two locations in the wake of a single cell.

It was not possible to obtain satisfactory decay rates for the shedding mode suppression when the controller was abruptly turned on. The reason for this can be seen in figure 7. The decay is not a simple exponential decay; it displays what appears to be a beating effect, or else some overshooting of the controller. This may be due to the propagation of shedding modes along the span (Williamson 1989; Albarède & Monkewitz 1992).

3.2. *Control in a single spanwise cell*

General

Control at a single point in a long span is an unsatisfactory method of investigating the underlying two-dimensional wake instability; the system is influenced by three-dimensional effects because when the controller acts the shedding amplitude varies along the span. Papangelou (1991, 1992*a*) has shown that a length of cylinder isolated by twin spheres as illustrated in figure 2 acts as a single 'cell' of vortex shedding, and that the shedding is approximately parallel to the cylinder at Reynolds numbers up to 150. With this system the onset of shedding is at a Reynolds number of 58, and suppression is possible up to about 70.

The cell wake can be stabilized by feedback as in the case of the long span, but it was found that in this case the stabilization prevented shedding throughout the cell. Figure 16 illustrates the control attainable; this shows the signal measured at the control sensor and the signal measured at the second sensor located at a different point in the cell, when the controller is abruptly turned off. The fact that the whole cell is stabilized together removes the complication of the effect of spanwise variation.

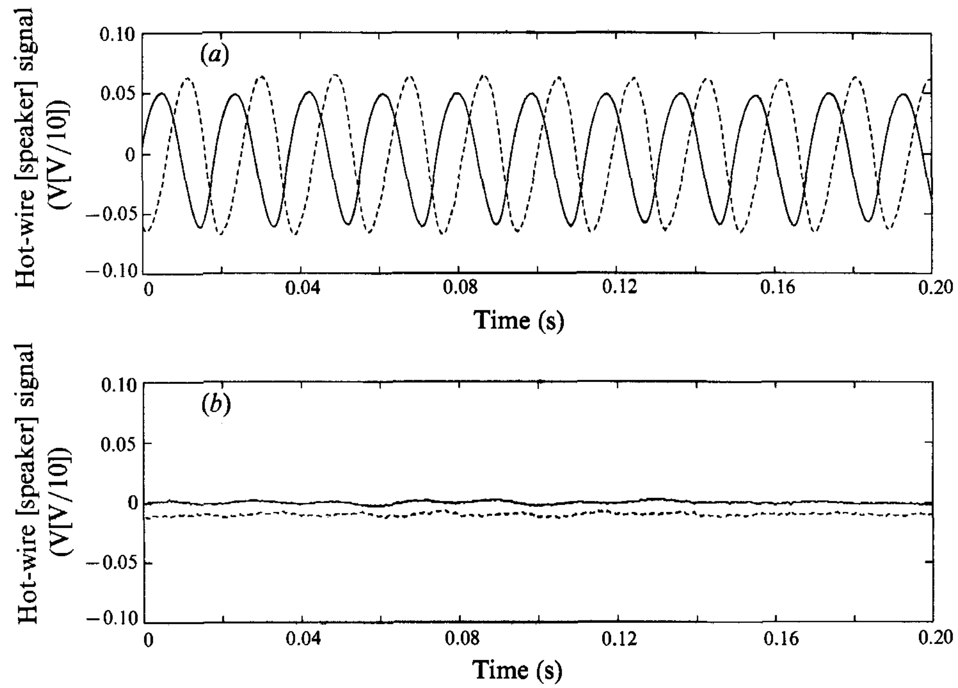

FIGURE 17. (*a*) Illustration of gain and phase relationship between sensor signal and amplifier output with loudspeakers disconnected, and (*b*) of control at this setting when loudspeakers reconnected (——, hot wire trace; --, speaker signal: $Re = 65$).

Sensitivity of control to feedback loop

It has been mentioned that stabilization with the long span was possible with direct feedback and with the untuned phase shifter, but not with the VOP 602 tuned phase shifter. The same was observed in the case of the single cell of shedding; this is illustrated in figures 17 and 18, measured at a Reynolds number of 65. Figure 17 shows the signal from the control sensor with direct feedback, and the signal sent to the loudspeaker, with the loudspeakers connected to and disconnected from the amplifier. The case with the speakers disconnected shows the gain and phase relationship between the sensor and speaker signal clearly; connecting the speakers, with the same settings, results in suppression as shown.

With the speakers disconnected, the VPO phase shifter was included in the feedback loop (see figure 4) and the gain and phase were adjusted so that the signal from the amplifier had the same relationship to the signal from the hot wire as in the case that suppressed shedding without the phase shifter; this is illustrated in figure 18. The hot-wire signal observed when the loudspeakers were reconnected is also shown; it is seen that the shedding amplitude is little affected, and is certainly not suppressed. Closer examination reveals that the shedding frequency has changed from 53 Hz to 57 Hz. Reference to figure 5 indicates that the effect of this frequency shift is to alter significantly the loop phase shift (compared with the case without the VPO 602 device). This new shedding mode can be regarded as the result of positive feedback at the altered frequency and phase shift, and the potential for such positive feedback probably explains why the tuned feedback loop was never able to fully suppress vortex shedding.

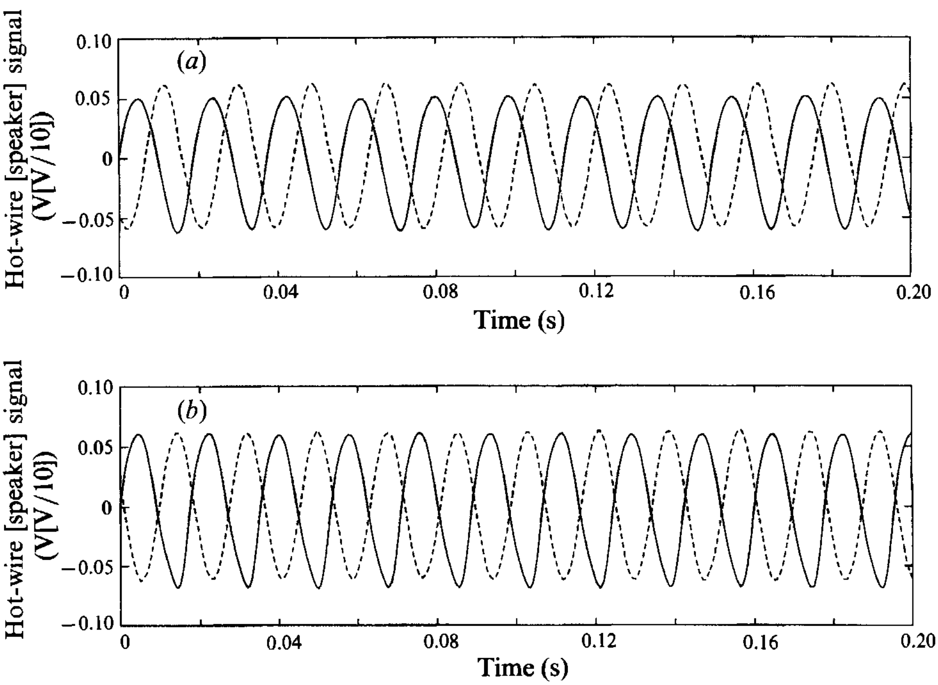

FIGURE 18. Illustration of failure of control loop when the tuned phase shifter is included, although gain and phase relationship with loudspeakers disconnected is the same as in figure 17 (——, hot-wire trace; – –, speaker signal: $Re = 65$). (*a*) Speakers disconnected; (*b*) speakers connected.

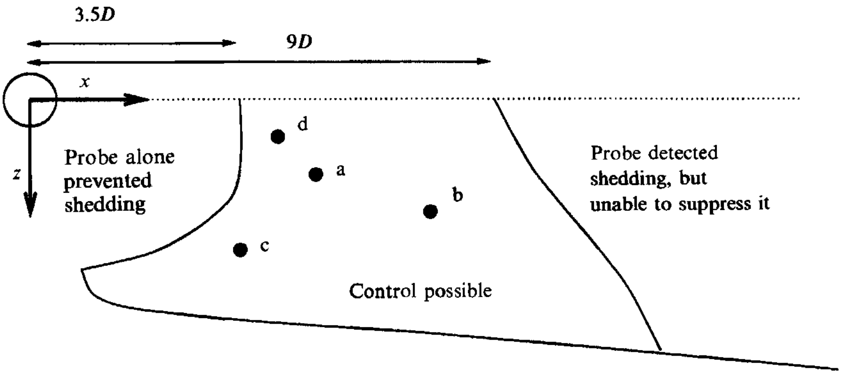

FIGURE 19. Approximate map of region in which sensor must be located for control of a single cell to be possible at a Reynolds number of 65.

Variation of control with sensor location

With the untuned phase shifter it was possible to locate the sensor in a range of locations in the wake and obtain suppression with appropriate phase shift. Figure 19 shows an approximate map of the region in which control was possible at a Reynolds number of 65. There are three main boundaries to this region. Near the cylinder, the presence of the probe alone suppressed vortex shedding; the mechanism must be similar to that observed by Strykowski & Sreenivasan (1990). Far from the centreline of the vortex street, the unsteadiness caused by the shedding is too weak to be used

Location (x/D, z/D)	Growth rates (s^{-1}) control, second sensor	Mean, standard deviation of growth rate (s^{-1})
'a'	11.6, 12.7	13.1, 3.1
(4.8, 1.2)	10.1, 10.0	
	15.3, n/a	
	18.7, n/a	
'b'	13.8, 13.3	12.4, 1.5
(6.7, 2.9)	13.1, 13.6	
	10.6, 10.2	
'c'	10.1, 12.5	11.8, 3.3
(3.6, 2.4)	9.7, 7.0	
	14.0, 17.4	
'd'	6.6, 6.3	7.0, 0.6
(4.2, 0.6)	6.3, 7.6	
	7.7, 7.4	

TABLE 1. Growth rates measured with control sensor at points in wake shown in figure 19

as a control signal. In the far wake, however, beyond about 9 diameters downstream, the vortex street was clearly detectable, but feedback using the signal from this part of the wake was unable to suppress the shedding.

It is evident that placing the sensor too close to the cylinder reduces the instability of the wake. This was confirmed by measuring growth rates by suppressing the shedding and then turning off the controller. This was done with the control sensor at the points marked 'a', 'b', 'c' and 'd' on figure 19, and the second sensor at a fixed location in the other shear layer and well behind the control sensor. (The control signal recorded at 'c' was very small, so control was hard to achieve and the growth rate hard to measure.) The growth rates observed at the control sensor and the second sensor are recorded in table 1 – it is worth noting that in each realization the two sensors recorded close results, and that the scatter is less than that shown in figure 14. It is seen from these data that locating the sensor at 'd' causes the growth rate to be significantly reduced. The variation between the growth rates measured with the control sensor at the other locations, particularly 'a' and 'b', is statistically insignificant, and so the lack of stabilizing interference from the control sensor is unlikely to explain why control is not possible with the sensor located far downstream.

3.3. *Control at higher Reynolds numbers*

Introduction

The experimental results reported by Ffowcs Williams & Zhao (1989) have already been described – they apparently succeeded in controlling vortex shedding at Reynolds numbers of around 400. Monkewitz *et al.* (1991) have pointed out that this is at odds with their theoretical expectations, and the experiments described above support their theory. The results reported by Ffowcs Williams & Zhao were therefore investigated further.

Experiments with the original equipment

The system of control hot wire, loudspeaker, and feedback loop was configured in the manner described by Ffowcs Williams & Zhao (1989), using the same wind tunnel and other apparatus (including the VPO 602 tuned phase shifter in the feedback

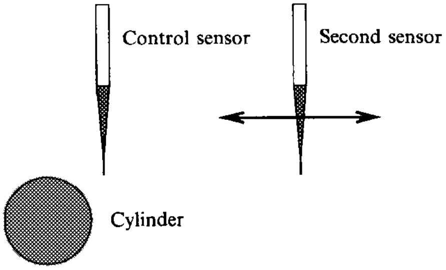

FIGURE 20. Arrangement of cylinder and sensors used for Ffowcs Williams & Zhao (1989).

loop). At a Reynolds number of 400 the attenuation of the vortex shedding frequency component at the control hot wire as reported by Ffowcs Williams & Zhao was attained at appropriate gain and phase settings. The amplitude of the envelope of the signal measured by the hot wire varied considerably with time in both the controlled and uncontrolled case. This is to be expected because at a Reynolds number of 400 the wake is known to be partially turbulent, and because of the presence spanwise cells of coherent shedding (Gaster 1971; Williamson 1989; Eisenlohr & Eckelmann 1989) whose boundaries wander along the span. The best estimate of the mean attenuation of the control-hot-wire signal at the vortex shedding frequency was about 15 dB. This estimate is very dependent on both the exact sensor location and the sharpness of the filtering used to estimate the vortex shedding component amplitude: feedback could cause the shedding frequency to change by about 2–3 Hz, so tuning with a bandwidth sharper than this could give the false impression that shedding was suppressed.

Ffowcs Williams & Zhao also made measurements in the wake at various positions downstream of the control hot wire. When these were repeated, however, it was found that the presence of the control hot wire and its supporting structure, in the absence of any control, sufficiently contaminated the wake downstream of the cylinder for measurements made of that wake to be of no value. The detailed arrangement of sensor and cylinder is shown in figure 20. Figure 21 shows a set of measurements of the shedding frequency component measured in the wake with the controller acting, with the controller not acting, and with the control sensor removed; this is the equivalent of figure 5 of Ffowcs Williams & Zhao (1989). When the controller was acting the shedding frequency component of the control sensor signal was attenuated by 15 dB. Although the details are not the same (results being so sensitive as mentioned above) it is evident that the control observed at the control sensor is not observed in the rest of the wake, and that the control sensor's presence disrupts the wake.

Experiments in the aeronautics wind tunnel

The attenuation of the control sensor signal at the vortex shedding frequency described above was also obtained in the less turbulent wind tunnel used for the earlier experiments, using the twin loudspeaker combination as actuation and hot-wire sensors arranged as in figure 3 (but with one located in the near shear layer, approximately 0.7 diameters behind and 0.6 diameters offset from the cylinder axis). The same VPO 602 tuned phase shifter was used in the feedback loop. The control attained was best observed by monitoring the signal in the feedback loop after this filtering; the effect of turning the controller on and off on this filtered signal is illustrated in figure 22 (*a*), which is similar to Ffowcs Williams & Zhao (1989, figure

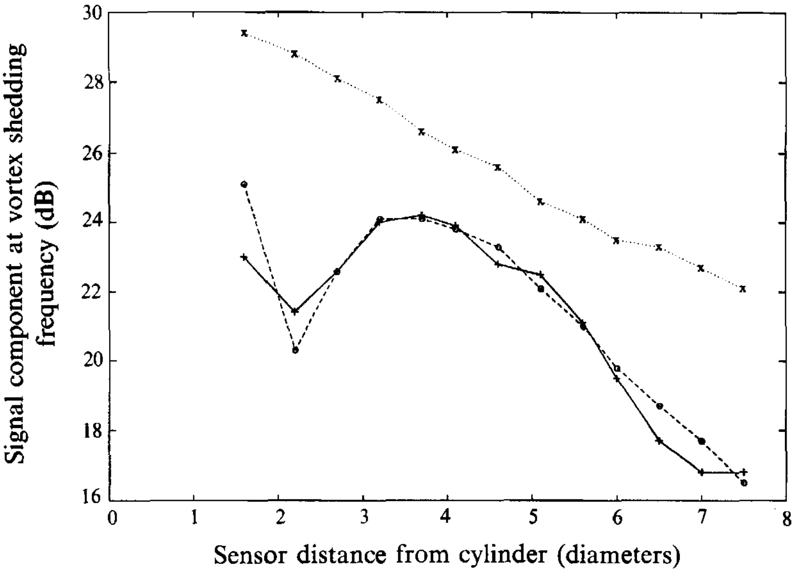

FIGURE 21. Measurements made by sensor throughout wake with control sensor in near shear layer, controller on and off, and with control sensor removed (×, no control sensor; ○, controller off; +, controller on).

3). Figure 22 also shows the simultaneously recorded actuation in the cylinder region and the unfiltered calibrated velocity signal measured by the control sensor and by a second sensor located 2 diameters behind the control sensor and in the other shear layer. Figure 23 shows the spectral content of the signal measured at the control and second sensors with the controller on and off.

It is clear from these figures that the component of the control signal at the shedding frequency is reduced by the feedback – the spectral component is reduced to below the noise level. The signal measured by the second sensor, however, is not so affected, and the signal at the control sensor shows increases at other frequencies, so that the total unsteadiness is little if at all reduced. The loudspeaker signal differs notably from that observed during suppression at lower Reynolds numbers (figure 7) – the magnitude of the excitation is much greater, and it does not significantly reduce as the controller acts.

It was not possible to locate a hot wire in the near shear layer, as required for control, without its physical presence disturbing the vortex street. It was therefore decided to perform similar experiments in a water channel, where dye visualization could be used to determine the nature of the wake in the controlled and uncontrolled state.

Water channel experiments

In Ffowcs Williams & Zhao's experiments the geometry of the cylinder and the sensor was constant, and the action of the actuator was presumably to superimpose on the mean flow in the region of the cylinder a varying component transverse to (probably also with a component in the direction of) the mean flow. It was not possible to use similar actuation in the water tunnel. It was therefore arranged for actuation to drive a cylinder and sensor together across the flow. This is not exactly analogous to the experiments of Ffowcs Williams & Zhao because the transformation

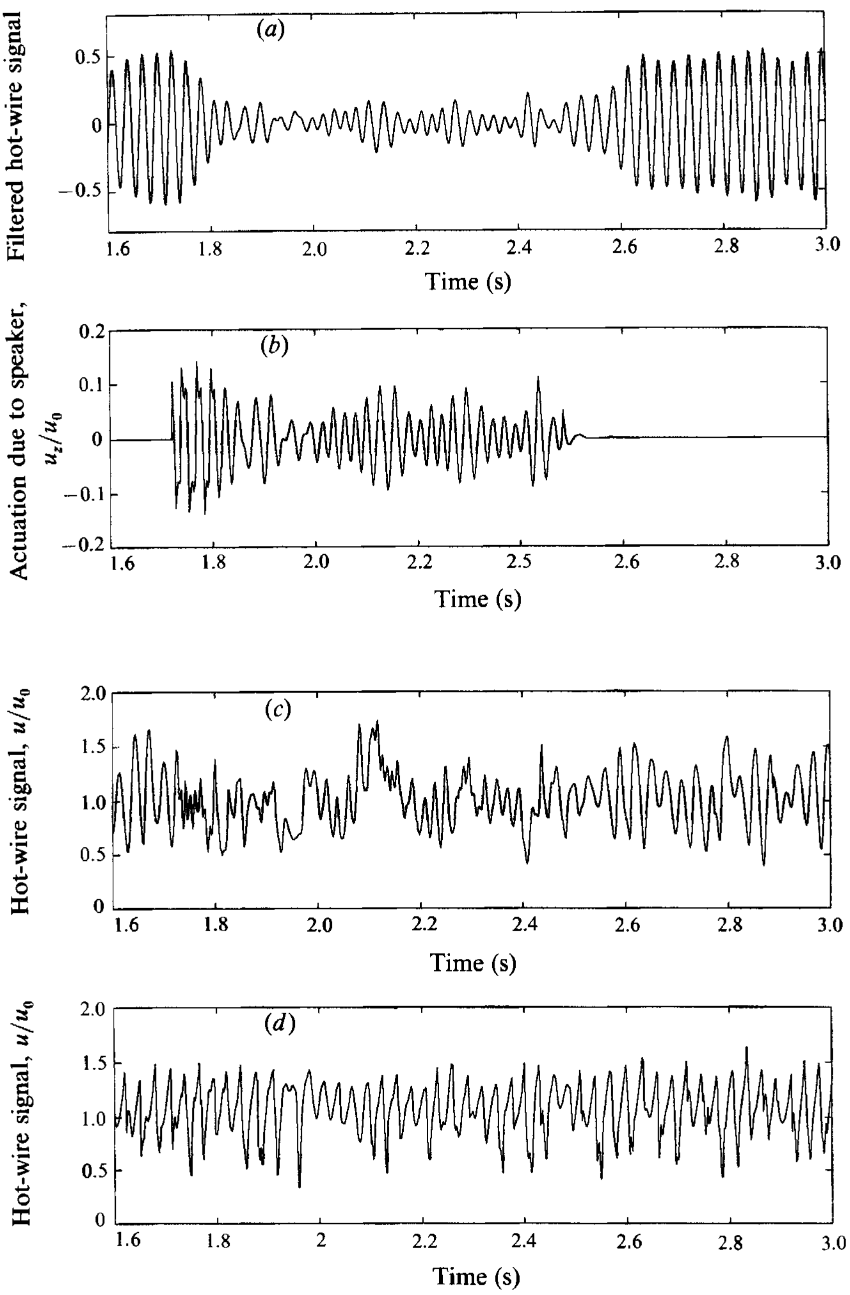

FIGURE 22. Illustration of control attainable using method of Ffowcs Williams & Zhao (1989), the actuation required and the signal measured at a second sensor in the wake ($Re = 400$). (*a*) Filtered control sensor, (*b*) loudspeaker signal, (*c*) unfiltered calibrated control sensor signal, (*d*) calibrated signal from second sensor in the wake.

is from a fixed to an accelerating frame of reference, but the results are nevertheless informative. A second probe was used to measure velocity fluctuations in the far wake.

The cylinder used was of diameter 6.4 mm, and its aspect ratio was relatively

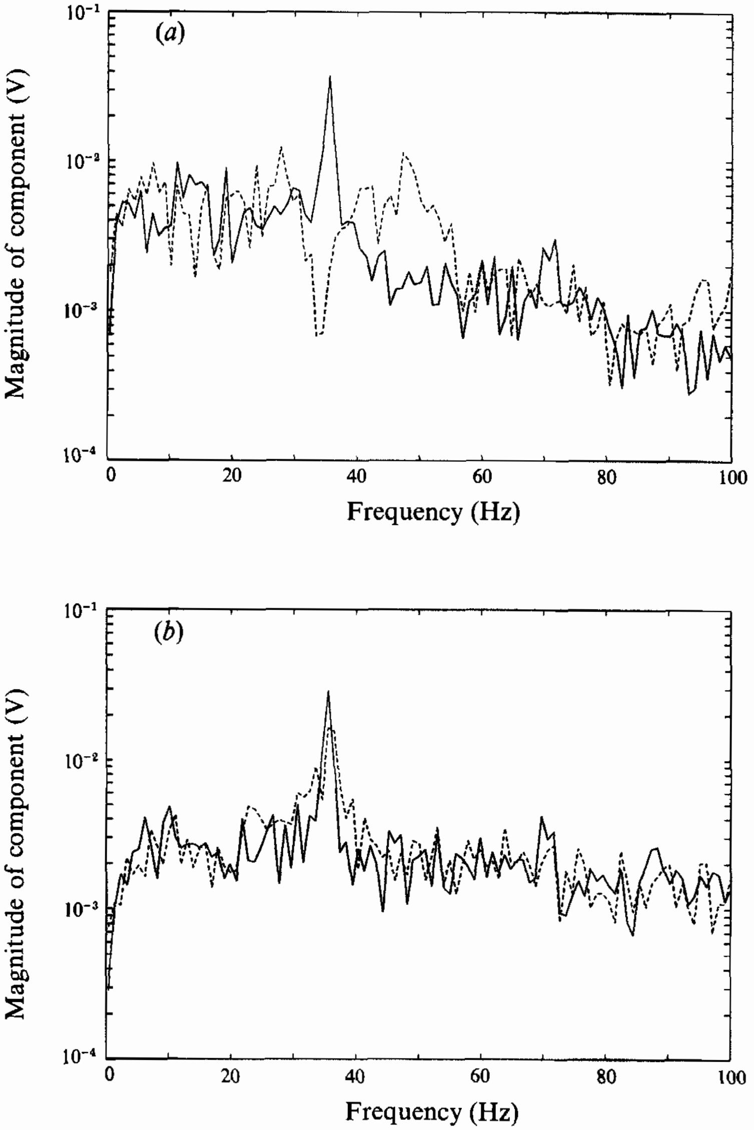

FIGURE 23. Fourier transform of signals measured at (*a*) the control sensor and (*b*) at a second sensor in the wake with controller on (----) and off (——).

small, about 12: although the onset of vortex shedding is at a higher Reynolds number than at higher aspect ratios the mechanism is probably not significantly different. In order to be able to sense the velocity in the near wake with minimal flow interference, the probe was located just below the free surface and supported from above the free surface. This configuration is illustrated in figure 24. Even with this configuration the flow was slightly influenced by the probe presence. Experiments were performed at a low Reynolds number, about 120, to avoid the complication of turbulence. This was well above the onset of shedding with this apparatus, which was at a Reynolds number of about 80.

The signal from the probe, processed by the computer, was used to locate the cylinder and sensor. It was found that the component of the sensor signal at the

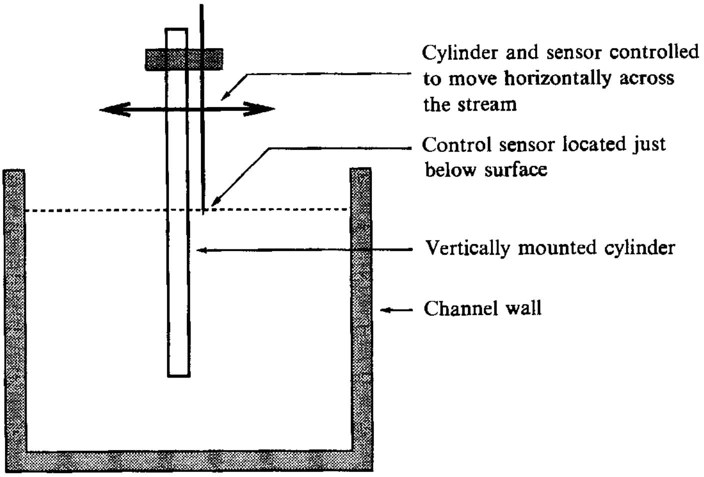

FIGURE 24. Configuration of hot film and cylinder in the water channel.

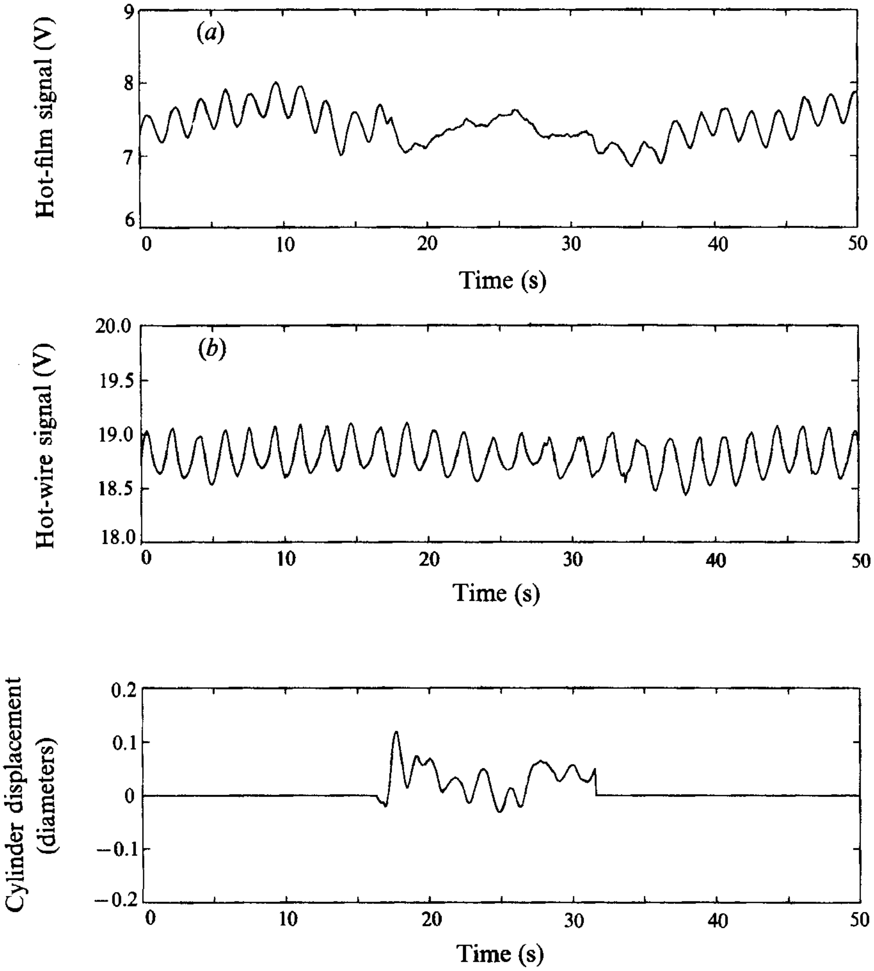

FIGURE 25. Illustration of controller action in the water channel: (a) control sensor, (b) second sensor in the wake, (c) actuator position signal.

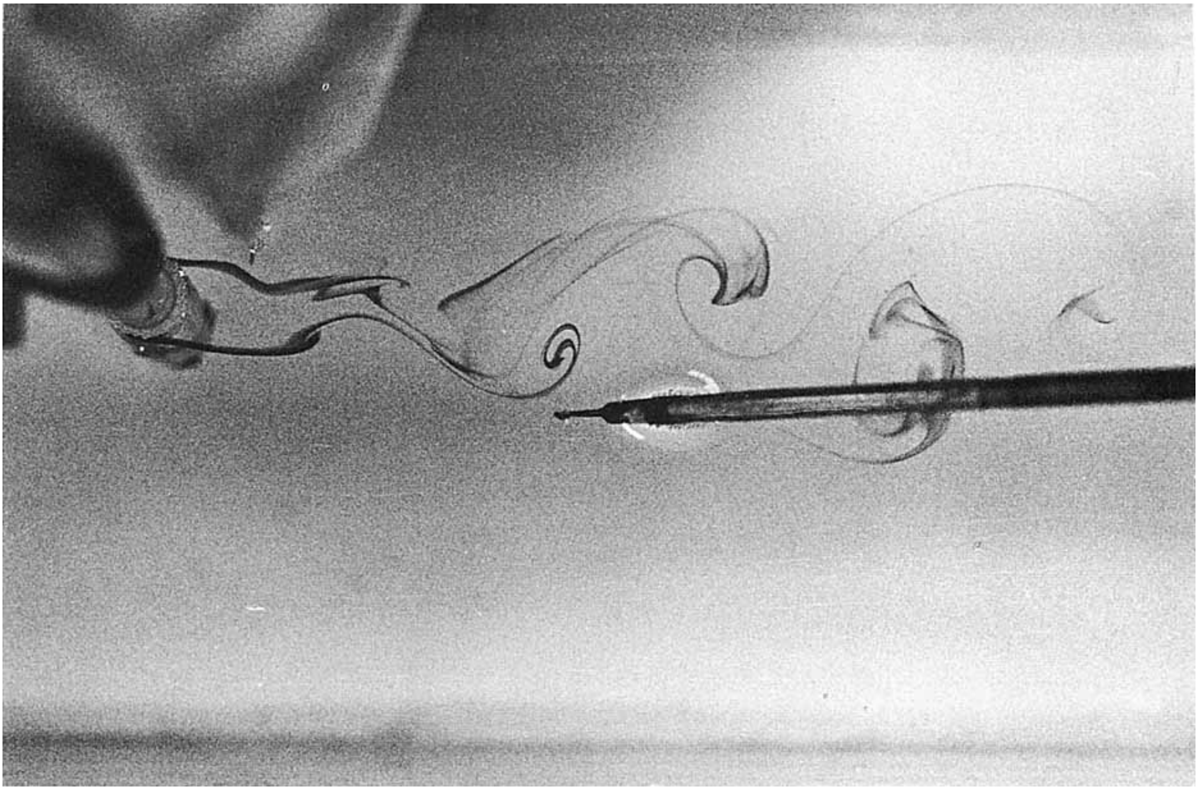

FIGURE 26. Dye visualization of the cylinder wake with the controller acting: control sensor near top shear layer, second sensor to rear and in bottom shear layer.

shedding frequency could be reduced readily, with actuation, by up to around 30 dB. This was approximately the discretization resolution of the controller. This control could be attained over a large range of phase shifts (approximately 180°), and was almost insensitive to changes in gain (above a certain value).

It was found, however, that neither the wake streaklines revealed by dye visualization, nor the velocity fluctuations measured in the far wake downstream, were altered significantly by the action of the controller. An example of the sensor signal with the controller turning on and off is given in figure 25; this figure also shows the actuator signal, and the velocity fluctuations measured in the far wake. Dye visualization of the wake with the controller on is shown in figure 26; in this view looking along the cylinder the control sensor is visible near the top shear layer, and the second sensor further back in the wake. Dye seeps into the flow through holes in the front of the cylinder and follows the separation streaklines. This photograph shows that vortex shedding is not suppressed by the controller action.

Experiments were also performed in which the sensor alone was moved, and the cylinder stationary; the control attained, and the sensitivity to changes in gain and phase, were almost identical. When the cylinder alone was moved with a stationary sensor, however, it was not possible to control the sensor signal (although there was a detectable influence on the flow).

Investigation of the control strategy of Monkewitz and Berger

Experiments were also performed to investigate whether the control strategy described by Berger (1964, 1967) and Monkewitz *et al.* (1991) could be reproduced in water. A cylinder of diameter 3.2 mm and aspect ratio 25 was used in the same water channel. Experiments were performed at Reynolds numbers about 4% above the onset of shedding. The sensor was located approximately 10 diameters downstream of, and 2 diameters offset from, the cylinder midspan. The sensor signal was filtered and phase shifted as before, and fed back with variable gain to control the transverse location of the cylinder. It was found that, with appropriate gain, phase, and filter bandwidth, it was possible to control the signal observed by the sensor, and it was clear from the dye visualization that vortex shedding was inhibited by the controller action, rendering the whole wake steady. The control was highly sensitive to interference from unsteadiness in the incident flow.

4. Discussion

4.1. *Feedback loop transfer function*

The analyses of the feedback control of wake instabilities presented by Monkewitz (1989) and Monkewitz *et al.* (1991) regard the controller action as being to feed back the oscillation amplitude at the sensor location with some fixed gain and phase shift to the controller. The implication is that the signal fed back is of a single frequency. This is reasonable only in a steady state and in the absence of noise. During transients such as those occurring when a controller is abruptly turned on, and in the real controlled state when incident noise is always 'fighting' the enforced steadiness, the signal fed back to the controller will not be a pure sinusoid. In these conditions the success of the control loop will depend on more factors than simply its response to excitation at the natural vortex shedding frequency alone.

We have demonstrated how two different control loop transfer functions can have the same gain and phase shift at the natural vortex shedding frequency, but have different effects on the instability; one suppressing it and the other not. The unsuccessful transfer function was characterized by being highly tuned to the vortex shedding frequency, and by the fact that the phase shift in the feedback loop changed relatively quickly with frequency in the region of the tuned frequency. It probably is a feature of the feedback control of such instabilities that, in loose terms, the feedback loop should be less sharply tuned than the instability being controlled. In the time domain this is equivalent to suggesting that the response rate of the controller should be faster than the growth rate of the controller.

4.2. *Feedback and global instability modes*

Monkewitz (1988, 1989), Huerre & Monkewitz (1990) and others have suggested that vortex shedding is essentially the limit cycle of a 'global' mode of instability, rather than being the result of localized effects associated with, for example, movements of the separation points or the recirculation zone. Monkewitz (1989) states that 'a global mode is understood to a solution of the form $f(x,y,z)\,\mathrm{e}^{-iwt}$ (with the vector f containing all dependent variables) of the disturbance equations, subject to suitable homogeneous boundary conditions'. If the mode is global even during transients then the (complex) amplitude of fluctuations at any two points in the wake would always be proportional. Schumm (1991) has demonstrated that growth rates in the wake are independent of location, and our measurements (see table 1) support this view. An exponential growth, however, cannot be said to have begun at any particular time, so it is meaningless to ask whether the growth started everywhere simultaneously.

If the mode is truly global during transients induced by actuation then a signal from anywhere in the wake should be a suitable control signal to suppress the mode. We have found, however, that there is a limited region within which the control sensor signal must be measured. At locations far downstream from this region a sensor can detect the shedding mode very distinctly but we could not use its signal as a control signal to suppress the instability. This observation implies that the transient instability mode is not global in the downstream direction, in the sense of the mode strength at all locations being instantaneously correlated. We think that this is because at far downstream locations the sensor is detecting 'old information'. If, as intuition and consideration of the well-known pattern of the Kármán wake suggests, there is a localized 'wavemaker' in the near-wake region, generating vortices which are subsequently convected into the far wake, then complete suppression would not be possible from locations in the far wake – if shedding restarted, the amplitude could rise significantly before the controller became aware of it. These observations are compatible with the knowledge (Huerre & Monkewitz 1990; Schumm 1991) that there is only a finite region of absolute instability in the streamwise direction, and that far downstream the wake is convectively unstable.

4.3. *Experiments at higher Reynolds numbers*

We have repeated the experiments described by Ffowcs Williams & Zhao (1989). Their control strategy is able to reduce considerably the vortex shedding component measured by the control sensor, which is located in the separated shear layer near to the cylinder. However we observed that the controller has very little effect on the rest of the wake. (T. Szentmártony has told us that he made the same observation when trying to repeat these experiments at the Technical University of Budapest.) The reduction in shedding component observed by Ffowcs Williams & Zhao throughout the wake in their experiments must have been due to interference from the physical presence of the control sensor.

Analogous experiments performed in a water channel and observed using dye visualization exhibited the same phenomenon – it was possible with feedback to greatly reduce the signal measured by a control sensor located in the separation shear layer, but this control had very little effect on the rest of the wake. The same results were obtained if the sensor alone was moved by the actuator. Control of the signal measured by the sensor was possible without stopping vortex shedding.

It seems to us that the signal measured by the sensor when it is located in the near shear layer is dominated by meanderings of the shear layer, but that these deviations are induced by, rather than the cause of, the shedding process. Moving the shear layer, a region of high velocity gradient, in a direction normal to the local flow would cause a sensor located in the shear layer to observe a significant change in velocity. The control of the sensor signal is explained if the actuator is considered to move the location of the shear layer relative to the sensor. The actuator used in the water experiments does this by moving the sensor itself (and the cylinder) normal to the flow, whereas in the wind tunnel experiments the loudspeaker action would tend to 'blow' the shear layer normal to the flow. The feedback loop can then be regarded as using negative feedback to keep the sensor located at the same position relative to the shear layer: the actuation is not required to suppress the vortex shedding, but merely to prevent it from being detected by a sensor located in the near shear layer.

5. Conclusions

Our experiments have confirmed that at Reynolds numbers just above the onset of vortex shedding it is possible to suppress the wake instability at one point in a long span with feedback. Up to about 5 units of Reynolds number (or 10%) above the onset of shedding, with the controller optimally adjusted, the wake unsteadiness was suppressed to such an extent that the spectral component of the signal from sensors located in the suppression region at the shedding frequency fell to the noise level, and the residual velocity flux at the cylinder location due to the actuator action was about 4 orders of magnitude below the incident flow speed. Up to 10 units of Reynolds number above the onset of shedding the wake unsteadiness was attenuated in the region of the control sensor by over 10 dB. The details of the suppression are to a great extent as predicted and described by Monkewitz (1989) and Monkewitz *et al.* (1991). Suppression is not possible if the feedback loop is highly tuned to the shedding frequency. Suppression is also not possible if the control sensor is located too far downstream of the cylinder, even if the sensor can detect the shedding mode clearly. Given these restrictions, however, the controller gain and phase can be varied significantly around the setting for maximum control without significantly affecting the suppression observed. At excessive gains the system inevitably became unsteady at a frequency slightly but distinctly below the natural vortex shedding frequency.

When shedding from a long span is controlled at a single spanwise location the attenuation is only local to the control sensor location; at distant points in the span the shedding is essentially unaffected by the controller action. The shedding at distant points in the span becomes uncorrelated with the shedding in the controlled region when the latter is attenuated by more than about 3 dB. The effect of the controller falls away smoothly with distance from the control sensor, and more than 20 diameters from the control sensor is under 0.5 dB. When a low-aspect-ratio cell is isolated from the rest of the span, it is possible to suppress shedding throughout the cell. In this case complete suppression is possible up to 10 units of Reynolds number above the onset of shedding, and significant attenuation up to 15 units of Reynolds number above the onset of shedding.

It has been shown that the growth rate of the instability can be determined by monitoring the mode after turning off the controller. In the case of long spans, however, the measured growth rates display significant scatter; we have ascribed this to the influence of the shedding in the rest of the span. The scatter was considerably less in the case of measurements made in the wake of the isolated short-span cell, and in the latter case it was confirmed that the same growth rates are observed at different locations in the cell.

The active 'control' of vortex shedding described by Ffowcs Williams & Zhao (1989) is really an active method of preventing a sensor from detecting vortex shedding. Their control strategy does not suppress vortex shedding at higher Reynolds numbers.

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