

Active Control of Vortex Shedding in the Far Wake of a Cylinder

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Abstract

This paper, some preliminary results reported from experimental observations of two-dimensional air flows with a Reynolds number of 170 passing a stationary circular cylinder and its active control was achieved in beginning of the far wake distance $x/d=7$. The free stream velocity of the wind tunnel maintained uniformly at $U_\infty=80.4$ cm/sec during the experiment.

The amplitude of velocity fluctuations measured vertically above the cylinder centerline with a hot-wire probe positioned at a stream wise station of $x/d=7$ (beginning of far wake) on center under natural and control conditions of the transitional flow in the wake of the cylinder.

The feedback hot-wire sensor was located in the upper shear layer of the cylinder at about $0.9d$ stream wise and about $0.8d$ above the cylinder axis. After the phase of the active signal phase shifted $180^\circ \pm 2^\circ$ and the amplifier gain adjusted, perturbations imposed at vortex-shedding frequency on the wake of the cylinder on both sides of the wind tunnel.

The induced perturbations were significant and the Karman vortex street responded vigorously to the active of the signal from the hot-wire sensor in the wake of the cylinder at vortex-shedding frequency. The power spectrum of turbulence velocity fluctuations significantly reduced at Strouhal frequency. This is interpreted as the control of vortex shedding achieved in the beginning of far wake of a cylinder. Thereafter, the amplitudes of velocity fluctuations were significantly reduced in the Karman vortex street. However, for further far wake distance no wake control was achieved.

In this experiment, we have been able to demonstrate the active of vortex shedding in the beginning of the far wake distance $x/d=7$ of the cylinder-wake at Strouhal vortex shedding frequency. However, shedding of the vortices in the wake not controllable at distance $x/d = 20$ and further downstream.

Keywords: Active control of vortex shedding; Bluff-body wake control; Drag-reduction; Fluid-structure interaction system; Free turbulence control.

1. Introduction

In 1940, Tacoma Narrows Bridge in the State of Washington was destroyed and collapsed completely as a result of moderate dynamic wind loading. Scientists, engineers, and bridge designers worked to understand what caused the bridge's collapse. For Scientists, the question was what physical mechanisms affected the disaster? Were they structural or material failures or both?

The above cited phenomena was not known to be connected with the 'singing wires' that bothered a Czech scientist Vincent Strouhal almost 137 year years ago in 1878 [1].

Because of Strouhal' curiosity [1], his observations of in windy days of singing overhead telegraph wires stretched in between two anchored to ground wooden posts. Followed by doing many experiments with different diameter of wires to qualitatively understand why wires sing when subjected to wind have persisted since then.

This category, known as 'Aeolian vibration' is analogous to ancient Greeks observed on their musical instrument the 'harp wires singing' in windy day during their festivities, when they left the instrument on the ground while by itself.

The interests in this area followed by von Karman [2] who based his analysis ideally on the stability of the vortex street [3], using Kirchhoff's model [4]. Later von Karman's and Rubach's [5] potential flow analysis for a perfect fluid in the near field of the cylinder provided a complete theory.

Natural disasters came under scrutiny as the general public demanded answers from scientists. From the engineer's point of view, the question was whether the designed structures be built with or without considering 'aerodynamic effect or instability' in the design. The mechanism of flow instability or 'vortex shedding', and 'aero elastic excitation' were given serious consideration. The flow shedding from a structure, and flow pattern can be unstable, even if the structure is stationary. Structures such as tall buildings, chimneys, giant broadcasting antennas, towers, stacks, cooling towers, suspension bridges are subject to vortex-induced vibration known as "VIV." The develop VIV forces are much larger than drag forces [6, 7].

When, vortex shedding from a bluff-body couples, with the natural frequency of bluff-body at 'aero elastic excitation' state, it causes body displacement exceeds finally, the structure collapses. See for more about aero elastic coupling by Davenport [8], Novak [9], Ruscheweyh [10], Scruton [11], and Wyatt [12]. This paper demonstrates a closed loop feedback control of wake of the cylinder in beginning of the far wake of a circular cylinder in transitional Reynolds

number 170. The feedback control method was described earlier by Keles and Chen [13].

The shedding of vortices from bluff-body structures essentially is a natural wind loading when structure subjected to wind. The feedback control is an innovative approach and a strategy control the trailing vortices, when properly applied it cancel out loading to the structure. Thereby, it provides an approach to control of displacement exceeding of the structure and prevents eventual collapse. Hence, it saves structures are rebuilt, enormous financial cost, saving human lives, societal and environmental impacts. Now a day structural engineers design structures with aerodynamic aspects included in their design from wind loading, along with other element of structure designs. Designer also uses other passive control strategies of the other passive control methods try to control vortex-shedding from structures using some of known novel passive techniques. These are attachment of helicoidally spoilers, splitter plates to the structures are common strategies have been used to passively control vortices affecting towers, stacks, antennas, tall buildings, suspension bridges, and bridge pillars of foundation.

2. Galloping Phenomena: Suspension Bridge Structures

Galloping is associated with self-excited crosswind dynamic response of structures in torsional excitation and bending moment mode of oscillations of suspension bridge structures. Also, there is interaction of vortex-shedding with galloping excitation. This has been studied in depth by various researchers including Del Hartog, whose formulation is known as Hartog's theory of galloping oscillations [14], Novak's theory of oscillations [9] and Scruton' study [11]. Also, please note Parkinson's explanation on the galloping excitation [15]. In Parkinson's hypothesis, the dynamic resultant force acting on the oscillating structure is the same as on the stationary structure at positive angles of attack in the wind velocity. There is a combined effect of the galloping and shedding of vortices from a structure.

Reynolds number is based on the cylinder diameter

defined by,

$$Re = U_{\infty} d / \nu \quad (1)$$

where,

$$\begin{aligned} \nu &= \mu / \rho [=0.150 \text{ cm}^2/\text{sec}] \\ \mu &= \text{Coefficient of viscosity} \\ \rho &= \text{Density of air} \\ U_{\infty} &= \text{Free stream velocity} \end{aligned}$$

Reynolds number provides a flow regime for organization of vortex shedding in the wake of an object.

The other aspect of the flow is that motion of the structure locks on to the vortex shedding frequency and to the structure's natural frequency over a range of velocities.

The lock on vortex shedding frequency on structure becomes important, because if there is a coupling of frequencies of incoming wind frequency and structure frequency, causes structure allowable displacement exceeds result in structure collapse and devastation to human life, inconveniences, environment, and financial impacts are substantial for rebuilding the structure again. Engineers and

scientist responsibility is that to design and build based on rigorous engineering study considering aerodynamics aspects during the design phase, ensuring that rebuild structure can stand against extreme natural forces and effects events such as wind, earthquakes, and aerodynamics build in design.

The aerodynamically considerations most significant such as shedding of vortices from structures and its wake and the viscous flow effects around a bluff-body produce pressure drag. The vortex shedding occurs on each side of the wake of the cylinder as shown in the Figure 1. These vortices are named Karman Vortex Street, in honor of von Karman.

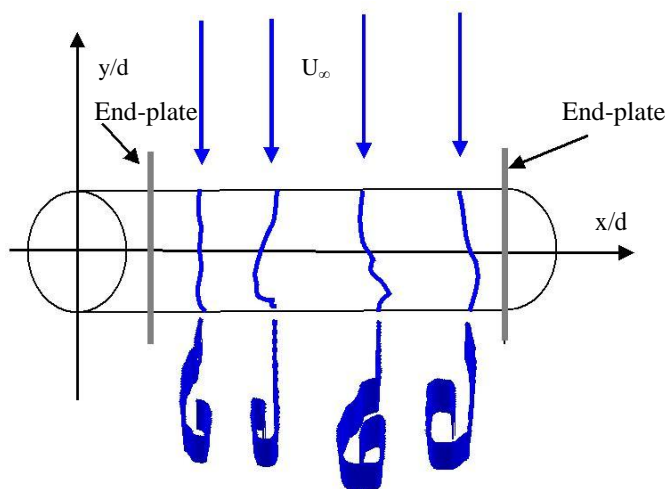


Figure 1: Roll up shedding-vortices from shoulders of a circular cylinder.

2.1. Brief Historical Review of Vortex Shedding from a Circular Cylinder

It was Strouhal who observed stretched wires singing when subjected to wind. He was the first to establish a relationship between the frequency of shedding vortices from wires and wire diameter and frequency by expressed by,

$$f_s \propto U_\infty / d \quad (2)$$

The proportionality constant, $\propto = St$

Then, we can write the equation (2),

$$f_s = St U_\infty / d \quad (3)$$

We can solve for St from equation (3),

$$St = f_s d / U_\infty \quad (4)$$

where,

f_s = Frequency of trailing vortices or vortex shedding frequency

d = Wire diameter

U_∞ = Free stream wind velocity

The equation (4) tells us when a wire is placed in a steady flow stream, trailing vortices shed from top and bottom of the wire is a function of the wire diameter and wind velocity. The alternatively shed vortex-shedding produces fluctuating pressure forces and can be easy measured in laboratory setting.

Later on Roshko [16] at Caltech conducted experiments with a circular cylinder from Reynolds number in stable range between $40 < Re < 150$; transition range $150 < Re < 300$; and irregular range $300 < Re < 10^4$. He observed that for stable range St (Re) is "rapidly rising", in the irregular range St (Re) remains "constant", and in the transition range St (Re) is "unstable." Therefore, by his experiments he showed that indeed St(Re) remains constant value at about 0.2 and is independent of Reynolds numbers in irregular range from $300 < Re < 10^4$.

Roshko later on studied Strouhal number variation aspect further by experiments with a circular cylinder measured that as Reynolds number increases beyond a critical value of 2×10^5 , the Strouhal number increases beyond known constant value, $St=0.2$. Based on that Roshko who first suggested to building a flow meter to determine flow regime when it would have a constant Strouhal number for practical purposes unless flow reached to critical Reynolds number. But, it was Gerrard [17] who hypothesis and explained the reason why Strouhal number remains constant for Reynolds number from $Re=300$ to 10^4 in Roshko's experiments because of underlying vortex formation mechanism region at two different characteristic length. One is scale of vortex formations region, the other is width of shear layers which diffuse at these Reynolds numbers. He divided the wake vortex formation region is into three parts, the one part is engulfed by growing vortices on the other part of a cylinder, then, other vortices are engulfed by the upstream shears layer diffuse into the vortices, while inside the wake reverses the vortex formation region. So, there is a physical basis of these characteristics between at low and above critical Reynolds number 2×10^5 . The implication is that at and above critical Reynolds number 2×10^5 vortex formation length changes, causing Strouhal number rapidly change, while below critical Reynolds number from $Re = 300$ to 10^4

the vortex formation length effect less pronouns, causing Strouhal number remains constant at about $St \cong 0.20$.

Later on Roshko [16] explained further details of the wake and of a vortex-shedding and provided wake flow details. Berger [18, 19] and Wehrmann [20] achieved suppression of the vortex shedding behind an oval "Bimorph transducer" that had a width of 0.69 mm and a length of 1.68 mm. Wehrmann [20] found a suppression range from $Re = 40$ to $Re = 80$ on an oblong "Bimorph transducer" cylinder.

Williams and Zhao [21] demonstrated the active control of vortex shedding behind a cylinder with a diameter of 0.6 cm at a speed of 1 m/sec and Reynolds number of 400. Far wake of cylinders have been studied by Williamson, and Prasad et al., [22, 23], Cimbalá, Nagib, and Roshko [24], Cimbalá and Krein [25], Meiburg, [26], Corke, Krull, and Mangano [27]. These studies are extensive and not reviewed here.

3. Description of the Experiment

3.1. Experiment Instrumentation Components

Schematic of the experimental setup and test section is shown in Figure 2.

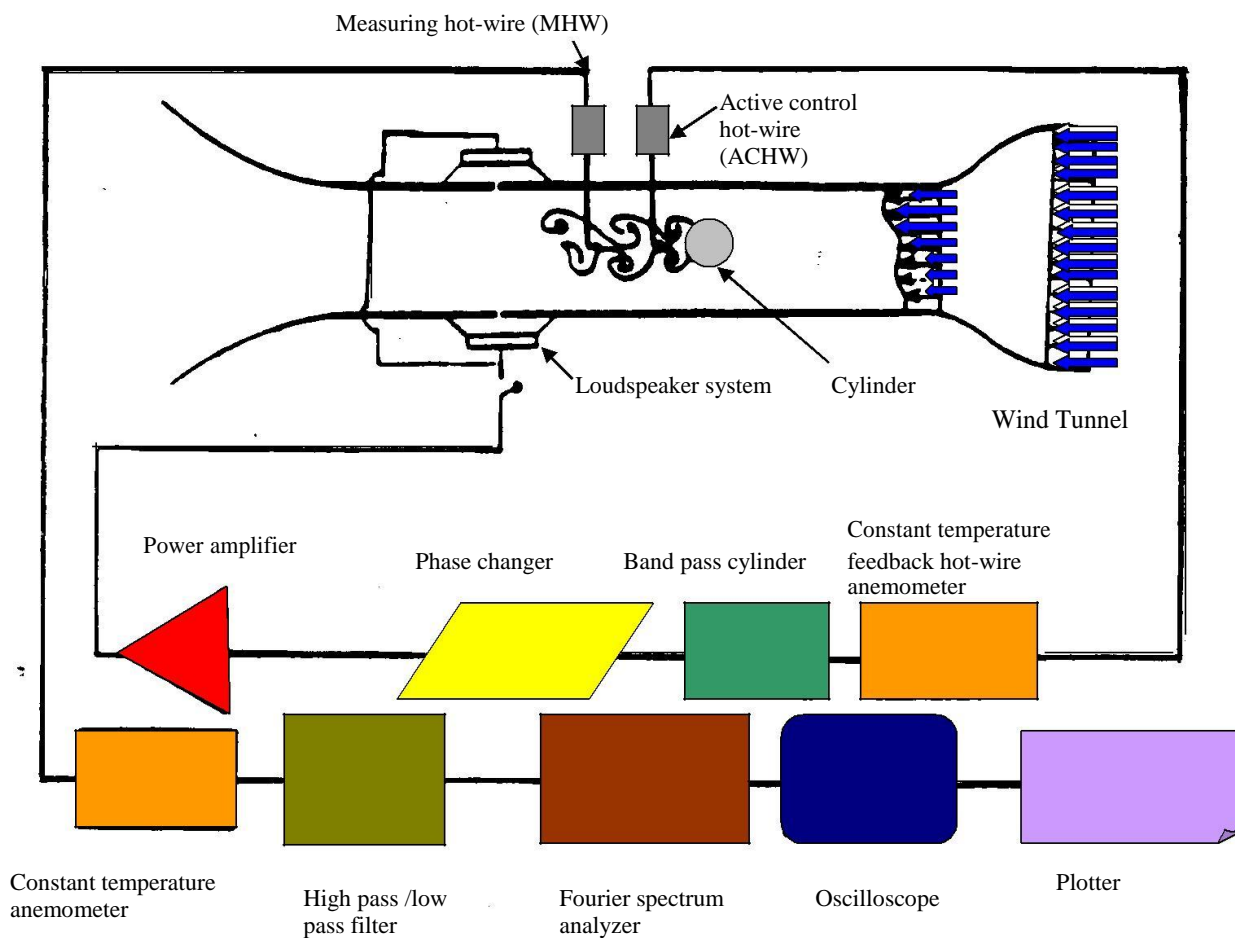


Figure 2: Top view of wind tunnel, the active control system, test section and schematics of experimental setup.

3.1.1 Wind Tunnel Set Up: This investigation was conducted in low turbulence with a turbulence intensity level of about 0.03% with an overall contraction ratio of 64 in the wind-tunnel. The test section of tunnel having width $W=0.152$ m, and height $H=0.152$ m.

3.1.2 Hot Wire-Probe: The hot-wire probe was made with a Wollaston wire with a diameter of 0.0002 inches in length. It has a platinum core and is formed from a silver-coated Wollaston wire, with a suitable length removed by etching which was operated at an overhead ratio of 1.5. The hot wire signal was high pass filtered below 4 hertz and low pass filtered above 2 Hertz.

3.1.3 Circular Cylinder: For the experiments a circular cylinder was used which made of polished brass drill rods with a diameter of 3.17 mm. All measurements were done with this. Also circular cylinder was fitted with two end plates.

3.1.4 Active Control Sub-control System: The feedback control system is shown schematically in Figure 3. Top-view of wind tunnel, the active control system, test section, and schematics of experimental setup.

4. Details of the Experiment

Prior measurements of the hot-wires were calibrated and then measurements in the wake were taken. The measurements were taken with the hot-wire probe moved in a span wise direction parallel to the cylinder at a stream wise distance from $x/d=7$ to $x/d=20$ and also vertically on center from the cylinder centerline at a transverse in the wake above the axis of the cylinder. Measurements were taken from $y/d=0$ to a distance $y/d=1/2$.

In this experiment, as in the Figure 4 show that the wind tunnel-measuring distances we defined and investigated the far wake beginning at a distance $x/d=7$ to $x/d=20$. At a distance $x/d=20$ in which the shedding of the vortices were not active-controlled and further downstream in the wake, we found that at a distance $x/d=7$, shedding of the vortices from cylinder was active-controlled.

Initially, the wake profiles in the near wake and far wake distance $x/d=7$, compared prior taking readings, to see if there was a possible influence between the measuring hot-wire and active control hot-wire. However, it was observed that placements of the active control hot-wire about half to two diameter in the upper shear layer next to the measuring hot-wire did not alter the measurements. Because, wake is very sensitive inserting active control hot-wire may affect the wake.

The observation of the signal was made after long hours of repeated and carefully selected characteristics of oscilloscope time, traced on plots to adequately describe the flow conditions that were recorded. At low turbulence level, the vortex-shedding signal was periodic in time and constant in amplitude.

The signal was taken by the active hot-wire probe at a

location in the upper shear layer of about $0.9d$ stream wise and about $0.8d$ above the cylinder axis in the wake, then band-passed, filtered, phase shifted, and fed into audio power amplifier to drive the loudspeaker. The feedback signal correctly phase shifted at about $180^{\circ} \pm 2^{\circ}$ and gain adjusted to drive a loudspeaker which was attached to the wind tunnel front wall and to the wake of the cylinder. Perturbations were imposed on the wake for active cancellation of the vortex shedding behind the circular cylinder.

In this experiment, the vortex shedding from a circular cylinder was controlled and prevented from reaching optimum level by the perturbation effect imposed upon wake by an actuator loudspeaker with an active control loop. A second hot-wire probe or measuring hot-wire was used to investigate and take measurement in the wake, while the active control hot-wire was used to control the free wake of the cylinder.

The signal detected by the measuring hot wire was processed by the signal analyzer which gave the power spectrum of the velocity fluctuations at the fundamental vortex-shedding frequency at $f=50$ Hertz. Simultaneously, the measuring hot-wire signal fed to an oscilloscope to monitor velocity fluctuations in the wake of the cylinder. While, the active controlled loop-imposed perturbations on the wake field of the cylinder. This effectively controlled and reduced the amplitude of velocity fluctuations at the active hot-wires probe location significantly.

Figure 3 shows that top view of experimental active control subsystem. This sub-control system was activated then data obtained several locations in the wake of the cylinder under control conditions.

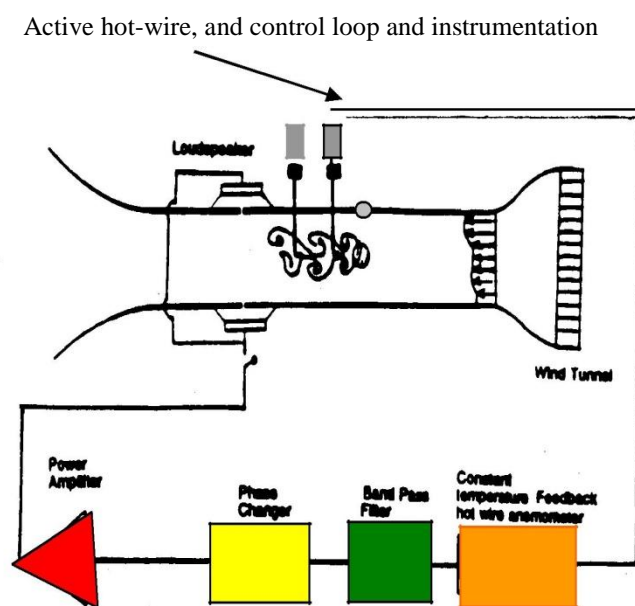


Figure 3: Top view of experimental Active control system.

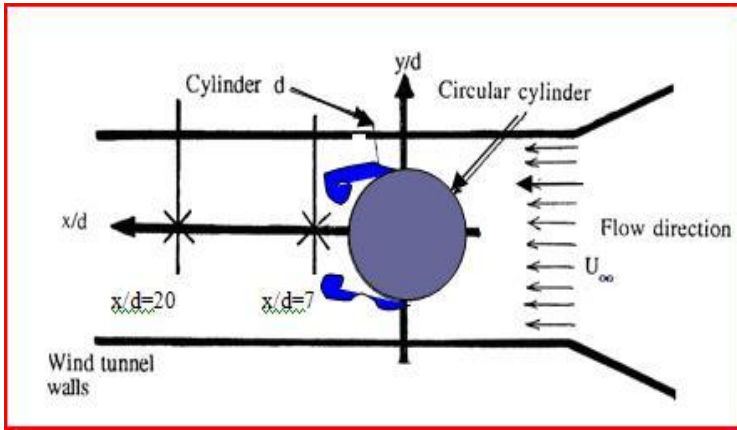


Figure 4: Top-view of wind tunnel-measuring distance at $x/d=7$ to $x/d=20$ for variation of longitudinal and vertical distances.

5. Results and Discussion

5.1 Power Spectrum Analysis

Power spectrum provides at a distance $x/d=7$ provides feedback control of shedding when following the imposed perturbations, the amplitude of velocity fluctuations was reduced in the Karman vortex street in the wake locations. It was remarkable to note how active forcing effectively reduced the amplitudes of velocity fluctuations its natural shedding, value at a distance $y/d=1/2$ respectively. When the active control system was turned-off, the shedding from the cylinder and velocity fluctuations returned to natural values in about 30 seconds. The reduction of the longitudinal velocity fluctuation was observed on the voltmeter and recorded. A dramatic reduction in the power spectra of the shedding-vortices frequency observed at first harmonics, at a fundamental vortex shedding frequency of 50 Hertz with feedback-control turned on as seen in Figure 5.

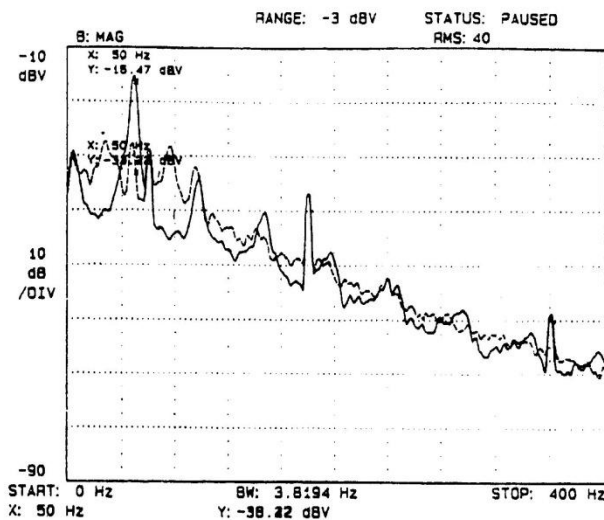


Figure 5: Power spectra of velocity fluctuations at a spanwise distance $x/d=7$ and $y/d=1/2$.

(a)_ Natural power spectrum (b)...Active-controlled power spectrum.

Furthermore, Figure 5 show that, the natural power spectra of the shedding-vortices showed 15.47 dBV. However upon activation of active control, this wave pattern and frequency drastically changed. A dramatic reduction in the power spectra of the shedding-vortices frequency of 32.22 dBV of first harmonics, at a fundamental vortex shedding frequency of 50 Hertz with feedback-control turned on at vortex shedding frequency 16.75 dB, reduction is achieved. This is interpreted as large-scale vortices cancellation. Also, characteristics of the wake flow change were captured on the recorded oscilloscope and time traces by a Tektronix digital oscilloscope. The time traces were plotted with a plotter at this control shedding, natural shedding at each location on the same plot as in Figure 7. It shows that fairly modulated time traces signal in (a) to a controlled and more stable time traces signal in (b). Vortex shedding signal were processed by the signal analyzer which gave the power spectrum of the velocity fluctuations reduction at the fundamental vortex shedding frequency of $f=50$ Hertz at first harmonics. Also, the power spectrum of the vortex shedding frequency dramatic reduction was observed dramatically at first harmonics. The controller phase and gain was again adjusted until reduced values on the power spectrum were recovered. When the active control was de-activated, the natural Karman vortex shedding signal on the power spectrum was recovered in approximately 30 seconds.

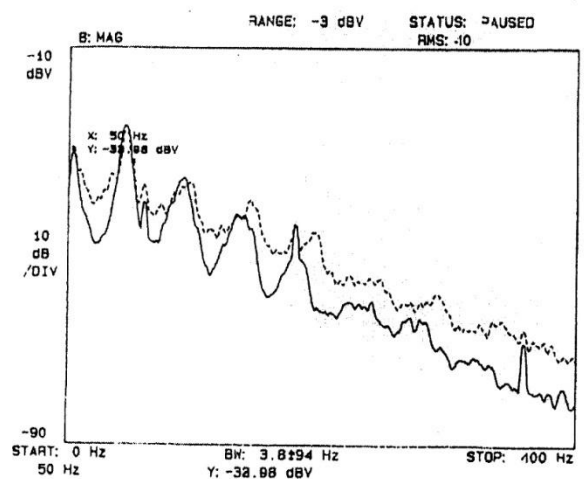


Figure 6: Power spectra of velocity fluctuations at a span wise distance $x/d=20$ and $y/d=1/2$ showing no active-control of vortex shedding achieved.

(a)___Natural power spectrum (b)...Active-controlled power spectrum.

Figure 6 shows the vertical positions of investigated fluctuations transverse the hot-wire location at a steam wise station distance $x/d=20$ and above the axis of the cylinder plane symmetry at a distance $y/d=1/2$. Upon activation of active control system, the power spectrum plots clearly show natural and active control power spectrum no change at 33.08 dBV. This is interpreted as no-active control of shedding was achieved at vortex shedding frequency 50 Hertz.

5.2 Oscilloscope Time Traces Analysis

During the experiments in addition power spectrum of shedding, we also observed of the time traces of shedding with characteristics of the wake flow changes and both locations at $x/d=7$ and $x/d=20$ locations with and without the active control conditions. These time traces were recorded on the oscilloscope as wake subject to active conditions at $f=50$ Hertz frequency characteristics of the vortex shedding. The time traces were simultaneously plotted by oscilloscope without control of shedding at a location $x/d=20$. Time traces show that there is not much change or flatting of the time traces at $x/d=20$ and further downstream locations as interpreted no shedding control was achieved in the far wake of the cylinder.

However, at a distance $x/d=7$ as the beginning of far wake vortex shedding signals processed by the signal analyzer which gave the power spectrum of the velocity fluctuations reduction at the fundamental vortex shedding frequency of $f=50$ Hertz at first harmonics. Also, the power spectra of the vortex shedding frequency reduction were observed dramatically at first harmonics. The controller phase and gain was again adjusted until reduced values on the power spectrum were recovered. Comparison of time traces shows that (a) for natural shedding In Figure 7, we can see clearly with active control, the shedding, the time traces are considerably controlled as in (b) compared to (a) where time traces signal is modulation mode. This is interpreted as that the vortex shedding controlled at a distance $x/d=7$ of the beginning of the far wake as defined herein.

On the other hand at a location $x/d=20$ for far wake the shedding spectrum shows that the active control is not possible as in Figure 8. This spectrum shows that for the far wake no-control is possible, thereafter from x/d for further downstream locations in the wake.

We have also captured time traces of shedding by Tektonix oscilloscope both at a location $x/d=7$, here control is possible, and $x/d=20$ and further downstream locations control is not possible. The investigated locations and hot-wire positions are shown in Figure 4.

It is important to note that a small active controlled signal from the cylinder wake was capable of controlling large velocity fluctuations and reduced amplitudes of longitudinal velocity fluctuations in the boundary layer of the circular cylinder so that, we achieved a significant shedding control of the first mode at vortex-shedding frequency.

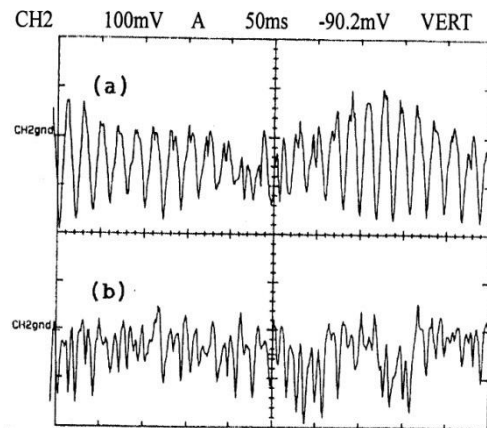


Figure 7: Oscilloscope time traces of velocity Fluctuations of far wake distance $x/d=7$ and $y=1/2$.

(a) Natural time traces; (b) Active-controlled time traces. Figure 7 shows oscilloscope the time traces of fluctuations.

It is clear that the velocity fluctuations are intermittent modulation between the two-modes. As fluctuations undergo irregular jumps to a slightly regular mode, an irregular state and finally back to an almost regular mode as in (a). Periodicity characteristics of fluctuations between the two modes are clearly apparent. When, the active control was tuned on, the fluctuations were more stabilized, indicating that velocity fluctuations large scales were controlled as in (b).

On the other hand oscilloscope time traces as shown in Figure 8, clearly, time traces of shedding at a location $x/d=20$ with active control turn on, the shedding was not possible as in (a) and almost identical to shedding with natural conditions as in (b). Oscilloscope time traces of velocity fluctuations far wake distance shown in Figure 8.

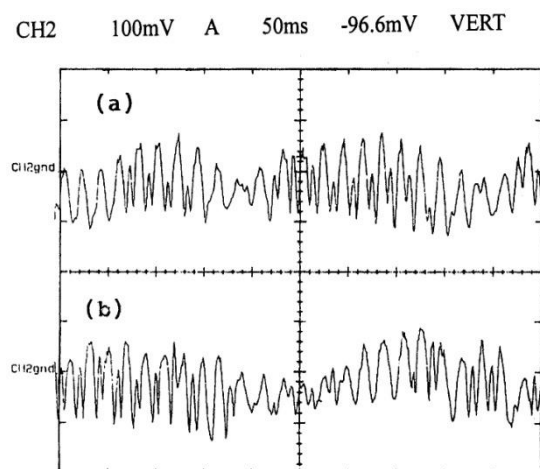


Figure 8: Oscilloscope time traces of velocity fluctuations of far wake distance $x/d=20$ and $y/d=1/2$. (a) Natural time traces; (b) Feedback-not-controlled time traces.

6. Conclusion

We examined the active control of vortex shedding in the beginning of a far wake, and far wake of a cylinder in a wind tunnel at Reynolds number 170. We conclude the following:

1. Active control shedding of the vortices achieved locally in the beginning of distance $x/d=7$ of far wake which extends to $x/d=20$ and further downstream behind the cylinder.
2. Reductions in the amplitude of fluctuation's behind the cylinder were suppressed in the beginning of far wake distance $x/d=7$.
3. In the further downstream of the far wake distance $x/d=20$ no active control shedding of vortices was achieved.
4. Significant reductions of the amplitude of the velocity fluctuations in the Karman vortex street were observed when

the active control was turned on in the beginning of far wake distance $x/d=7$.

5. When the active control was turned off, velocity fluctuations regained their amplitudes and the natural vortex shedding from the cylinder returned to the original condition within 30 seconds.
6. We have demonstrated that it is possible to set up a closed-loop active control system to control vortex shedding from a circular cylinder of transitional Reynolds number range in the wake of a circular cylinder.

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Nomenclature

- AR - Aspect ratio [$=L/d$]
d - Diameter of circular cylinder [$=3.17$ mm]
f - Natural frequency of the cylinder [$=50$ Hz]
 U_∞ -Free-stream velocity [$=80$ cm/sec]
Re -Reynolds number based on cylinder diameter [$Re=170$]
 f_s - Strouhal vortex-shedding frequency from the cylinder [$St= f_s d/U_\infty$]
 ρ - Mass density of air [$=1.21$ kg/m³]
 μ - Kinematic viscosity of air $\mu=\rho/\nu$ [$=0.150$ cm²/sec]
 ν - Coefficient of viscosity [$=0.99$ N.s/m²]
St - Strouhal number based on cylinder diameter [$St= f_s d/U_\infty$]
z - Distance in span wise direction normal xy plane
u - Longitudinal velocity component in the boundary layer
v- Normal velocity Components in the boundary layer
u'- Longitudinal root mean square (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
L - Distance between end-plates of the cylinder
w - Width of test section of wind-tunnel [$=15.2$ cm]
Y - Distance from center of cylinder in normal direction
H -Height of test sect of wind tunnel [$=15.2$ cm]

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