An experimental investigation into a novel small-scale device for energy harvesting using vortex-induced vibration

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Abstract

Renewable energies could be a good solution to the problems associated with fossil fuels. The storage of wind energy by means of small-scale devices rather than large-scale turbines is a topic that has gained lots of interest. In this study, a compact device is proposed to harvest wind energy and transform it into electrical energy, by means of oscillations of a magnet into a coil, using the concept of vortex-induced vibration (VIV) behind a barrier. For a more comprehensive investigation, this system is studied from two viewpoints of fluid mechanics (without magnet) and power generation (with the magnet). For this purpose, an oscillating plate hinging on one side and three barriers with different geometrical shapes including cylindrical, triangular and rectangular barriers are used. In addition to the effect of barrier geometry, the impacts of various barriers dimensions, the distance between the plate and the barriers as well as inclination angle of the plate with respect to the horizon on the amplitude of oscillations and generated power are investigated. Results showed that in each case, there is a unique Reynolds number in which the frequency of vortex shedding equals to the frequency of plate oscillation and the output power from the energy harvester device is maximum. Besides, by increasing the barrier dimensions, the amplitude of oscillations increases up to three times, which leads to a higher generated power. Finally, by considering the studied parameters, the best conditions for generating energy using the VIV method are presented for design purposes. Among all the considered cases, the cylindrical barrier with the highest diameter and nearest distance to the plate led to the highest efficiency (0.21%) in comparison with other barriers.

Keywords: vortex-induced vibration, vortex shedding, energy harvesting, wind power, small-scale devices

1. INTRODUCTION

Renewable energies can be a good alternative to fossil fuels and can protect the environment from the dangers, which fossil fuels could cause. Nowadays, one of the major problems that the Earth is facing is global warming. The main factor that contributes to global warming is fossil fuel consumption, in such a way that not only human life but also the lives of all living things in the world are affected [1]. There are several sources of renewable energies, including hydroelectric, solar [2, 3], marine, geothermal and wind energies [4]. All of these options for power generation may have both positive and negative effects. Many attempts have been done to improve the performance of renewable energy systems [5–7].

In the past, only large-scale wind turbines have been utilized that indeed require higher magnitudes of wind speed. On the other hand, these turbines contain complex and expensive gearboxes and also need an expensive persistent maintenance [8]. In order to cope with the problems embedded with large-scale turbines for electricity generation from wind, several small-scale innovative devices have been designed and proposed. For instance, vortex bladeless turbines [9] and vortex hydropower harvesting devices [10] can be mentioned. In recent years, especially extensive research has been conducted on small-scale wind turbines for electricity generation.

Piezoelectrics are the most common method utilized in harvesting energy in the small scale. Li and Lipson [11] studied a
Many experiments have been carried out in connection with energy harvesting from vortices. Shukla et al. [25] investigated the effect of parameters on energy harvesting from vortices. They experimentally studied the problem of a hinged-rigid splitter in the wake of a circular cylinder in such a way that the splitter plate could rotate about the hinge at the base of the cylinder. In fact, they mainly investigated the effects of Reynolds number and the splitter plate length to cylinder diameter ratio on the rotations. They found that the splitter plate length to cylinder diameter ratio is crucial in determining the character (periodic or aperiodic) and magnitude (amplitude) of the oscillations. For small splitter plate lengths, the oscillations appeared to be nearly periodic with large amplitudes. As the splitter plate length was increased largely, the oscillations became aperiodic with much smaller amplitudes. Raghavan and Bernitsas [26] also recorded the optimum flow condition for energy harvesting as a function of Reynolds number. They found that the optimum Reynolds number lies between 10^4 and 10^5. They stressed the role of the Reynolds number on the physics of recorded oscillations as an important factor. Li and Sun [27] numerically studied harvesting vortex energy in the cylinder wake with a pivoting vane from a flow with fixed Reynolds number. The vane was pivoted at its leading edge, while the rest was unconstrained. They optimized three parameters including the gap between the vane and the bluff body, the length of the vane and the mass of the vane during their investigation. They found that local vortex dissipation along the vane and pressure gradients induced by large vortices in the wake had major contributions in oscillation. Additionally, they encountered both constructive and destructive interactions of the vortices, which had a considerable impact on the energy harvesting ability of the device.

Given the importance and cost effectiveness of energy harvesting in small-scale, a novel small-scale device for energy harvesting is proposed in this article that can generate electricity from oscillations that are caused by vortices. The main purpose of introducing this novel device is to produce electricity in the small-scale from low wind speeds. According to previous research and studies, a lot of information from the fluid dynamics point of view about fluid flow over a cylinder and vortex creation is available in the literature [28–31]. Thus, in order to use the vortexes created behind the barrier as a passive method of electricity generation, a device that is made up of a light galvanized sheet hinging from one side and being held by a spring from the other side is utilized. The performance of the device is investigated in a wind tunnel, and a magnet that is embedded with the plate, along with a coil for producing electricity, which is placed below the oscillating plate, were used. In this paper, it is tried to find the best condition to harvest the maximum power based on the fluid dynamics feature of the system. In addition to the effect of the inclination angle of the oscillator plate, the effect of barrier shapes including cylindrical, rectangular and triangular have also been studied for the first time. In other words, the effect of the geometrical shape of barriers on producing vortices and their impact on the
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Figure 1. The experimental setup.

Figure 2. Schematics of the experimental tests carried out by placing various barriers, (a) a cylinder, (b) a triangle and (c) a square.

vibration of the plate behind has been investigated. According to the mechanism of this device, in which wind power is transformed to oscillation and then oscillation power is converted to electricity, the efficiency of each step is compared to find the step that limits the harvesting energy using VIV method.

2. EXPERIMENTAL SETUP AND PROCEDURE

In order to investigate the possibility of generating electricity by oscillations caused by vortices, all tests were performed in the wind tunnel with 50 cm × 50 cm test section at Sharif University of Technology’s fluid mechanics laboratory. The air velocity was changed by adjusting the airflow through the wind tunnel blower and measured by a hot wire (Testo425) with an error of ±0.01 m/s. Also, in order to unify the wind, a metal grid was placed in the wind tunnel path.

As shown in Figure 1, the wind energy harvester device from VIV, consisted of a galvanized stainless steel plate with a length of 40 cm and 15 cm in width. This plate had a major role in oscillations during experiments. This plate was held in either horizontal or inclined (30° relative to the horizon) positions by a spring, which was fixed at the middle of the plate and near to the rear end (5 cm from the end). The spring was used for both balancing the plate’s position and avoiding unusual oscillations. The minimum and maximum spring lengths were ∼1.5 and 3 cm, respectively. The plate was also connected to a 0.5 cm in diameter wooden rod where two sides of this rod were attached to a ball bearing with an inner diameter of 0.5 cm and an outer diameter of 2 cm. This would let the plate to hinge easily from one of its ends. The bearings were also attached to the vertical walls of the frame. As it is widely known, spring stiffness and the total mass have major contributions to the vibration characteristics of the device (natural frequency). Accordingly, it has been tried to lighten the total mass of the device in order to produce larger oscillations and, consequently, attain a higher amount of electricity in the intended range of flow velocity (between 3 and 5 m/s).

Figure 2 shows the schematic of the setup containing the plate and a spring that is attached to it. A 1 cm in diameter cylindrical magnet with a power of 250 gauss was used to produce an alternating magnetic field. It was embedded in the lower part of the plate and 35 cm away from the end. During oscillations, this magnet oscillated in a coil, which was placed below the plate, and consequently, electricity was generated in the coil as a result of consecutive alteration in the magnetic field. The cylindrical-shaped coil was made in 3000 rounds with an outer diameter of 6 cm and an inner diameter of 2 cm and with a resistance of 124Ω. This coil had been co-centered with the magnet that was connected to the plate in order to avoid any collision between the magnet and the wall of the coil. The total mass of the device with and without the magnet was 230 and 80 g, respectively. After placing the device in the wind tunnel, due to the characteristics of the flow in the tunnel, not any notable oscillation or movement of the plate was observed. Therefore, by placing barriers with different shapes and dimensions such as cylinders with diameters of 9, 11 and 12 cm, triangles with dimensions of 8 cm × 8 cm × 8 cm and 15 cm × 15 cm × 15 cm and rectangles with dimensions of 8 cm × 10 cm and 15 cm × 20 cm across the wind flow, it was attempted to produce oscillation on the intended plate (Figure 2). All the barriers had a length of 25 cm and were placed at four distances of 90, 75, 60 and 50 cm from the center of the wooden rod. Barriers were placed in the flow path in a way that is depicted in Figure 2a–c. Additionally, the experiments were conducted for five different speeds of the wind flow (all between 3 and 5 m/s).

As it was mentioned earlier, the main reason of putting barriers across the wind flow was to generate vortices that could apply
Figure 3. The dimensionless amplitude versus Reynolds for various dimensionless distances of cylinder and angle of 30° with respect to the horizon: (a) \( D/L = 0.225 \), (b) \( D/L = 0.275 \) and (c) \( D/L = 0.3 \).

Figure 4. Variation in the maximum amplitude of oscillation as a function of the barrier’s size for various distances from the plate.

perpendicular forces (lift) on the plate, which led to the fluctuation and oscillation of the plate. The oscillations of the plate were imaged and measured by a 1200 fps Nikon1 J4 camera. All of the experiments were carried out for three different in shape barriers and two angles of attack (0° and 30°) with respect to the horizon and also the barriers were placed in four different distances in the wind tunnel with respect to the wooden rod. The amplitude of vibrations was measured in two steps: first, without connecting the magnet (without power generation) and second, by connecting the magnet to the plate (power generating mode). It should be noted that, although the flow regime in the tunnel is steady, the flow regime between the barrier and the plate, where the vortices are generated, is definitely unsteady.

3. RESULTS AND DISCUSSION

To determine the total accuracy of the experiments, all the tests were repeated three times and their average was used as the result of each test. Taking the repeated tests into consideration, the repeatability error of the tests is 5%, which is less than the discrepancy between the curves. In Figure 3a, the error bar of the tests is shown.

For a more comprehensive investigation, first, in Section 3.1, the fluctuation of the plate without concerning electricity generation (without using the magnet) is discussed, in which the wind speed and the geometric parameters that led to the best performance was obtained. In Section 3.2, the system efficiency is obtained when the electricity was generated and compared with the results of the previous attempt. Reynolds number is used in the figures in order to express the magnitude of velocity in a non-dimensional form.

\[
Re = \frac{\rho v L}{\mu}
\]

(1)

Where \( \rho \) and \( \mu \) are the density and viscosity of air, \( v \) is the velocity of airflow, and \( L \) is the length of the plate (40 cm).

3.1. Oscillation with no use of magnet

In this section, variations of the oscillations’ amplitude at the various air velocity and geometrical conditions are investigated. Finding the appropriate Reynolds number for the best performance of the system has been done in the previous studies [32, 33]. Amplitudes were measured with respect to the peak-to-peak
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Figure 5. Variation in the non-dimensional amplitude as a function of Reynolds for different inclination angles and D/L = 0.3.

distances and are presented here in a non-dimensional form (A/L). Here, the effects of the following parameters on oscillations’ amplitude are examined:

- non-dimensional distance between the barrier and the hinge (s/L)
- dimensionless size of the barrier (cylinder: D/L, triangle: t/L, square: a/L)
- the angle of the plate relative to the horizon (α)
- the shape of the barrier (cylinder, triangle and square).

In Figure 3a–c, the variation of the dimensionless amplitude is depicted in terms of the Reynolds number for the cylinder barrier when the angle of the plate is 30° relative to the horizon. As can be seen from Figure 3, all plotted graphs contain a maximum within the variation of the Reynolds number. Therefore, for each distance between the barrier and the plate, there is an optimum speed in which the amplitude of oscillation reaches its maximum value. At this optimum speed, the frequency of vortex formation becomes equal to the natural frequency of the oscillating plate, at which the resonance phenomenon occurs. In Figure 3, this optimal speed for different distances and barrier sizes are recognizable. Additionally, it is evident from the curves that, for low and high amounts of Reynolds number, the distance between the plate and the barrier did not have much effect on the amplitude of oscillations. For these amounts of Reynolds number, the amplitudes were similar and relatively low. In all three curves of Figure 3, it is observed that at the minimum distance between the barrier and the plate, the oscillation amplitude is improved for all wind speeds compared to other distances.

It can be inferred from the curves in Figure 3 that the Reynolds number in which maximum amplitude of oscillation occurred varied with the distance between the barrier and the plate (s/L). However, at low distances (s/L = 1.25), the Reynolds in which maximum amplitude occurred was not sensitive to the size of the barrier. At this distance, the highest magnitude of amplitude has occurred, approximately, at Reynolds number of 92 653 for all three sizes of the barrier. Therefore, by increasing the size (diameter) of the barrier, for a fixed non-dimensional distance between the plate and the barrier (s/L = 1.25), the Reynolds number in which the maximum amplitude occurred, remained almost constant. While according to the trend from Figure 3a–c, by increasing the size of the barrier, the amplitude of the oscillations increased and the curves shifted upward.

Variation in the maximum amplitude of oscillation as a function of the barrier’s size is plotted in Figure 4 for various distances from the plate. From this figure, the maximum amplitude rose with the increment of the size. At a fixed distance between the plate and the barrier (s/L = 1.5), the amplitude increased 80%, by increasing the size of the barrier (D/L) from 0.225 to 0.3.

To examine the effect of the inclination angle of the plate, all the previous experiments shown in Figure 3 were repeated for the horizontal condition. For the inclination angle of 0°, again a certain amount of Reynolds number was found to produce the best results. In all cases, the 30° inclination angle produced better results compared to the horizontal condition. For example, in Figure 5, for the largest barrier (D/L = 0.3) and for two different distances between the plate and the barrier, the difference between the amplitudes by switching from an inclination angle of 0° to 30° is presented. It is seen that the oscillation amplitude increased significantly by giving a 30° inclination angle to the plate, given that the vortices induced by the cylinder alternately collided below the oscillating plate at the right periods of time. The maximum of the A/L curve when the plate was tested with 30° inclination angle
was 5.3 times and 2.5 times greater than the curve of the horizontal plate for $s/L = 1.25$ and $s/L = 1.5$, respectively. In addition, by comparing maximum points in Figure 5, it can be seen that in almost all of the curves, the Reynolds number in which the maximum oscillation amplitude occurred was increased by switching from $30^\circ$ inclination angle to $0^\circ$. Hence, in the low-speed velocities, the device works more efficiently for the inclination angle of $30^\circ$.

To compare the effect of the shape of the barrier placed in front of the oscillating plate, all of the previously mentioned tests were repeated for the other proposed shapes (triangle, square). The same condition was provided for all the repeated tests in order to be able to distinguish the effect of the shape of the barrier. Therefore, Reynolds numbers, distances between the barrier and the oscillating plate and the inclination angles were all the same for each barrier shape. However, despite the barriers used with cylindrical cross-section, the barriers with rectangular and triangular shapes were used in just two different sizes, small and large. The results of using these two kinds of barriers showed that they could apply greater oscillations on an inclined plate compared to the horizontal one. Also, larger triangular and rectangular barriers produced larger amplitudes. These trends were also noted when a cylindrical barrier was used. Figure 6 shows the recorded amplitudes of oscillations while using larger rectangular and triangular barriers in terms of Reynolds number for different distances between the inclined plate and the barrier.

Figure 6 illustrates that the higher the distance, the higher the maximum amplitude is. It is unlike the cylinder barrier in which maximum amplitude occurred in less distances.

Figure 7 depicts the maximum amplitude of oscillation for each kind of barrier with respect to the barrier position. Furthermore, only the best results achieved for different kind of the barriers, without considering the effect of barriers’ size and the flow velocity, are shown in Figure 7. Indeed, as it was discussed earlier, larger barriers and inclined position of the plate produced oscillations with larger amplitudes.

Figure 7 shows that in the experimental tests of the present work, the cylindrical barrier had the best impact on the plate for producing oscillations with larger amplitudes.

**3.2. Electricity generation**

Another important parameter that could greatly influence the amount of generated power in the device is the frequency of oscillations. According to the Faraday’s law of induction (Equation (2)), the rate of change in the magnetic field of a coil is directly proportional to the voltage that is induced in the coil. This means that, the greater the magnet moves within the coil, the greater the produced voltage (or power) would be.

$$V = -N \frac{d\phi_B}{dt}$$

Where $N$ is the number of coil rounds, $\phi$ is the magnetic flux, and $V$ is the induced voltage in the coil.

In the previous section, just the amplitudes of oscillations have been discussed. It is obvious that the larger amplitude would not always result in larger velocity. However, if both amplitude and frequency of oscillation increase, the velocity of oscillation will also increase.

In this section, results are reported for the condition in which the magnet was connected to the plate and by means of the oscillation of the plate, the magnet fluctuated within the coil and...
Table 1. Optimum conditions for energy harvesting.

| Shape and size | A/L  | Frequency (Hz) | s/L  | Re    | Efficiency % |
|----------------|------|----------------|------|-------|--------------|
| Cylindrical   |      |                |      |       |              |
| L (D/L = 0.3)  | 0.125 | 6              | 1.25 | 119126 | 0.21         |
| M (D/L = 0.275) | 0.15  | 6              | 1.25 | 119126 | 0.15         |
| S (D/L = 0.225) | 0.15  | 6.5            | 1.25 | 105890 | 0.14         |
| Triangular    |      |                |      |       |              |
| L (t/L = 0.375) | 0.0375 | 8              | 1.25 | 92653  | 0.08         |
| S (t/L = 0.2)  | 0.025 | 8              | 1.25 | 119126 | 0.05         |
| Rectangular   |      |                |      |       |              |
| L (a/L = 0.375) | 0.0375 | 9              | 1.5  | 105890 | 0.05         |
| S (a/L = 0.2)  | 0.1   | 8              | 1.875| 105890 | 0.14         |

led to generate electricity by changing the magnetic field in the coil. By measuring the induced voltage and the coil resistance, the induced electric power was measured as follows.

\[ P_{\text{electrical}} = \frac{V_{\text{rms}}^2}{R} \]  

(3)

Where \( V_{\text{rms}} \) is the root mean square voltage and is equal to \( \frac{V_{\text{peak to peak}}}{2\sqrt{2}} \). Thus, the produced electrical power value is calculated as follows.

\[ P_{\text{electrical}} = \frac{V_{\text{peak to peak}}^2}{8R} \]  

(4)

Also, to calculate the overall efficiency of the device, the amount of produced electrical power is divided by the flow (wind) power.

\[ P_{\text{wind}} = \frac{1}{2} \rho AV^3 \]  

(5)

\[ \eta = \frac{P_{\text{electrical}}}{P_{\text{wind}}} = \frac{V_{\text{peak to peak}}^2}{4\rho AV^3 R} \]  

(6)

In the above equations, \( A \) is the projection area of the barrier perpendicular to the wind direction.

In this section, the amplitude of oscillations along with the electrical power produced by the device is presented. Furthermore, the amplitude of oscillations is compared with the previous section when no electricity was generated. In Figure 8a and b, the dimensionless amplitude and efficiency of the device in terms of Reynolds number at different distances of the cylinder (barrier) and for the inclination angle of 30\(^\circ\) and barrier size of D/L = 0.275 is plotted. As can be seen from the curves, although the weight of the plate with the magnet is 150 gr and the weight of the plate without magnet is 80 gr, the same trend shown in Figure 3 (without magnet) is observed in Figure 8. In other words, there was a velocity (Reynolds) in which the amplitude of oscillation reached its maximum. As was discussed earlier, at this Reynolds, the frequency of vortex shedding is equal to the natural frequency of the system. Moreover, the Reynolds of maximum amplitude in case of with magnet was higher than that of without magnet and the maximum amplitude, in this case, was less than that of without magnet. It was attributed to the higher weight of the system in the presence of the magnet. A point to be mentioned is that though the maximum amplitude decreased with increment of the distance between the plate and the barrier (s/L), the Reynolds of maximum amplitude was not sensitive to this distance.

As it was shown in Figure 8b, there is a Reynolds in which the efficiency of power production is maximum that is approximately the same as Reynolds of maximum amplitude. In fact, it can be inferred that the efficiency is highly dependent on the amplitude of oscillations. In addition, at near distances of barrier and plate (s/L = 1.25), the efficiency is much higher than away distances.

Table 1 shows the conditions in which and size of the barriers. It should be noted that, as it was anticipated, the best results were all achieved while the plate was used in the inclined position.

By comparing the data in Table 1 with the results of the previous section, it can be found that the amplitudes had changed noticeably after attaching the magnet to the plate. This outcome was obvious since by attaching another mass to the plate, physics of oscillation altered. The resistive force that prevents current changes in the coil is also applied in the opposite direction to the magnet movement. Furthermore, the place of attachment also could have a great impact on the oscillations. Although, as it was asserted earlier, both the amplitude and frequency should be considered for enhancing the power generation. According to the recorded data, the largest cylinder used as the barrier had the best influence on the oscillating plate and as a result, it can be regarded as one of the best options for energy harvesting for this particular device that was investigated in the present work. At the optimum condition, although the frequency of oscillations was not much high, the maximum efficiency of 0.217% was achieved. By providing these conditions, this method could be very promising for wind energy storage applications.

At last but not least, in VIV systems, converting wind energy to electricity is divided into two steps: converting wind energy to oscillations of the plate and transforming oscillation energy to electrical energy. In order to investigate the efficiency of each step and determine the step limiting the total efficiency, each step efficiency and total efficiency are defined as follows:

\[ \eta_1 = \frac{P_{\text{oscillation}}}{P_{\text{wind}}} \]  

(7)

\[ \eta_2 = \frac{P_{\text{electricity}}}{P_{\text{oscillation}}} \]  

(8)

\[ \eta_{\text{tot}} = \eta_1 \times \eta_2 \]  

(9)
where $\eta_1$ and $\eta_2$ are the efficiencies of the first and second steps, respectively. In the above equations, $P_{\text{oscillation}}$ is calculated as follows:

$$P_{\text{oscillation}} = \frac{1}{T} \int_0^T \int_0^L \rho(\omega t)^3 mndl$$

(10)

where l, m and n are the length, width and thickness of the plate, respectively, and $T$ is the period of the oscillations, $\rho$ also is the density of the plate, and $\omega$ is the angular velocity of the oscillator plate that is defined as follows:

$$\omega = B \sin \left( \frac{2\pi t}{T} \right)$$

(11)

where $B$ is defined according to the average angular velocity of the plate.

$$B = 2\pi f \sin^{-1} \left( \frac{A}{L} \right)$$

(12)

$$P_{\text{oscillation}} = \frac{\rho L^3 B^2}{12} mnf$$

(13)

Considering the condition in which maximum total efficiency has gained ($\eta_{\text{tot}} = 0.21\%$), the efficiencies of the first and second steps are 43% and 0.49% (%43 × %0.49 = %0.21), respectively. Therefore, the efficiency of converting oscillation energy to electrical energy is significantly less than the efficiency of converting wind energy to oscillation energy. In other words, the second step limits the total efficiency and needs to be promoted.

4. CONCLUSION

In this work, an innovative small-scale device was proposed to harvest energy from oscillations that are generated by vortices created behind barriers and convert this energy to electricity. For this purpose, a light galvanized plate was held by a spring in order to oscillate in a wind tunnel and a magnet was embedded with the plate to produce electricity in a coil. The effects of barrier shape, the distance between the plate and the barrier and the size of barriers on the oscillation amplitude and power efficiency were studied. Therefore, three shapes of barrier including cylindrical, triangular and rectangular with small and large sizes were utilized and experimentally investigated. The following conclusions were drawn from the following results:

• There was a Reynolds in which the frequency of vortex shedding and the natural frequency of the system were equal. In this Reynolds, the amplitude of oscillations was maximum for each case.
• As the distance between the barriers and the plate ($s/L$) decreased, the amplitude of oscillation increased for cylindrical barrier.
• By increasing the size of the barriers, the amplitude of the oscillations increased. At a fixed distance between the plate and the barrier ($s/L = 1.5$), the amplitude increased by 80% as the size of the barrier ($D/L$) increased from 0.225 to 0.3.
• By comparing the maximum amplitude in non-inclined (0°) and inclined positions (30°) of the plate, it was shown that oscillation amplitude increased significantly by giving a 30° inclination angle to the plate, given that the vortices induced by the cylinder alternately collided below the oscillating plate at the right period of time. For $D/L = 0.3$, the maximum of the $A/L$, when the plate was stated with 30° inclination angle, was 5.3 times greater than the horizontal state.
• The Reynolds number in which the maximum oscillation amplitude occurred was reduced by switching from 0° inclination angle to 30° inclination angle.
• The barriers with larger sizes ($D/L$) were the best barriers to be used in terms of oscillation amplitude produced.
• The cylindrical barrier had the best impact on the plate for producing oscillations with larger amplitudes.
• It was found that the amplitudes change noticeably after attaching the magnet to the plate. It was due to the higher mass of the system in the presence of the magnet.
• The optimum conditions for energy harvesting in terms of maximum power generation was achieved and proposed to be used in the study and design of VIV systems. The maximum efficiency of the proposed method was 0.21% which belonged to largest cylindrical barriers with Reynold of 119126 and nearest distance ($s/L = 1.25$).
• The step related to the conversion of oscillation energy to electricity limits the total efficiency of the system, and its efficiency is slightly less than that of the step related to the conversion of wind energy to oscillation energy.

Given the potential of wind energy in the production of electrical energy, the VIV method can be used as a suitable device in the field of wind energy storage, applying the parameters considered in this research. It is worth mentioning that this technique is an applicable method to transform mechanical energy of useless winds blowing in the places such as along the highway or subway tunnel to electricity energy. On the other hand, in comparison with harvesting energy using piezoelectrics, this method is more cost effective. Besides, this method has been proposed for the first time and thus, it is a promising method that opens the window to the future studies on this field. In fact, in this research the method was studied conceptually and it is vital to improve the efficiency of this novel method, especially in converting kinetic to electricity energies step.

CONFLICT OF INTEREST

The Authors declare that there is no conflict of interest.

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