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Optimal active control of laminar flow over a circular cylinder using Taguchi and ANN

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ABSTRACT

Increasing the lifetime of engineering structures is dependent on the unsteady forces exerted by vortex shedding. Flow controllers can be used for suppression of vortex shedding behind the cylindrical structures. The main objective of this paper is to minimize the wake generated behind a circular cylinder in laminar flow, Re=150. Two counter rotating controllers inject the momentum in the wake region or actively control the vortex shedding. The important parameters for defining the effectiveness of flow control are the lift and drag fluctuations besides the drag coefficient. The computational methodology is based on the finite volume method using the SIMPLE algorithm. The parameters that affect on the wake control are the rotation rate, diameter of controllers, radial and the angular distances. Determining the optimum governing parameters is important. A neural network is used for finding these optimum parameters. The input data for training this neural network were provided by the Taguchi method. Moreover the Taguchi method clarified the influence of each parameter on the wake generation. At the optimal obtained conditions the drag coefficient reduced up to 99.99% and the vortex shedding suppressed appropriately.

1. Introduction

The external flow over a circular cylinder because of its tremendous engineering application has a great importance in the fluid mechanics science. Some of the applications are heat exchangers, boilers, nuclear reactors, cooling towers, electronic cooling, vortex flow meters and dividers, etc. A complete review of the researches based on flow over the cylinder is reported by Zdravkovich [1,2], Sumer and Fredsoe [3] and Tropa et al. [4].

As the flow passed over a cylinder, the separation occurs and a very strong wake region is generated. Roussopoulos [5] indicated that by increment the Reynolds number of the flow over cylinder greater than $Re = 58$, flow separated from the surface of cylinder and instabilities increased tremendously. For higher Reynolds numbers, a Karman street is established in which vortexes are shed downstream with a particular frequency. In The range, $58 \leq Re \leq 190$, the 2D vortex shedding happens and for $Re \geq 190$ again the instabilities are decreased and the wake patterns change to 3D. Some of the numerical works, have been concerned the exact and precise solution of Navier–Stokes equations for the flow over a cylinder, like Shu et al. [6] and Sengupta et al. [7]. The structure and dynamics of the vortex shedding are discussed by Maurel and Petitjeans [8], Brocchini and Trivellato [9]. Drazin [10] and Newman [11] studied the instabilities of flow over the circular cylinders. Recently, Rashidi et al. [12] performed a review on the vortex shedding suppression and wake control.

The idea of tidal energy production leads to development in capturing the vortex energies. Therefore, some of the vortex shedding studies have been concerned this subject recently. For example, Lee and Bernitsas [13] invented a new device for capturing the induced energy of vibrations from Karman Vortex Street, which is named as VIVACE converter.

The unsteady forces caused by vortex shedding can decrease the lifetime of the structures and even are one of the main reasons of their fluid induced vibrations (FIV). Blevins [14], Paidoussis [15,16] and Kaneko et al. [17] studied the fluid induced vibrations. Bao et al. [18] used a new method for correct three dimensional VIV prediction of the long flexible cylinder. They evaluate the performance of the thin strip approach for both laminar and turbulent flow regimes and studied the parameters influencing on VIV prediction.

Norgaard et al. [19] performed the optimization for prediction of the unsteady effects of flow over a cylinder, such as vortex shedding and time-varying boundary conditions using the lattice Boltzmann method.

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Nomenclature

A	The amplitude of drag/lift coefficient
C	Drag/Lift coefficient
d (m)	Controller diameter
d_D	Dimensionless controller diameter
D (m)	Cylinder diameter
f	Function
$F(N)$	Force
I	Reduction index
L (m)	Length
p (N/m^2)	Pressure
r (m)	Radial coordinate
r_D	Dimensionless radial coordinate
Re	Reynolds number
t (s)	Time
u_∞ (m/s)	Free-stream velocity
$\vec{V}$ (m/s)	Velocity vector
X	Longitudinal distance
Y	Transverse distance

Greek symbols

α	Dimensionless angular velocity
θ(degree)	Angular coordinate
μ (kg/m s)	Molecular viscosity
ρ (kg/m^3)	Density
$\vec{\omega}$ (rad/s)	Angular velocity
$\vec{\nabla}$	Derivative operator

Subscripts

C	Controller
D	Drag
L	Lift

For increasing the lifetime of the structures, controlling the wake region behind a cylinder is an engineering solution. The accessible methods for the suppression of vortex shedding downstream a circular cylinder can be classified into passive and active control techniques. Oruç [20] appropriately classified the flow control methods. Some typical samples of the active controllers are application of splitter plates, installation a small cylinder near the main cylinder, modification in the trailing edge geometry and base bleed.

He et al. [21] introduced the rotation of fluid flow around the cylinder as an active flow control way. They performed a parametric study to find the optimum forcing amplitude and frequency which they are caused to optimum drag reduction for flow around a spinning cylinder at low Reynolds numbers. Bergmann and Cordier [22] studied optimal control of the cylinder wake in the laminar regime by trust-region methods and POD reduced-order models. The control parameters were the amplitude and the frequency of the time-harmonic cylinder.

Wu et al. [23] used a flexible plate behind a circular cylinder as a controller. They showed that when the plate is shifted to the upstream of the cylinder, the regular vortex shedding is observed and when it is in the wake region, it can separate the vortex shed from the cylinder. Also, by increasing the oscillation amplitude of the plate, the drag of the cylinder can be reduced compared to the rigid plate case. Maiti and Bhatt [24] studied the effect of a small rectangular cylinder for controlling the flow past a main square cylinder. They studied the effect of the gap flow between the upstream control cylinder and main cylinder, height of the control cylinder and the distance to the wall on vortex shedding.

Chen and Chao [25] experimentally studied the effect of a fix smaller object with four different geometries, namely the square, circular, triangular, and strip cross sections, as flow controllers. They showed that the vortex shedding from the cylinder can be suppressed using these elements and the square element make the largest effective zone on wake control, whereas the triangular element has the smallest.

Ding et al. [26] performed experimental measurements of the flow induced motion of two circular cylinders with passive turbulence control cylinders in tandem. Also for numerical simulation they used two-dimensional unsteady Reynolds-averaged Navier–Stokes (2-D URANS). Ma and Kuo [27] numerically studied two dimensional laminar flow around a circular cylinder with a normal slit and indicated that the periodic blowing/suction by slit can significantly delay the boundary layer flow separation. Tammisola [28] studied optimal wavy surface to suppress vortex shedding. He showed that the optimal surface passively controls the instabilities and generate different types of control.

McClure and Yarusevych [29] studied the vortex shedding and structural loading characteristics of finned cylinder. They showed that the addition of fins leads to an increase in the mean drag and develop the wake structures. Law and Jaiman [30] studied the effect of suppression devices with faring, connected-C, disconnected-C and splitter plate shapes on wake stabilization and compare them.

To develop the application of flow controllers, some researchers offered one cylinder as flow controller. Mittal and Raghuvanshi [31], Dipankar et al. [32] and Pralits et al. [33] explained the mechanism of controlling the vortex shedding using a rotating controller in the wake region.

Afterwards, the application of two small rotating cylinders, were examined by Mittal [34], Korkischko and Meneghini [35] and Jian Sheng et al. [36]. They showed that the rotating controllers could decrease the drag coefficient and the unsteady forces on the main cylinder. The rotating controllers move the surface of boundary-layer by injection the momentum within the wake. Zhu et al. [37] studied the rate of vortex-induced vibration suppression in the presence of the two rotating controllers when they rotate in the reverse direction. Muddada and Patnaik [38] experimentally studied the role of two rotating cylinders on the vortex shedding suppression. They studied the effect of the rotation rate of the controllers at a fixed position on the separated flow. Then they studied the flow control with two rotating cylinder for turbulent flow too [39].

As it reviewed, many parameters contributing in this subject and optimizing and finding the optimum amount of these parameters are interesting. Review the literatures of flow control indicates that only a few studies have been conducted on the optimization. The artificial neural networks (ANN) and Taguchi method can be used for optimizing these problems. The Taguchi method is a systematic methodology for analyzing data so that an investigation conducted more effectively. The ANN can be used to estimate or predict the linear or nonlinear relations between the input and output parameters. Lauret et al. [40] studied the 2D modeling of turbulent flow around a cylindrical storage tank by ANN. They showed that the application of artificial neural network can reduce the time and cost of numerical works and leads a better prediction. Matsuno et al. [41] preformed parameter design optimization of plasma actuator configuration for the separation control. They tried to obtain the efficient and stable conditions in the multivariable design problem using Taguchi method. Seo et al. [42] applied the Taguchi method to derive the optimal design parameters for the grooves formed on the upper surface of a circular cylinder.

The findings of the aforementioned papers clearly indicates that vortex shedding behind a circular cylinder can actively control