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Feedback Control of Vortex Shedding Behind a Cylinder

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Abstract

In this paper, some preliminary results are presented from the experimental observations of a two-dimensional air flow passing a stationary circular cylinder of Reynolds number at 170. The velocity of the wind tunnel was maintained uniformly at U_∞ =80.4 cm/sec during the experiment.

The amplitude of velocity fluctuations was measured vertically above the cylinder centerline with the hot-wire probe positioned at a stream wise station of x/d=2 (near wake) on center under natural and control conditions of the transitional flow in the wake of the cylinder.

The feedback hot-wire sensor takes the signal at the location in the upper shear layer of the cylinder at about 0.9d stream wise, and about 0.8d above the cylinder axis. The phase of the feedback hot-wire signal shifted 180°±2°, then the feedback perturbations were Imposed upon the wake of the cylinder by a pair of loudspeakers which were placed on both sides of the wind tunnel. Then the well-known Karman vortex street responded rigorously to the feedback of a signal taken from a hot-wire sensor in the wake of a cylinder at vortex shedding frequency. The power spectrum of turbulence velocity fluctuations was significantly reduced at Strouhal frequency fs. This was interpreted as the control of vortex shedding achieved in the wake of a cylinder. Additionally, it was observed that a significant reduction of the amplitude of velocity fluctuations occurred when the control was activated.

In this experiment we have been able to demonstrate the feedback control of vortex shedding at Strouhal vortex shedding frequency fs in the cylinder wake at transitional Reynolds number 170.

CE Database Subject Headings

Feedback control of vortex shedding; Active wake control; Wake transition flows; Fluid-structure interaction systems, Bluff-body wake control, Free turbulence control, Drag reduction.

Introduction

Despite the fact that singing wires were known in ancient Greece as Aeolian harp tones, it was Strouhal [1] who first presented measurements of the frequency of vortex shedding from a wire with known diameter. His discovery showed the relationship between the frequency of vortex shedding from harp wire and that the wind velocity produced Aeolian harp tones. More about Aeolian harp tones see Phillip [2] and Etkin et al. [3].

His discovery showed the relationship between the frequency of vortex shedding in a qualitative relationship often referred to as Strouhal frequency law where fs is the frequency [1], in cycle per unit time, of the vortices which are shed alternatively from top and bottom of the cylinder in a steady flow

$$f_s \;\alpha\; U_\infty / d \qquad (1)$$

Strouhals proportionality constant α is set to St and named in his honor. The non-dimensional Strouhal number is expressed by

$$St = f_s\, d / U_\infty \qquad (2)$$

Where,

fs is the frequency, in cycle per unit time, of the vortices shed from shoulders of the cylinder.

Later, Rayleigh [4] also recognized these peculiar sounds and connected them to the periodic instability of the vortex shedding from wires. In nature, many phenomena are governed by Strouhal's number. Despite Strouhal’s observations in 1878, our understanding of the wake behind a cylinder is far from being completely understood. Strouhal's first measurements of the shedding frequency from a wire were a remarkable discovery [1]. However, its practical significance was not acknowledged by his contemporaries at the time.

Significant contributions toward theoretical understanding were made by Kirchhoff who introduced the idea of free streamlines in 1889 [5], and by Karman [6, 7] at beginning of this century.

Kirchhoff's model of the flow of an ideal, in viscid fluid with streamlines was an original contribution to all branches of applied mechanics. Although this theoretical understanding is more than a century old, researchers have yet to relate the flow to that of turbulent wakes behind a bluff-body, Karman [6, 7] based his analysis ideally on the stability of the vortex street [8], using Kirchhoff’s [5] model. No one has been able to go beyond Karman's potential flow analysis for a perfect fluid in the near field of the cylinder to provide a complete theory [7].

Despite the passing of almost a century year's research study on vortex shedding from a bluff-body remains a significant challenge to researchers. That is because there is still no suitable theoretical treatment for the problem of vortex shedding from bluff-bodies.

The related problem of drag on bluff bodies is important from a practical standpoint because it involves significant fuel consumption in a powered vehicle. Most of the power is spent to overcome drag.

Vortex Shedding from Cylinders: Brief Review

Since Berger and Wille's review of vortex shedding from bluff-bodies there has been continued interest in the study of wakes of bluff-bodies [9]. From a practical standpoint, control of vortex shedding from bluff-bodies is extremely important because it would be possible to reduce or control unsteady, periodic pressure loading from both sides f the bluff-body. This causes transverse flow which increases the displacement of the bluff-body at resonance, and leads to collapse of the body. A well-known example of this natural phenomenon occurred when the Tacoma Bridge collapsed in the State of Washington in 1940. Additionally, a slight control of vortex shedding significantly alters the form-drag of the bluff body.

Bearman reviewed the problem of shedding from stationary bluff bodies [10, 11]. In particular he re-examined the vortex formation rate of shedding from cylinders examined by from Fage and Johansen [12] to Roshko [13]. They made estimates of the rate of shedding of circulation and fraction of original circulation that formed the vortex shedding bluff-bodies based on the mean base pressure.

Gerrard hypothetically postulated vortex formation from bluff-bodies known as Gerrard's vortex shedding model, asserted "vortices grow and develop almost in a stationary position for one half of a shedding period until they are strong enough to draw the other shear layer across the wake so that the subsequent vortex is cut-off from further supply of the circulation" [14]. Gerrard's remarkable intuitive description of "formation region" has been experimentally verified by Bearman [10] and more recently by Hoyt and Sellin [15] developed a new dye-streak formulation effective in visualizing turbulent and separated flow. They were able experimentally showed and beautifully capture the high speed mode of vortex shedding at high Reynolds number in the "formation region" Hoyt and Sellin [15] as hypothesized in 1966 by Gerrard [14].

Zdravkovich attempted to create a catalog of experimentally observed different modes of vortex shedding from bluff bodies. He explained low-speed mode and high speed-mode and provided a good discussion of various kinds of synchronized vortex shedding from cylinders [16].
A more complete categorization of the observed vortex shedding modes experimentally was shown by Williamson [17]. He re-examined the detail of the various instabilities and flow regimes of vortex shedding regimes and provided excellent qualitative discussion and up to date work [17].

The Wake Control

Recently the Wake control problem has been summarized by Monkewitz [19]. The Wake control is not only of interest to academics but also practitioners because one can control unsteady loading to structures as well as reduce form drag of bluff-bodies. Also Wake control means to control problems caused by vortex shedding of marine structures including submerged, surface vessels and submarines subject to steady and unsteady hydrodynamic loading.
A recent review by Griffin and Ramberg provided an outline of problems caused by vortex shedding and vortex excited oscillations of marine structures [19]. For many other structures such as submerged vessels, submarines, underwater sonar and acoustics there exists no reliable experimental data which addresses the possible problems associated with vortex shedding that might, for example, be caused to submarines as bluff-bodies in steady current flows. Research in these areas is important for better design and manufacture of submarines and other vehicles. In the 21st Century especially for better design of sea water vehicles for nuclear submarines operates at high speed at sea becoming practically important from US Navy point on view. Research needed especially in sea water tunnel environment to understand how of these nuclear powered vehicles should operate and what are the adverse effects to operate in deep waters or at sea level.
At a Reynolds number of about 150, the wake of the cylinder undergoes a transition to turbulence and there appears of a three-dimensional pattern in cylinder wake. This fact was observed by Roshko [20] in the form of irregularities in the wake velocity fluctuations. Further, Roshko explained that, in the wake of a vortex shedding cylinder, transition to turbulence must occur in the shear layer before the vortices are fully formed and must take place away from the cylinder in the range of Re=150 to Re=300. Roshko further pointed out that near wake flow is independent not only of the separated shear layer, but also of the near of the wake dynamics Roshko [21].

Recently Prasad and Williamson investigations have shown that it is possible to control three-dimensional patterns in a cylinder wake at low Reynolds numbers in which shedding occurs in a laminar manner [22].

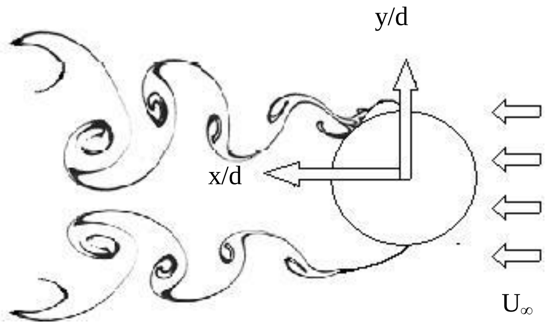


Figure 1. Top view of a stationary circular cylinder and von Karman vortex street formation patterns in the cylinder wake.

Gallaire, Francois, “Periodic forcing of the flow past a cylinder” reference to Taneda [23] studies. For further illustrations and modifications by author.

von Karman vortex street pattern formation behind a cylinder

Figure 2. The vortex shedding rolled from upper shoulder of a stationary circular cylinder.

Gallaire, Francois, “Periodic forcing of the flow past a cylinder” reference to Taneda [23] studies. For further illustrations and modifications by author.
By suitable manipulation cylinder end conditions at Reynolds number Re=200 to Re=10 000 they were able to demonstrate the method to induce parallel and oblique shedding from the cylinder [22]. Sreenivasan and Strykowski inserted a small diameter of a wire in the near wake of a cylinder, which enabled them to completely suppress the vortex shedding from the cylinder in a water-channel of passive control of vortex shedding with the fact that he played a trick to nature by placing that small wire in the wake of the cylinder and claimed that they achieved suppression of vortex shedding [24].

The claim of suppression was error. They should have realized that the wake extremely sensitive to external interference and then wake profile changes rapidly, but not a claim of passive suppression was achieved at low Reynolds number [24].

Among other passive method used of base bleeding was utilized by Wood [25] and Bearman [11] to suppress the vortex shedding behind circular cylinders at high Reynolds numbers.

The idea of wave cancellation originated with Schubauer and Skramstadl used it in their famous experiment to control disturbances for wall turbulence to control laminar boundary-layer flow with zero pressure gradients [26].

Later on Berger [27] and Wehrmann [28] introduced the concept to free turbulence. They were able to suppress vortex shedding and turbulence behind oscillating cylinders. They conducted experiments to suppress the vortex shedding behind an oval "Bimorph transducer" having a width of 0.69 mm and a length of 1.68 mm [27, 29]. Wehrmann found a suppression range from Re=40 to Re=80 on an oblong "Bimorph transducer" cylinder [28]. Later on Berger [27, 29] was able to demonstrate suppression of the wake behind an oblong Bimorph transducer cylinder with an aspect ratio L/d=2.33 from Re=77 to Re=80. He also confirmed the existence of transition at "low-speed" and "high-mode" at transitional Reynolds numbers in the irregular range. However, he found that in the range from Re=126 to Re=160, there was a "basic mode" that sometimes occurred in the "high-speed mode" [27].

Monkewitz theoretically demonstrated, with model feedback, the control of global oscillations in a fluid system with a single sensor and actuator [30]. Monkewitz, Berger and Schumm repeated Berger's original experiment and confirmed the suppression of vortex shedding only at low Reynolds numbers [18]. Williams and Zhao were able to demonstrate, with feedback, control of vortex shedding behind a cylinder having a diameter of 0.6 cm at a speed of 1 m/sec with a Reynolds number of 400 [31].

Roussopoulos [32] repeated Williams Ffowcs and Zhao Zhao's [31] experiment and concluded that the feedback control was possible only at a Reynolds number 20% higher than the critical Reynolds number. He claimed that Ffowcs William's feedback control of vortex shedding at high Reynolds number at about 400 was really feedback control probe when affected, and prevented a second sensor from detecting vortex shedding [32]. He attempted to show this by visualizing the flow in a water channel and showing that there was no control of vortex shedding, he concluded that Williams and Zhao' claim of control at Reynolds number 400 was an error. However, he himself could not provide flow visualization pictures of feedback control even at low Reynolds number in his water channel experiment [32].

There is currently much debate concerning whether the closed loop of feedback control is possible only at low Reynolds number but not high Reynolds number. At a Reynolds number Re of about 48 to 55, periodic vortex shedding begins in laminar flow regime.

However, Huang and Weaver were able to show experimentally the control self sustained shear-layer-oscillations of air-flow past an axisymmetric cavity in a pipeline these oscillations were entirely eliminated by the controller with a right phase-shift adjustment to the feedback signal. They provided photographs showing the first three modes of shear-layer instability across the cavity and their elimination feedback control method [33].

Until recently there was no known photograph of flow visualization by feedback control of a vortex shedding from a cylinder, even at low Reynolds number of about 48.5, the number at which from circular cylinders vortex shedding in the water channel begins. Therefore, Tao, Huang, and Chan' flow visualization results to show that the response of wake flow behind a cylinder to the feedback suppression of vortex shedding s at Reynolds number 48.5 to 51, which is 18% to 24% above the onset of Reynolds number at shedding frequency about 1.05 Hz to 1.1 Hz [34]. At x/d= 10 and x/d=30 locations the visualization photographs of the cylinder wake directly illustrated under the feedback suppression and complete elimination of vortex shedding, and flow-streak lines were reduced to almost a straight line in the cylinder wake [34].

Experimental Method

Description of the Experiment

The experiments were performed in a low speed suction-type wind tunnel as shown in Figure 3. The wind tunnel had a test section of W=15.2 cm, H=15.2 cm, and the ceiling, floor, and side walls were made of plexi-glass in order to facilitate visualization and photography. The velocity in the test section was maintained at U_∞ =80.4 cm/sec throughout the measurements. The Reynolds number is given by

$$Re= U_{\infty}\ d/ \nu \qquad (3)$$

where, ν is the kinematics viscosity of air.

The characteristic length in the definition of Reynolds number 170 was based on the cylinder diameter. A schematic of the associated instrumentation is shown in Figure 3. From experimental observations it is determined that the maximum attainable velocity in the wind tunnel is about 5m/s. Also, the free-stream turbulence intensity level is about 0.03% at 5 m/s in the absence of acoustic excitation at low speed wind tunnel with low turbulence.

The wind tunnel has an overall contraction ratio of 64 with a section containing three screens between two contractions. The flow conditions can be varied by adjusting a suction valve. During the experiments the mean velocity of the flow was monitored with a pitot-static tube.

A circular cylinder was made from a polished brass drill rod fitted with two end plates and the cylinder which spanned the wind tunnel test section. The cylinder was fitted with two end plates which were made seven to ten times greater than the diameter of the cylinder as prescribed by Stansby [35], Nishioka and Sato [36], and Ramberg [37]. The effect of end-plates on the two-dimensionality of a vortex wake and the vortices are only shed two-dimensionally well discussed by Graham [38].

The frequency of the shed vortices in the wake of the circular cylinder was detected by a hot-wire anemometer probe. The I-hot wire had a diameter of 0.0002 inch and a platinum core. The length of the etched portion was about 1.5 mm and the hot wire was operated at an overheat ratio of 1.5. A DANTEC constant-temperature hot-wires anemometer and a DANTEC 55D26 signal conditioner with amplifier were used. The probe's signal was high-pass filtered below 4 kHertz and low-pass filtered above 2 Hertz. The hot wire signals were fed simultaneously to a HP-Spectrum analyzer, a Textronic digital-oscilloscope, and an rms volt meter. The uncertainty of detecting the peak vortex shedding frequency was estimated at about f_{nat} =50±0.0025 Hertz in this experiment.

Feedback Control System (FCS)

A schematic of the feedback control system (FCS) is shown in Figure 3. This feedback loop consists of: (a) a feedback hotwire probe; (b) a DISA 55M10 constant-temperature anemometer (c) a DISA 55D26 signal conditioner; (d) a narrow band-pass filter; (e) a phase changer; (f) a Panasonic audio power amplifier with 110 watts per channel; and (g) 8-inch loudspeakers attached to the front side of the wind tunnel 1/2 m downstream from the cylinder centerline.

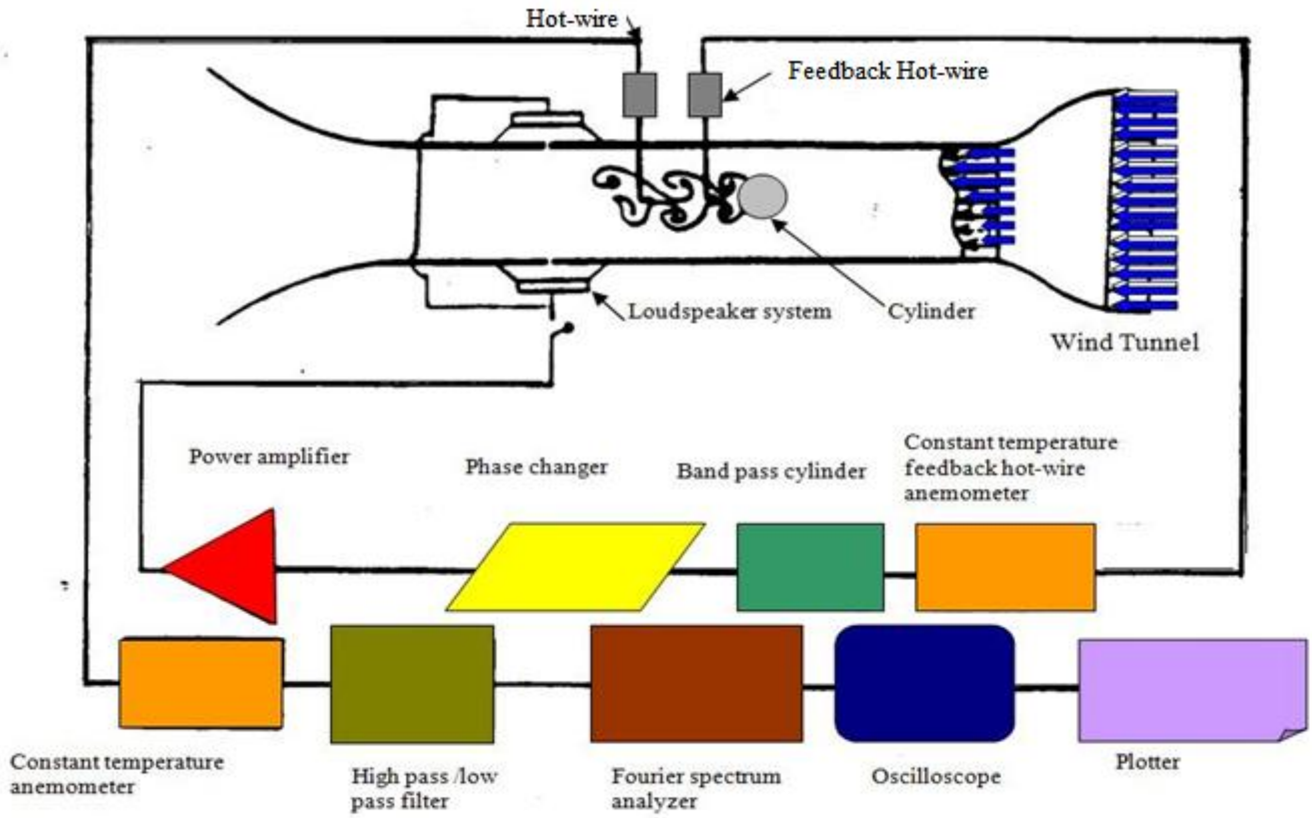


Figure 3. Top view of experimental setup and feedback control loop

Top-view schematic of wind tunnel and associated instrumentation Experiments were carried out in a suction-type; low speed boundary layer wind tunnel. The background turbulence level is estimated at about 0.03 per cent. The Reynolds number was maintained at 170.

Assuming two-dimensionality of the flow maintained with end plates, the experiments were conducted and measurements were taken in the midsection of the cylinder axis and vertical section. All measurements were taken under this flow condition.

A second hot-wire probe was used to take measurements in the wake when control activated. The feedback signal drove the loud speakers to impose controlled sound perturbations upon the wake flow field. The hot-wire signal was fed to an oscilloscope to monitor turbulence velocity fluctuations in the wake of the cylinder.

The signal from the feedback hot-wire probe at a location in the upper shear layer about 0.9d stream wise and about 0.8d above the cylinder axis in the wake of the cylinder was then band-passed, filtered, phase-shifted, and fed into the audio power amplifier to drive the loudspeakers where sounds were superimposed upon the Figure 3: Top view of experimental setup and feedback control loop flow field.

A layer of sponge and wool material covered the area surrounding the 40 mm hole and the inner side walls of the wind tunnel for the purpose of minimizing sound reflection by the tunnel plexi-glass walls.The feedback signal was phase-shifted at about 180±2 and with optimum gain to drive the loudspeakers. Controlled perturbations were imposed on the wake field of the cylinder through location on the same plot. A hole 4 cm in diameter. The power amplifier provided 19.25 watts to drive the loudspeakers. The signal detected by the hot wire was processed by the signal analyzer which gave the power spectrum of the turbulence velocity fluctuations at Strouhal frequency fs.

The power spectrum was obtained with the second hot wire probe at natural and when the control was activated. Following the imposed sounds the power spectrum of the longitudinal component u' of the velocity fluctuations' spectrum's f_{nat} was reduced to about 16.75-dB in the Karman-vortex-street in the cylinder wake. This is interpreted as control of vortex shedding in the cylinder wake at Strouhal frequency fs. It was remarkable to observe how feedback forcing effectively reduced the amplitude of velocity fluctuations to about 40 % of their natural values at various positions in the wake. The reduction of the amplitude of velocity fluctuations was observed on the and recorded. When the feedback control system was turned off, the shedding from the cylinder and velocity fluctuations returned to natural values in about 30 seconds.

The natural vortex shedding frequency f_{nat}=50 Hertz was measured by the hot-wire anemometer, and frequency analyzer indicated peak frequency of shedding. The uniform flow conditions at U=80.4 cm/sec and the same shedding frequency was maintained throughout the measurements.

Therefore, the vortex shedding frequency typically corresponds to a Strouhal number of approximately St=0.197.

Also, a dramatic reduction in the power spectra of the vortex shedding was observed at Strouhal frequency with the feedback control on. For comparison purposes, the oscilloscope time traces were plotted separately at each fluctuations and reducing amplitudes in the Karman vortex street at Strouhal frequency fs. It is important to note that a small feedback signal from the cylinder wake was capable of controlling large turbulence velocity.

The Experimental Results and Discussion

At Re=170 the wake of the cylinder responded dramatically to the feedback forcing of the Karman vortex street. This response was studied to determine the longitudinal component u' of fluctuations with the hot-wire probe positioned at various vertical positions y/d above the cylinder wake at a stream wise station of x/d=2 (near wake) on center and about 1/2 diameter above the cylinder centerline.

Following the imposed sound perturbation by feedback control to about 40 % reduction in the amplitude of the turbulence velocity fluctuations was observed on the voltmeter. Additionally the power spectrum of the turbulence component u' of the velocity fluctuations' spectra, at Strouhal frequency fs was reduced to about 16.75-dB of the Karman vortex street in the cylinder wake. This is interpreted as the control of vortex shedding in the cylinder wake at Strouhal frequency.

Figure 4 shows the distribution of longitudinal velocity fluctuations versus vertical diameters in the near wake x/d=2. The measurements were obtained at sixteen different locations in the cylinder wake. The plot shows the natural and feedback control of velocity fluctuations we to note with feedback forcing the fluctuations reduced 40 % of their values at y/d=0.634 and y/d=0.640 respectively.

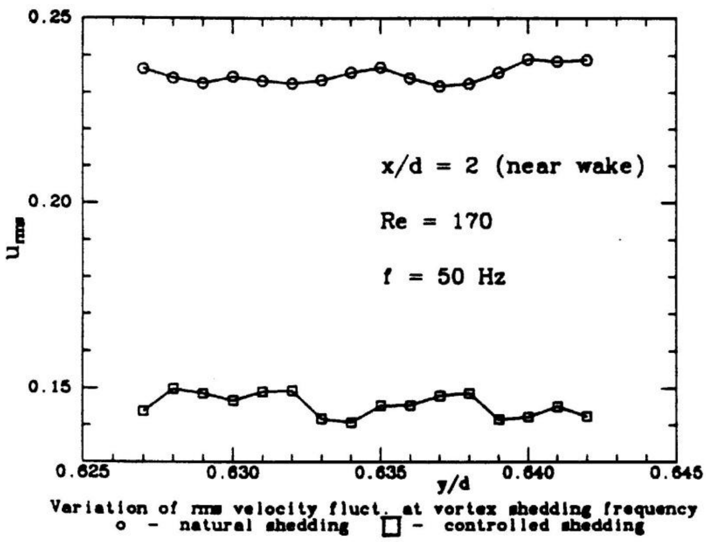


Figure 4: Longitudinal velocity fluctuations versus vertical locations.

The plot shows that the velocity fluctuations are uniform in the wake in a natural state. In the control state the plot shows more uniformity vertically with small-scale velocity fluctuations. Figure 5 shows the ratio of velocity fluctuations (u'_{con}/u'_{nat}) versus various vertical locations in the near wake at the stream wise station x/d=2. The effect of control in the near wake shows a slight uniformity and control holds at y/d=0.634 and y/d=0.640. No significant wake oscillations can be seen which indicative of rolled-up vortices due to shear layer induced isolation of the wake behind the cylinder.

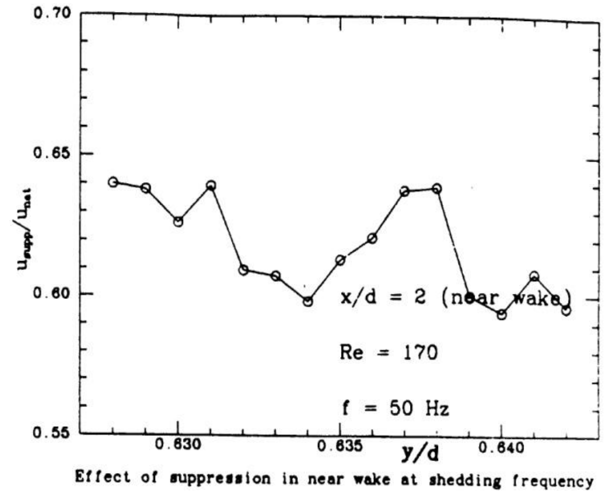


Figure 5: (u'_{con}/u'_{nat}) versus vertical location

Figure 6 shows turbulence intensity versus vertical locations in the near wake of the stream wise station at x/d=2. Measurements were taken at a stream wise station of x/d=2 behind the cylinder from y/d=0.01 to y/d=0.06 inch, approximately half-diameter vertically up from the cylinder center. Under the natural and controlled conditions, it appears that the distribution of velocity fluctuations was uniformly controlled from a distance y=0.010 to y=0.06 in the wake except a small kink at a distance y= 0.012.

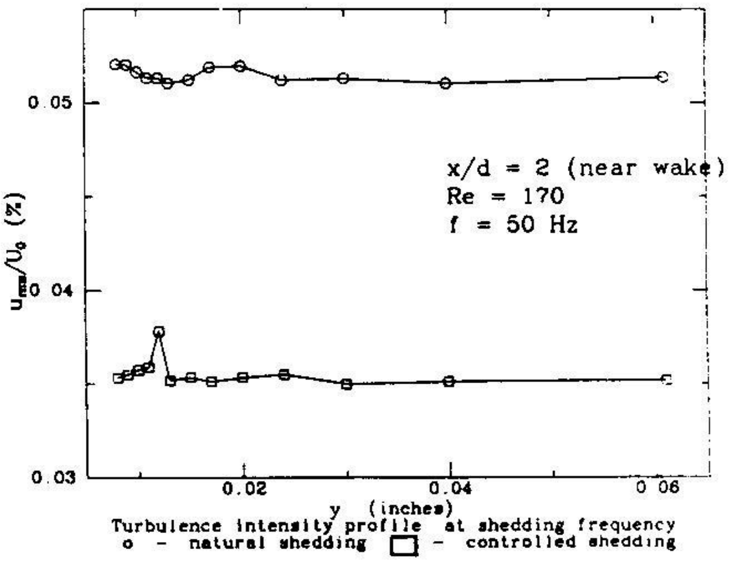


Figure 6: Turbulence intensity versus vertical locations.

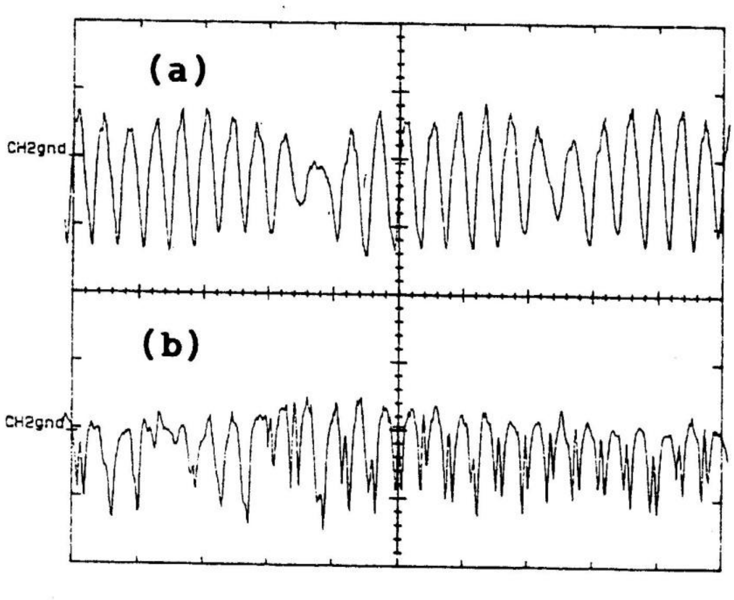
The wake profiles compared in prior readings were taken to see whether or not there was possible influence between the feedbacks and second hot-wire. However, placements of the feedback hot-wire about two-diameter in the upper shear layer next to the second hot-wire did not alter the measurements taken by the second hot-wire. On the basis of this, the feedback control activated and measurements were taken by the second hot-wire probe in the wake.

Oscilloscope Time Traces and Spectra: Analysis

During this investigation, instantaneous pictures of the flow were recorded by plots of oscilloscope time traces. When the feedback control was turned on, a dramatic change in time traces of velocity fluctuations occurred. Comparison of time traces shows that from

(a) natural conditions to (b) control conditions the time traces of velocity fluctuations was considerably flattened. This change was interpreted to indicate that vortex shedding control has been, to a large extent, achieved.

Oscilloscope time traces of turbulence velocity fluctuations at a vertical distance y/d=0.634 are shown in Figure 7. Figure 7 shows intermittent velocity fluctuations between the two modes. Fluctuations undergone initially at one-wavelength changes to irregular jumps followed by periodic jumps at a four-wavelength for two-wavelength to a slightly regular mode with periodic repeat, back to an almost regular mode. Periodic fluctuations between the two-modes are apparent. At control conditions fluctuations flattened indicating that velocity fluctuations were controlled except for a few spikes at y/d=0.631.



CH2 200mV A 50ms -90.6mV VERT

Figure 7: Oscilloscope time traces of velocity fluctuations at a vertical distance y/d=0.634. (a) Natural time traces, (b) Controlled time traces

Figure 8 shows power spectra of velocity fluctuations measured with a frequency analyzer in a band of 0-400 Hz, subdivided in forty intervals of 3.8194 Hz for natural and controlled conditions.

Figure 8 shows that spectra were reduced 16.75-dB, indicating a significant reduction of the component to u' of the turbulence velocity fluctuations in the Karman vortex street. Those power spectra do not correlate with the flow velocity but are treated as representative of the spectra typical of velocity fluctuations in the wake.

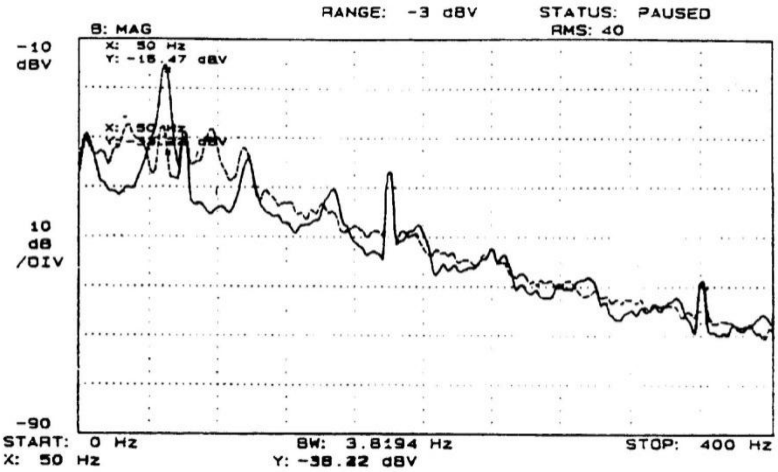


Figure 8: Power spectra of velocity fluctuations at a vertical distance y/d= 0.634. (a) Natural power spectra, (b) Controlled power spectra.

These results are rather encouraging, considering these are our very preliminary results by feedback control of vortex shedding in the wake of a cylinder at these flow conditions. Tao et al. [34] recently provided flow visualization pictures at low Reynolds number.

The flow visualization pictures at transitional Reynolds number by feedback control are yet to come and will support these research results.

This study demonstrated that the cylinder wake was directly affected by sounds and vortex shedding was controlled by the acoustic feedback control at Strouhal frequency.

Nomenclature

ν Kinematic viscosity of air $\nu = \mu / \rho$ [=0.150 cm^2/sec]

ρ Air-Mass density of air [=1.21 kg/m^3]

μ Coefficient of viscosity [=0.99 N s/m^2]

U_∞ Free-stream velocity [=80.4 cm/sec]

Re Reynolds number based on cylinder diameter [Re=170] [Re= $U_\infty d/ \nu$]

St Strouhal number based on cylinder diameter [St=f_s d/ U_∞]

d Diameter of circular cylinder [=3.1 7 mm]

fnat Natural vortex shedding frequency of the cylinder [=50Hertz]

fs Strouhal vortex shedding frequency [f_s=fnat]

u Longitudinal velocity component in the boundary layer

v Normal velocity component in the boundary layer

u’ Longitudinal turbulence (rms)velocity fluctuations in x-direction

v'- Longitudinal root mean square (rms) velocity fluctuations in y-direction

x Distance from center of cylinder in stream wise direction

y Distance from center of cylinder in normal direction

z Distance in span wise direction normal xy plane

L Distance between end plates of the cylinder

We reached our aim is to demonstrate that the feedback control method described here offers an alternative for actively controlling vortex shedding in the wake of a circular cylinder thereby protecting structures against unsteady loading.

Conclusion

In this study, we examined vortex shedding behind a cylinder and its wake in a wind tunnel at the transitional Reynolds number 170. The results from a series of experiments have been presented. We conclude the following:

1. The power spectrum of the turbulence velocity fluctuations were reduced by about 16.75-db at Strouhal frequency f_s.
2. We report that about 40 % of reductions of the amplitude of the turbulence velocity fluctuations in the Karman vortex street in the wake of the cylinder were observed to various positions when the feedback control was turned on. When the feedback control was turned off, velocity fluctuations regained their amplitudes, and the frequency of natural vortex shedding from the cylinder returned to the original condition within 30 seconds.
3. We have demonstrated, in principle, achievement of the feedback control of vortex shedding at Strouhal frequency fs in the wake of a circular cylinder.

Acknowledgement

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