Triangular Separation Distance Effects on Wave Electrical Energy Harvester Performance

M N F M Kazim, M R M Rasani, A A Abd Rahman, M Z Nuawi, Z Harun, N A M Amin
1 School of Mechatronic Engineering, Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau, Perlis, Malaysia.
2 Centre for Integrated Design for Advanced Mechanical Systems (PRISMA), Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia

E-mail: fakhzan@unimap.edu.my

Abstract. Energy scavenging has become a topic of interest toward green and environmentally friendly. Vortex generated in the wake region behind a bluff body is potential to be harvested and transform the mechanical vortices into electrical energy. Therefore, the study of the fluid flow and piezoelectric material is highly potent and a promising research area. Thus, the vortex-induced vibration (VIV) energy harvesting of two bluff bodies in a tandem arrangement is investigated using the 3D simulation. There are four sets of bluff bodies with various distance ratio, x/D from 3 to 6, were analyzed in this simulation. The coupling analysis was analyzed using ANSYS Transient Structural and computational fluid dynamic Fluent module. The triangular width, to 100 mm and the fluid average flow velocity is 1.46 ms$^{-1}$, which corresponds to Reynold number (Re) of 10k. Four types of analysis have, out; velocity vector, turbulence kinetic energy, piezoelectric tip deformation, and generated output voltage. The results show the bluff shape with spacing ratio 6 has better vortex shedding formation and turbulence kinetic energy formed on both upstream and downstream triangular bluff body. The tips mesh displacement for piezoelectric is highest at spacing ratio 6 with 7.0 x 10$^{-5}$ m. While the voltage generated is, at spacing ratio 6 with 0.2 V produced. The obtained results are essential to VIV analysis of the dual triangular cylinder with piezoelectric film, which is vital in energy scavenging knowledge.

1. Introduction

Many researchers are interested in studying about energy harvesting in a fluid using Vortex-induced Vibration (VIV). VIV is a non-linear resonance that occurs when the body oscillates in resonance system struck by the fluid flow with a certain velocity and harvest a vortex shedding frequency that is close to the natural frequency of the body [1–6]. In other words, VIV are motions induced on bodies interacting with an external fluid flow, produced by periodical irregularities or the motion producing periodical irregularities on this flow. Its occur in many fields of engineering, as mention by Williamson et al. [1] and Xu Xu et al. [5]. Xu Xu et al. [5] also mention that the effect caused by VIV is considered as an undesirable effect in the certain engineering field. This effect may lessen the structure lifetime by reduction its performance, its integrity, or fatigue loading. But, the effect of the VIV is useful in some field. It has led to many fundamental studies, many of which are reviewed by Williamson and Govardhan [1], Sarpkaya [3], and Bearman [4]. Bernitsas et al. [7]
proposed to obtain the electricity by converting the hydrokinetic energy from the ocean or river streams using VIV. Further studies in this field have been reported by Sanchez-Sanz and Velazquez [8], Barrero-Gil et al. [6], Nishi [9], Mackowski and Williamson [10], Meliga et al. [11], Stappelbelt et al. [12], Song et al. [13], Mehmood et al. [14] and Dai et al. [15, 16].

On the other hand, the study of piezoelectric in the VIV in the airflow have been carried out by many researchers. Mehmood [14] has carried out scientific research on VIV of a circular cylinder with piezoelectric energy harvester on Re number between 96 and 118. Gao [17] has experimented laminar and turbulence flow for piezoelectric energy harvester system. He also proposed to examine the blunt-body with different cross-section area in the VIV. Dai [16] focus his study on the circular cross-section cylinder based on the base excitation and the VIV. The VIV enhance study in the wind have been testified by Zhao [18], Sirohi [19,20], and Abdelkefi [21]. The idea is to convert the kinetic energy of the incoming fluid flow into the oscillatory mechanical energy via VIV.

The flow of the fluid can affect the solid structure; even the effect is minor. The interaction of the fluid and structure is called fluid-structure interaction (FSI). FSI is the interaction of a structure that moved or deformed with fluid flow, either internally or surrounding [22]. It is a multiphysics coupling between the fluid region and the structural region. FSI can be stable or oscillatory. In oscillatory interactions, the strain-induced to the solid structure will cause it to move and at the same time causing the strain to reduce, and the structure reappearance to its former state for the repetition process [23]. The deformations of the structure can be quite large or very small. It depends on the flow pressure and velocity and the structure material properties. To hypothetically treat the fluid-structure interaction associated with VIV, this study adopts wake oscillator model [2]. Tamura and Matsui [24] and Nishi et al. [25] has created a model that represents the real phenomenon of viscous flow around a moving body. They describe the change in hydrodynamic force using the equation derived by introducing the oscillatory motion of a rigid bar. Di Silvio [26] shown that the wake area of a body exposed to a steady stream displays swing – like motion and periodically lengthens and shortens alongside growth and shedding of vortices. In the models of Tamura and Matsui [24] and Nishi et al. [25], they introduce the wake oscillator is a virtual rigid bar with the mechanical motion of a bar to replace the periodic phenomenon of viscous flow. This simplification allows the model to be applied for computing hydrodynamic forces acting on a long elastic structure. Previous studies of this case have been done by Violette et al. [27] and Xu et al. [28] without computational expenses.

Achenbach and Heinecke [29] have identified six regimes for the flow around a circular cylinder which are the laminar flow, steady separated region, periodic laminar wake, subcritical regime, critical regime, supercritical regime, and transcritical regime. The classification of the flow was made based on visual observation and changes in the Strouhal number. Further studied by Zdravkovich [30], he classified the fluid flow according to the boundary layer characteristics over the cylinder surface and the separated shear layer. Fifteen types of flow regime have been classified, and Most of the previous studies of VIV have focused on relatively low Reynolds numbers, less than $3 \times 10^4$ [31]. Previously, most of the experiments conducted lie in the transition of the shear layer 2 (TrSL2) regime ($1 \times 10^3 \leq \text{Re} \leq 4 \times 10^4$). This regime is classified under the subcritical regime and according to Raghavan and Bernitsas [32], the completed transition in the shear layer of TrSL2 regime from laminar to turbulent. Therefore, in this analysis, the Reynolds number used is $1 \times 10^4$ which fall in the TrSL2.

Many works have been done to enhance the production of vortex shedding in VIV, including the efficiency of the VIV. Based on previous studies, to improve the efficiency of VIV, the mass – damping ratio should be reduced so that the amplitude and the frequency are increases [33]. The effectiveness of the VIV can affect energy extraction in the energy harvesting system, and it is one of the factors to enhance the energy harvesting system based on VIV.

Another factor that can affect the energy extraction in energy harvesting is the cross-section used in the system. The bluff body uses to create the vortex shedding. Many types of cylinder cross-section have been used to optimize the vortex shedding. According to Ordia et al. [34], the characteristics of a good vortex shedder is the stability, and the strength of the vortex generated minimum power losses and the least dependence of Strouhal’s number. All these characteristics depend on the vortex shedder geometry. Ding et al. [35] proved that a cylindrical and trapezoidal-
shaped was performed better in the movement induced excitation vortex-induced vibration (MIEVIV) harvester system out of all shapes designed. But triangular and trapezoidal are the most commonly used shapes as those are easy for manufacturing. Ordia et al. [34] observed that the wake width increases with the streamwise length of the bluff body. They also studied different bluff body shapes to find the factor that influences the performance of the blunt-body. Ding et al. [37] have studied a single bluff body VIV with different cross-section via numerical simulations. The amplitude and frequency of the VIV vary with the cross-section of the bluff body. Thus, we can improve the energy conversion efficiency of the VIVACE converter by choosing the suitable cross-section of the bluff body. Nevertheless, the triangular cross-sectional bluff body is preferable in this research.

Vortex shedding also can be enhanced by looking at the number of the bluff body in the system. In the past few years, many researchers give a great effort to improve energy harvesting by using VIV. Thus, they come up with one method of developing this system which by using two bluff bodies in tandem formation. A narrow gap separates the bluff bodies. Based on the above approach, Song et al. [37] show that there is an improvement in power production when two cylinders are combined with piezoelectric harvesters. The Strouhal number of the system also changes. Bachal and Shrivastava [38] show that dual bluff body has higher Strouhal number than the single bluff body. The increasing of the Strouhal number is due to the increase of the oscillating flow mechanisms. In another case, Zhang et al. [39] investigated the VIV response will be higher if the intensity of vortex around downstream is greater than the intensity of vortex around the upstream. In term of pressure fluctuation, Tam Nguyen et al. [40] found that the dual bluff body in tandem arrangement gives a higher pressure fluctuation behind the bluff bodies than that of the single bluff body. This finding to be valuable in the design of energy harvesting. From their work, this condition can be achieved by using a dual bluff body.

In the VIV energy harvesting model, vortex excitation can be achieved only with the deformation of the plate of the energy harvester device. The flow shedding that excites VIV on the plate can be generated by installing the bluff body upstream of the system [41], and the position of the piezoelectric film is at the downstream. Ordia et al. [34] that studied the vortex shedding using the visualization method. They show that visualization of the vortex flow can help us to understand that the piezoelectric film should be located at the vortex formation length for a particular body. Still, this research does not state the specific location of the piezoelectric film. But, Bachal and Shrivastava [38] have stated the location of the piezoelectric film in their experiment. They specify the position of the piezoelectric film is 3 mm behind the bluff body.

However, this analysis will focus on dual triangulate bluff body that arranges in tandem formation with the piezoelectric film placed downstream. The analysis will perform in a wind tunnel environment and air as a test medium. The simulation run in ANSYS 17.0 using two modules; Transient Structural and Fluid Flow (Fluent). Both modules coupled by using fluid-structure interaction (FSI) technique. The purpose of this analysis is to look into the effect of the energy converter performance by applying the different distance between the bluff bodies.

2. Methodology

The simulation run using the fluid-structure interaction (FSI) simulation technique in ANSYS software to investigate the vibrational performance of the coupled bluff body and the piezoelectric film.

2.1. Theoretical & Navier-Stoke Equation

A reliable coupling method of FSI numerical operational is governed by the incompressible Navier-Stokes equation coupled with a transient structural model through a partitioned approach. The flow motion is governed by the incompressible Navier Stokes equation. An accelerated frame of reference attached to the cylinder is used to solve the incompressible Navier-Stokes equation. The momentum equation is added with a new non-inertial force, which is known as the acceleration’s reference frame. The governing equations of the fluid flow are given by

\[
\frac{\partial u_i}{\partial x_j} = 0
\]  (1)
\[
\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} (u_j u_i) = -\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j} - \ddot{x}_i
\]  

(2)

where \(i, j = 1, 2, 3\), \(u_i\) represent the Cartesian velocity components \((u, v, w)\), \(\rho, \nu, \) and \(p\) are the density, kinematic viscosity of the fluid, and pressure, respectively. Here, \(\ddot{x}_i = a\) is used to denote the cylinder acceleration in the cross-flow direction.

2.1.1. Basic Element

In this project, two ANSYS module was used, which are Transient Structural and Fluid Flow (Fluent). In the Transient Structural module, the piezoelectric film is analyzed in terms of its deformation, total velocity, energy probe, and voltage. These characteristics generated to analyze the performance of the energy converter device. The total deformation shows the deflection of the film when the flow strikes its total velocity shows the speed of the deflection. Lastly, the energy probe and the voltage show the power generated during the analysis. For Fluid Flow (Fluent), this module is used to analyze the flow of the air. Specifically, this analysis is to analyse the vortex shedding according to the different distance of the bluff bodies.

2.1.2. Geometry

The model of the energy harvesting system was developed in a 3D model. The bluff body in this analysis is limited to the triangular cylinder shape. The dual bluff bodies arranged in the tandem formation. The piezoelectric as an energy converter device placed behind the second bluff body, as shown in Figure 1.

![Figure 1. Vortex-induced vibration energy converter system](image)

The characteristic length, \(D\) fix at 0.1 m. The separation length, \(x\) is various, as shown in Table 1, to optimum ratio of the separation length to the characteristic length, \(x/D\). While distance \(b\) is fixed at 0.1 m [38]. The details of the length of \(b, D,\) and \(x\) are in Table 1. In the analysis, a uniform velocity profile was applied at the inlet. Its flow along the direction of the inlet flow. The flow velocity determined using a derivation of Reynolds number formula.

\[
v = \frac{ReV}{\rho D}
\]  

(3)

The velocity, \(v\) is 1.46 ms\(^{-1}\) equivalent to Re number 10k, \(V\) is \(1.789\times10^{-5}\) kgm\(^{-1}\)s\(^{-1}\), \(\rho\) is 1.223 kgm\(^{-3}\) and \(D\) is 0.1 m, is the Reynolds number in turbulent condition, dynamic viscosity and density of the air and the characteristic length of the bluff body, respectively. This analysis is considering the non-slip conditions \((v = 0\) ms\(^{-1}\)) alongside the wind tunnel’s walls, and the incompressible flow.


### Table 1. Parameter that used in the analysis

| Characteristic length, \( D \) (m) | Separation length, \( x \) (m) | The ratio between separation length and the bluff body width, \( x/D \) | \( b \) (m) |
|----------------------------------|-------------------------------|-------------------------------------------------|---------|
| 0.3                              | 0.3                           | 3                                               |         |
| 0.4                              | 0.4                           | 4                                               | 0.1     |
| 0.1                              | 0.5                           | 5                                               |         |
| 0.6                              | 0.6                           | 6                                               |         |

2.1.3. **Modeling with ANSYS**

The geometry of the model was designed in ANSYS Design Modeler. The model designed on \( z \) – plane. Then, it was extruded according to the dimension shown in Figure 3. The piezoelectric film assigned as a solid domain. While wind tunnel and the bluff bodies assigned as a fluid domain. The simulation is carried out in the fluid domain with 3 m length \( \times \) 1.5 m width \( \times \) 0.5 m height wind tunnel and air as the test medium. The dimension of the bluff body is given by \( 0.1 \) m \( \times \) \( 0.1 \) m \( \times \) \( 0.5 \) m height.

The height of the bluff body is set to be the same as the wall height to avoid the vortex shedding from the top and bottom of the bluff body. The analysis just considered the vortex shedding that directly hit the piezoelectric film horizontally.

2.1.4. **Mesh Generation**

The mesh for this analysis is generated using ANSYS build – in a meshing module. The mesh generates in both Structural and Fluent modules by focusing on the different part to run the analysis. The Structural module will be a focus on the piezoelectric film while the Fluent module will be a focus on the fluid-solid interface.

In the ANSYS Structural module, the analysis will be focused on piezoelectric film. The meshing for the model runs automatically by setting up the mesh sizing. In the sizing section, the relevance center and the span angle center were set to fine with high smoothing. The size of the element was set to default.

As a result, the structural part shown in Figure 2 possesses 200 number of nodes and 21 elements. The mesh skewness for the structure is near to zero which the average value is \( 1.3061 \times 10^{-10} \).
2.1.5. The setting of Dynamic Meshing

A fluid domain grid was applied with 0.005 m to 0.06 m of unstructured tetrahedral mesh, as shown in Figure 3. Another meshing method also applied in this domain, which is edge sizing method. This method was applied on the fluid-solid interface, the bluff body surface, and the fluid wall domain as shown respectively.

On the fluid-solid interface, all eight edges; vertical and horizontal, are selected to be mesh. The mesh type was specified to be element size. It was set to be 0.003 m of element size at all edges.

For the bluff body surface, the all vertical edges were selected, and the size of the element was specified to be 0.03 m. Finally, the fluid domain wall was also set to apply the edge sizing mesh method. All the edges of the air domain wall were selected and have been specified to be 0.05 m of the element size which generates 45,348 nodes and 248,513 elements in fluid domain mesh with the maximum skewness achieving 0.79876.

2.2. Boundary Conditions

The wall of the wind tunnel, the surface of the bluff bodies and the structural model, were established as a wall boundary. The wall boundary that set at the wind tunnel is a non-slip wall boundary, while at the structural model is a fluid-solid interface boundary. The inlet velocity is 1.46 m/s at the inlet boundary. Overall, the fluid domain has established to be a stationary domain except for the fluid and the fluid-solid interface. Both zones were established as a deforming domain and system coupling domain, respectively. Therefore, it can allow the movement of the grid when it interacts with the displacement of the structural model.

2.3. Fluid-Structural Interaction

The fluid-structure interaction (FSI) technique was used in this analysis to analyze the relation of the structural body and the fluid flow. FSI technique applied by combining two modules; Transient Structural and Fluid Flow (Fluent) module. The turbulence model applied in this simulation was the two-equation k-ε model with scalable wall function. The ANSYS System Coupling module was used to carry out FSI analysis. The FSI coupling was a steady two-way coupling approach. This approach allows the data exchange between the structural and CFD module occurred in a single coupling iteration. The converged solution was attained before moving to the next time step. The time step size was set at 1×10^{-2} s to run for 2×10^{3} s with 1 to 10 coupling iteration for each time step. A maximum of 100 repetitions in CFD solver and ten iterations in coupling solver were set for each time step.

3. Result and Discussion
3.1. Flow Structure

The flow structure of the velocity vector around the bluff bodies are presented in Figure 4. The VIV responses of upstream bluff bodies strongly influenced the responses of the downstream bluff bodies. The spacing between the bluff bodies gives effect on the vortex shedding development.

![Figure 4. The velocity vector](image)

From the observation, the different spacing ratio results in the various concentration velocity vector at the vortex shedding. Figure 4 a) and b) with spacing ratio x/D of 3 and 4 shows no shedding pattern after the second bluff body. The length of the tail of the non-shedding area is 4D. The vortex shedding starts to develop when the spacing ratio x/D is greater than 5. Spacing ratio x/D of 6 in Figure 4 d) gives the active vortex shedding, and the velocity circulation is seen at the downstream of the piezoelectric film.

The velocity contour shows the fluid flow in the system. Only Figure 4 d) shows the deflection of a fluid flow at the downstream of the second bluff body, which at the piezoelectric film position. From the observation, the piezoelectric film deflected by this flow and generate the electricity. The other figure only shows the same trend of the fluid flow. From this case, it can be concluded that the spacing ratio of the bluff body from 3 to 5 is too small.

Another factor is that the flow structure is the turbulence kinetic energy figure, as shown in Figure 5. From the observation, Figure 5 (a) and Figure 5 (b) shows that vortices are close to each other. The intensity of vortex at the downstream of the second bluff body is lower than the downstream of the first bluff body. Thus, it results in lower VIV response for the spacing ratio of 3 and 4.
Figure 5. Turbulence kinetic energy

Figure 5 c) shows that the vortex amplitude at the downstream of the second bluff body is the same as the first bluff body. However, the vortices are shorter than the vortices at the downstream of the first bluff body. For Figure 5 d) cases, the vortex shedding is almost similar. The intensity of the vortex around the downstream bluff body is higher than the upstream bluff body. Therefore, it results in higher VIV response.

3.2. Deformation of the Piezoelectric Film

The deformation of the piezoelectric film shows the performance of the power produced where the piezoelectric film is deflected by the fluid flow to generate electricity. Figure 6 shows the trend of deflection.
3.3. Voltage Analysis

Figure 6 (a), (b) and (d) shows the deformation of the piezoelectric structure decreases. An attenuation trend is observed for deflection of the piezoelectric film due to the energy exchange in the fluid-structure model. It is noticeable that the velocity circulation weakens during the whole period. The vorticity decrement is due to the rotational kinetic energy carried by the vortex disperses all the time from the beginning to the end. Figure 6 (c) shows the trend to be consistent. Figure 6 (d) shows the decreases in trend, but consistently toward the end of the simulation. The graph at the initial simulation is high because of the development of the vortex shedding. It decreases throughout the time because of the stability of the fluid flow at the downstream. However, for the spacing ratio 3 and 4, the deformation is decreased to zero because the spacing of the bluff body is too close. Thus, small vortex shedding developed after a few seconds.

3.3. Voltage Analysis

Theoretically, the distance of the bluff bodies can affect the performance of the energy converter due to the vortex shedding development. Therefore, Figure 7 is presented to show the differences in the voltage with the difference spacing ratio of the bluff bodies.

![Figure 6: The deformation of the piezoelectric film](image)

![Figure 7: Voltage Produced for Space Ratio](image)
From Figure 7, the voltage produced by Figure 7 (c) is consistent. For the spacing ratio of 3 and 4, Figure 7 (a) and (b) produced the same trend of the voltage which high voltage produced during the initial simulation but decreases throughout the time and its end close to zero-voltage produced. While spacing ratio 6 gives a better result. Although it decreases according to time, the trend shows the voltage produce consistently at the final simulation.

4. Conclusion and Recommendation

The result shows that spacing ratio 6 gives a better performance compared to the other spacing ratio. Spacing ratio 6 gives high VIV response compared to another spacing ratio, and this is because of the vortex shedding development at the downstream of the bluff bodies. The conclusion is spacing ratio 3 and 4 are too small. Thus it cannot develop a perfect vortex at the downstream of the bluff body and gives lower VIV response. Therefore, for this simulation, the dual bluff body with the spacing ratio of 6 gives better performance in developing the vortex and producing voltage.

In this research, a few distances of the dual bluff bodies are analyzed to find the optimum distance to maximize the energy converter. The simulation had not correctly done due to some unexpected issues.

References

[1] Williamson C H K and Govardhan R 2008 A brief review of recent results in vortex-induced vibrations *Journal of Wind Engineering and Industrial Aerodynamics* **96** pp 713–35

[2] Nishi Y 2013 Power extraction from vortex-induced vibration of dual mass system *Journal of Sound and Vibration* **332** pp 199–212

[3] Sarpkaya T 2004 A critical review of the intrinsic nature of vortex-induced vibrations *Journal of Fluids and Structures* **19** pp 389–447

[4] Bearman P W 1984 Vortex Shedding from Oscillating Bluff Bodies *Annu. Rev. Fluid Mech.* **16** pp 195–222

[5] Xu-Xu J, Barrero-Gil A and Velazquez A 2016 Dual mass system for enhancing energy extraction from Vortex-Induced Vibrations of a circular cylinder *International Journal of Marine Energy* **16** pp 250–61

[6] Barrero-Gil A, Pindado S and Avila S 2012 Extracting energy from Vortex-Induced Vibrations: A parametric study *Applied Mathematical Modelling* **36** pp 3153–60

[7] Bernitsas M M, Raghavan K, Ben-Simon Y and Garcia E M 2008 VIVACE (Vortex Induced Vibration Aquatic Clean Energy): A New Concept in Generation of Clean and Renewable
Energy from Fluid Flow *Journal of Offshore Mechanics and Arctic Engineering* 130 041101-041101–15

[8] M. Sanchez-Sanz, B. Fernandez and A. Velazquez 2009 Energy-Harvesting Microresonator Based on the Forces Generated by the Karman Street Around a Rectangular Prism *Journal of Micromechanical Systems* 18 pp 449–57

[9] Nishi Y, Ueno Y, Nishio M, Quadrante L A R and Kokubun K 2014 Power extraction using flow-induced vibration of a circular cylinder placed near another fixed cylinder *Journal of Sound and Vibration* 333 pp 2863–80

[10] Mackowski A W and Williamson C H K 2013 An experimental investigation of vortex-induced vibration with nonlinear restoring forces *Physics of Fluids* 25 087101

[11] Meliga P, Chomaz J-M and Gallaire F 2011 Extracting energy from a flow: An asymptotic approach using vortex-induced vibrations and feedback control *Journal of Fluids and Structures* 27 pp 861–74

[12] Stappenbelt B, Johnstone A D and Anger J D L 2016 Vortex-Induced Vibration Marine Current Energy Harvesting *Fluid-Structure-Sound Interactions and Control* ed Y Zhou, A D Lucey, Y Liu and L. Huang (Springer Berlin Heidelberg) pp 401–6

[13] Song R, Shan X, Lv F and Xie T 2015 A study of vortex-induced energy harvesting from water using PZT piezoelectric cantilever with cylindrical extension *Ceramics International* 41 S768–73

[14] Mehmood A, Abdelkefi A, Hajj M R, Nayfeh A H, Akhtar I and Nuhait A O 2013 Piezoelectric energy harvesting from vortex-induced vibrations of circular cylinder *Journal of Sound and Vibration* 332 4656–67

[15] Dai H L, Abdelkefi A, Yang Y and Wang L 2016 Orientation of bluff body for designing efficient energy harvesters from vortex-induced vibrations *Applied Physics Letters* 108 053902

[16] Dai H L, Abdelkefi A and Wang L 2014 Piezoelectric energy harvesting from concurrent vortex-induced vibrations and base excitations *Nonlinear Dynamics* 77 967–81

[17] Gao X, Shih W-H and Shih W Y 2013 Flow Energy Harvesting Using Piezoelectric Cantilevers With Cylindrical Extension *IEEE Trans. Ind. Electron.* 60 1116–8

[18] Zhao L, Tang L and Yang Y 2013 Comparison of modeling methods and parametric study for a piezoelectric wind energy harvester *Smart Mater. Struct.* 22 125003

[19] Sirohi J and Mahadik R 2012 Harvesting Wind Energy Using a Galloping Piezoelectric Beam *J. Vib. Acoust.* 134 011009

[20] Sirohi J and Mahadik R 2011 Piezoelectric wind energy harvester for low-power sensors *Journal of Intelligent Material Systems and Structures* 22 2215–28

[21] Abdelkefi A, Yan Z and Hajj M R 2014 Performance analysis of galloping-based piezoelectroelastic energy harvesters with different cross-section geometries *Journal of Intelligent Material Systems and Structures* 25 246–56

[22] Dowell E H and Hall K C 2001 Modeling Of Fluid-Structure Interaction *Annu. Rev. Fluid Mech.* 33 445–90

[23] Lavooij C S W and Tusseling A S 1991 Fluid-structure interaction in liquid-filled piping systems *Journal of Fluids and Structures* 5 573–95

[24] Tamura Y and Matsui G 1980 Wake-Oscillator Model Of Vortex-Induced Oscillation Of Circular Cylinder *Wind Engineering* ed J E CERMAK (Pergamon) pp 1085–94

[25] Nishi Y, Kokubun K, Hoshino K and Uto S 2009 *Quasisteady theory for the hydrodynamic forces on a circular cylinder undergoing vortex-induced vibration*, vol 14

[26] DiSilvio G 1969 Self-Controlled Vibration of Cylinder in Fluid Stream *Journal of the Engineering Mechanics Division* 95 347–62

[27] Violette R, de Langre E and Szydlowski J 2007 Computation of vortex-induced vibrations of long structures using a wake oscillator model: Comparison with DNS and experiments *Computers & Structures* 85 1134–41

[28] Xu W-H, Zeng X-H and Wu Y-X 2008 High aspect ratio (L/D) riser VIV prediction using wake oscillator model *Ocean Engineering* 35 1769–74
[29] Achenbach E and Heinecke E 1981 On vortex shedding from smooth and rough cylinders in the range of Reynolds numbers $6 \times 10^3$ to $5 \times 10^6$ Journal of Fluid Mechanics 109 239–51
[30] Gerrard J H 1997 Flow around Circular Cylinders; Volume 1. Fundamentals. By M. M. Zdravkovich. Oxford Science Publications, 1997. 672 pp. £120. - Journal of Fluid Mechanics 350 375–8
[31] Williamson C H K and Govardhan R 2004 Vortex-Induced Vibrations Annu. Rev. Fluid Mech. 36 413–55
[32] Raghavan K and Bernitsas M M 2011 Experimental investigation of Reynolds number effect on vortex induced vibration of rigid circular cylinder on elastic supports Ocean Engineering 38 719–31
[33] Rostami A B and Armandei M 2017 Renewable energy harvesting by vortex-induced motions: Review and benchmarking of technologies Renewable and Sustainable Energy Reviews 70 pp 193–214
[34] Ordia L, Venugopal A, Agrawal A and Prabhu S V 2013 Influence of after body shape on the performance of blunt shaped bodies as vortex shedders 7 p 6
[35] Ding L, Zhang L, Wu C, Mao X and Jiang D 2015 Flow induced motion and energy harvesting of bluff bodies with different cross sections Energy Conversion and Management 91 416–26
[36] Ding L, Zhang L, M. Bernitsas M and Chang C-C 2016 Numerical simulation and experimental validation for energy harvesting of single-cylinder VIVACE converter with passive turbulence control Renewable Energy 85 1246–59
[37] Song R, Shan X, Lv F, Li J and Xie T 2015 A Novel Piezoelectric Energy Harvester Using the Macro Fiber Composite Cantilever with a Bicylinder in Water vol 5
[38] Bachal A S and Shrivastava D R 2018 Study of Strouhal’s number for dual trapezoidal bluff body 13 p 9
[39] Zhang B, Song B, Mao Z, Tian W and Li B 2017 Numerical investigation on VIV energy harvesting of bluff bodies with different cross sections in tandem arrangement Energy 133 723–36
[40] Tam Nguyen H-D, Pham H-T and Wang D-A 2013 A miniature pneumatic energy generator using Kármán vortex street Journal of Wind Engineering and Industrial Aerodynamics 116 40–8
[41] Chin W, Ong Z, Kong K, Khoo S, Huang Y-H and Chong W 2017 Enhancement of Energy Harvesting Performance by a Coupled Bluff Splitter Body and PVEH Plate through Vortex Induced Vibration near Resonance Applied Sciences 7 p 921