The analysis of vibrations induced by variation section vortex in tension leg platform for a floating wind turbine

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Abstract

During the previous decade, several offshore wind-farms were constructed for offshore wind energy generation showed promise as a source of green energy. However, there are several challenges to be met in the design and construction of the foundations for offshore wind turbines. The fatigue load plays an important and crucial role in the design of the supporting structures. In this paper, the vortex-induced vibrations of the tension leg platform were studied. Two types of structures namely; cylindrical Tension Leg Platform (TLP) and variable cross-section TLP were designed and studies on them were conducted to compare the advantages and drawbacks resulting from vortex-induced vibrations. Both uniform and shear flow were considered to simulate water flow through the structures. The variable cross-section TLP, which possesses outstanding mechanical properties, gave lower vortex shedding frequency compared to the cylindrical TLP for the same velocity. This is the objective desired in vortex-induced vibration.

Keywords: vortex-induced, tension leg platform, variation section

1 Introduction

With increasing population and economy, many countries began to exploit the natural ocean resources such as offshore oil and wind energy. The foundation of the wind turbine is the most important component. For its operation at increasing depths the traditional foundation fails to meet the necessary requirements. At 60m-100m, the TLP is not only economical but also stable [1].

The TLP is the vertical basis of mooring and compliant structure, similar to the combination of rigid and flexible systems. It is a complex nonlinear dynamic system. Its structural principle is producing a greater weight than force of buoyancy for offsetting the gravity and preload. Besides, the flexibility of TLP can realize the plane movement conforming to the external load. As a result the structural internal load is not needed [2, 3].

The TLP works in a complex environment. One of its serious operational problems is vortex-induced vibration. When there is an ocean current flow over a flexible cylinder, there will be a shedding vortex behind the structure because of the non-uniform pressure distribution. The vibrations in the structure will be produced by the shedding vortex because of the cross-flow and in-line flow pulse pressure. The vibration is the main factor for the fatigue of the structure [4].

Three methods are employed to study the vortex-induced vibrations. These are experimental empirical modelling and numerical simulation. Feng [5] conducted experiments on the vibrations of one-degree-of-freedom of a circular cylinder in air flow. In his study, the vibration of the cylinder was confined to the cross-flow direction where only typical lock-in phenomenon was presented. In general, when a cylinder is subjected to a flow at a high mass ratio, only two amplitude response branches exist. These are initial and lower branches. If the cylinder is placed in a flow at low mass ratios, the third branch (i.e., upper branch) is also observed. The mostly known empirical model includes the VIVA, VIVANA, SHEAR7 and VICoMo. Along with the advances in computers, the science of Computational Fluid Dynamics (CFD) developed rapidly. Anagnostopoulos and Iliadis [6] carried the out numerical studies on the 1 DOF VIV of a circular cylinder in the stream direction and found that the response of the cylinder was amplified significantly, if the oscillatory flow frequency was close to the natural frequency of the cylinder. Zhao and Cheng [7], Zhao et al [8] simulated 1 DOF VIV of a cylinder in oscillatory flows at KC=10 and 20 and found that the response of the cylinder included more than one frequency as the reduced velocity exceeded KC=8. Ding [9] studied two-dimensional vortex-induced vibration with numerical simulation method and found that the lift coefficient and drag coefficient transformation laws were functions of the Reynolds number. Willden [10] researched on the vortex-induced vibration under the shear flow and observed a new locus for the movement of the structure.

The entire published research focused on the vortex-induced vibration of cylinder. The effect of varying section did not receive the attention of the researchers. Yanqiu Dong proposed the structure of non-uniform cross section for the oil platform, without analysing the mechanical characteristics for the structure. In this paper wake pattern lift and drag were compared for the cylindrical and cylindrical-conical structures at different stream velocities.

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2 Numerical methods

The material of the TLP was steel, with ρ=7850 kg/m^3, E=2.06E+11, and Poisson ratio of 0.3. The dimensions of the TLP were: 100min length, and 2m in diameter. For the variable cross-section of TLP, the diameter was 1m-3m. There was a preload of 100N at top of the TLP. The top of TLP was fixed to the floating structure with hinged joint and the bottom was fixed with the seabed foundation. The software ICEM was used to generate the mesh. The dimensions of the domain were 80m×40m×100m. The distance from the inlet and side face to the TLP was 20m. The grid elements around the TLP were encrypted because the subdomain was complicated and not only included fluid breakdown, but also vortex shed. All of the grid elements were in form of a structured grid. The geometrical and mesh models are shown in Figure 1a and Figure 1b respectively.

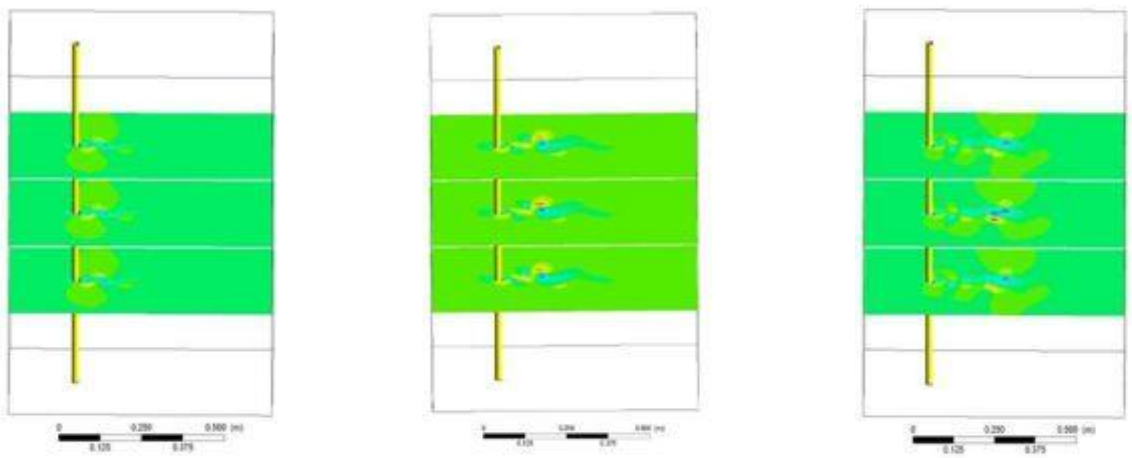
a) The geometric model b) The mesh model

FIGURE 1 The geometric and mesh models

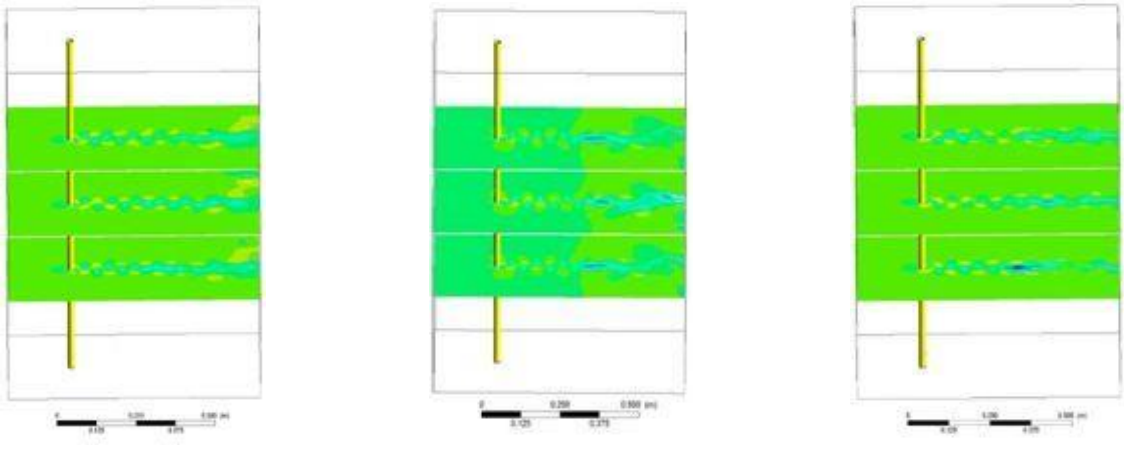
The initial and boundary conditions were set in CFX-pro, the TLP was non-slipping boundary, the top and bottom sides were walls, the left and right sides were in symmetry. In this paper, discretization format was Second-order central difference and k-ε was chosen as the turbulent model. All of the residuals were limited to 10E-4, the time step was chosen as 0.05s and the terminating time was 40s.

3 Results

In this section, three velocities 0.2m/s, 0.4m/s and 0.2y+0.2 [0<y<1] (m/s) were chosen. The results for cylinder section and the cone section were obtained. Figure 2 shows the process of cylinder section vortex shedding. The corresponding times are 1.5s, 3s and 5s, the left column of figures is for the velocity 0.2m/s and the right column of figures is for 0.4 m/s. The results obtained from the velocity contour are that Reynolds number has a significant effect on the wake. Higher the Reynolds number sooner is the vortex generation and higher is the amount of energy is stored in the vortex. Besides, the linear distance between adjacent vortexes is less at 0.4m/s than that at 0.2m/s.



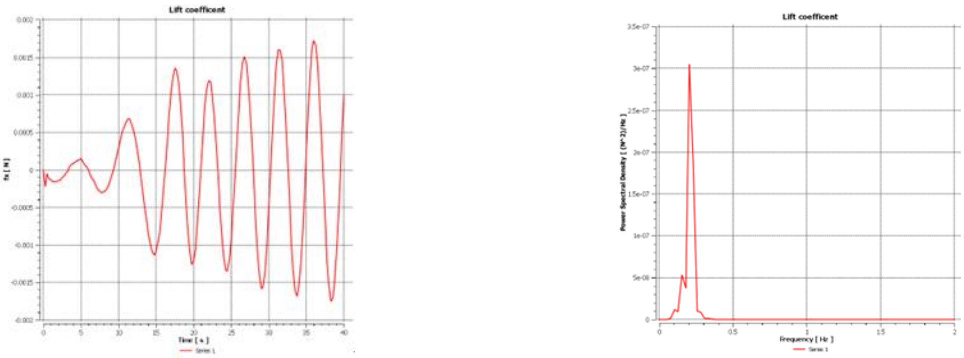
a) 1.5s at 0.2m/s b) 1.5s at 0.4m/s c) 3s at 0.2m/s



d) 3s at 0.4m/s e) 5s at 0.2m/s f) 5s at 0.4m/s

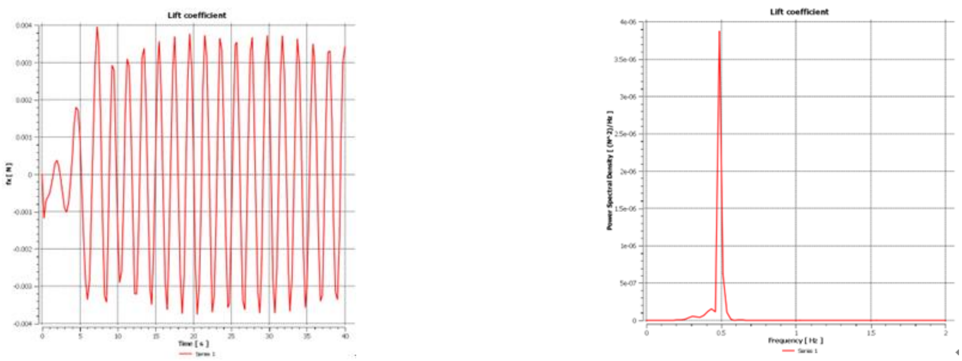
FIGURE 2 The velocity contours of cylinder TLP at different instants of time

The lift force, drag force time history curve and frequency spectrum for cylinder TLP and variable cross section TLP result are shown in Figure 3 to 10. It can be seen from these figures that when the velocity increases, the amplitude of lift force and the frequency increases. This means that the frequency of vortex shedding is accelerated. The lift force frequency is 0.251Hz at 0.2 m/s and the corresponding Strouhal number S_t is 0.23. When the velocity is 0.4 m/s, the lift force frequency is 0.498Hz and the S_t is 0.21. The above simulation results are in agreement with those in literature in which S_t was reported as about 0.2 when $300 < R_e < 1.5 \times 10^5$.



a) The time history curve of lift force b) The spectrum

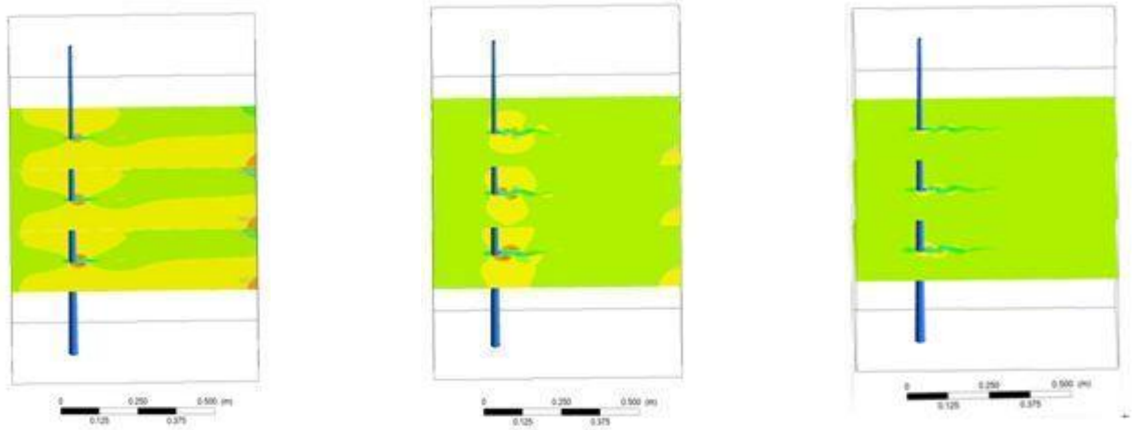
FIGURE 3 The time history curve of lift force and its spectrum at 0.2m/s for cylinder TLP



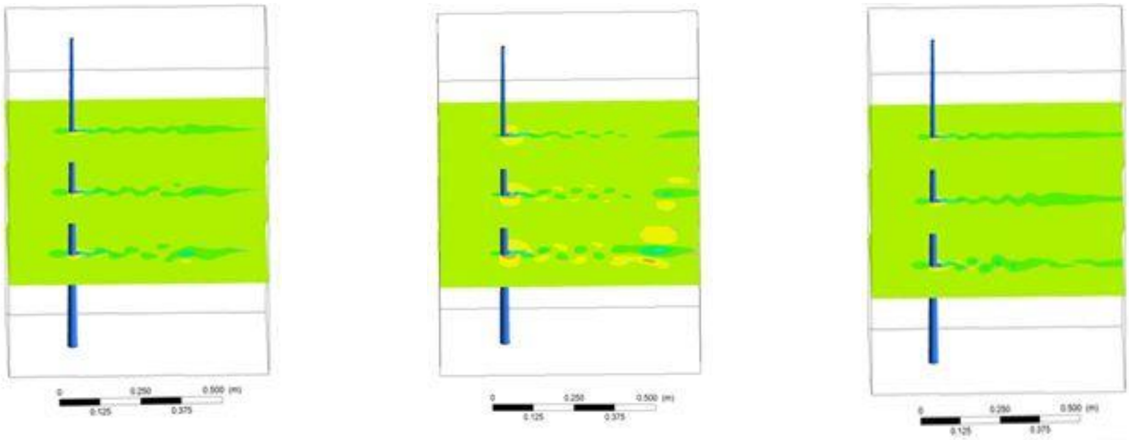
a) The time history curve of lift force b) The spectrum

FIGURE 4 The time history curve of lift force and its spectrum at 0.4m/s for cylinder TLP

The contours shown in Figure 5 below illustrate the variation of vortex at different times and positions. The effect of velocity is similar for the cylinder TLP, but vortex changes with the altitude and size of the section also has influence on the vortex. The diameter of the vortex is larger and the distance in-line between adjacent vertexes is more at bottom than at the top.



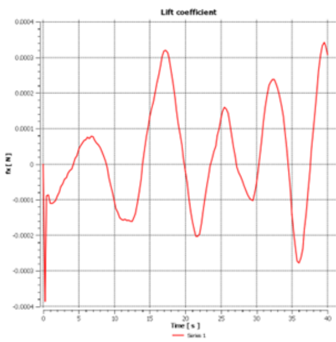
a) 1.5s at 0.2m/s, b) 1.5s at 0.4m/s c) 3s at 0.2m/s



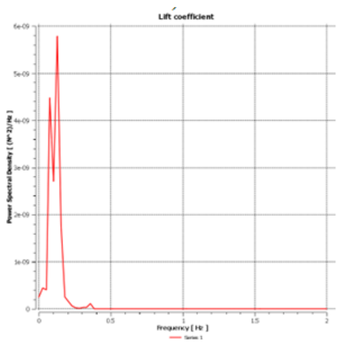
d) 3s at 0.4m/s e) 5s at 0.2m/s f) 5s at 0.4m/s

FIGURE 5The velocity contours at different instants of time for variable cross-section TLP

The time history curve of lift force in Figure 6 below shows the period of variable cross-section TLP is larger than of the cylinder TLP for the same velocity. Their frequencies are 0.11-0.198Hz at 0.2 m/s and 0.352Hz at 0.4 m/s. The stiffness of variable cross-section TLP is larger than that of the cylinder TLP. In fact, the stiffness has significant effect on the frequency of the vortex shedding. The trend of the time history curve for variable cross-section TLP is similar to that of cylinder TLP at different velocities.

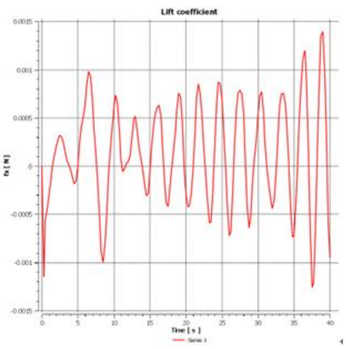


a) The time history curve of lift force

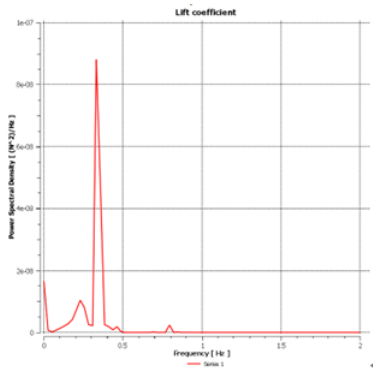


b) The spectrum

FIGURE 6 The time history curve of lift force and its spectrum at 0.2m/s for variable cross-section TLP



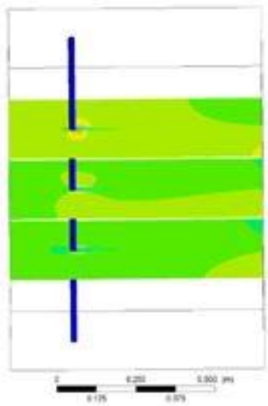
a) The time history curve of lift force



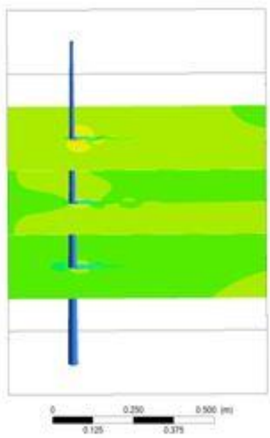
b) The spectrum

FIGURE 7 The time history curve of lift force and its spectrum at 0.4m/s for variable cross-section TLP

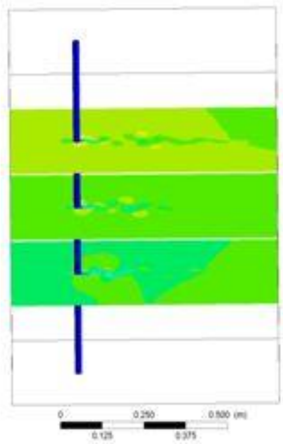
As uniform flow cannot simulate the true environment of the TLP, shear flow is considered in this section. Firstly, the velocity contours of the variable cross-section TLP (Figure 8 b), d), f)) and the cylinder TLP (Figure 8 a), c), e)) are displayed below. For the cylinder TLP, the vortexes are different at different positions. The bottom of variable cross-section TLP does not show visible vortex, but it does not affect the top. There is vortex shedding at the top.



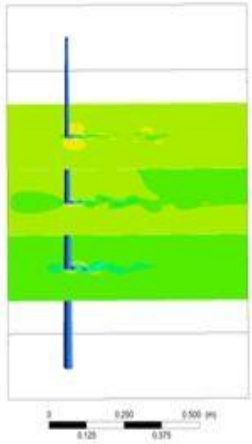
a) 1.5s at 0.2m/s



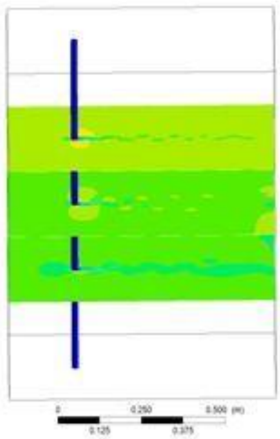
b) 1.5s at 0.4m/s



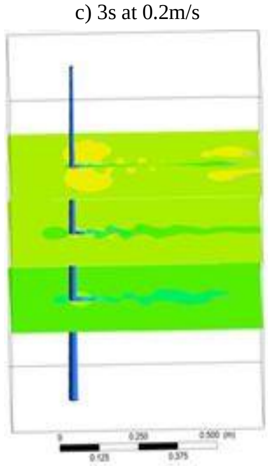
c) 3s at 0.2m/s



d) 3s at 0.4m/s



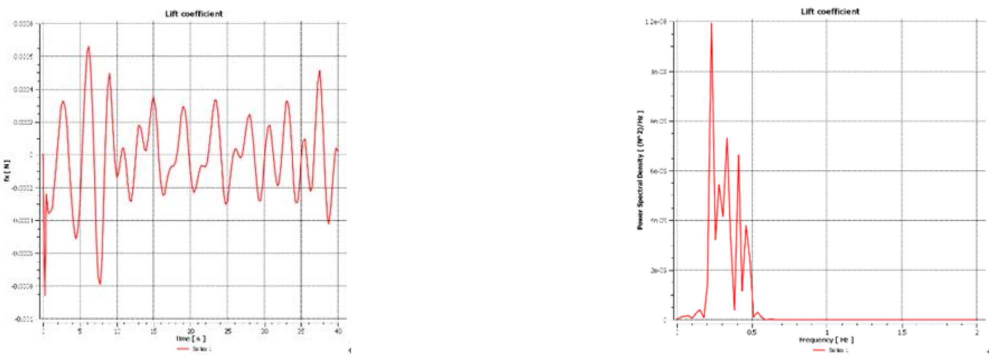
e) 5s at 0.2m/s



f) 5s at 0.4m/s

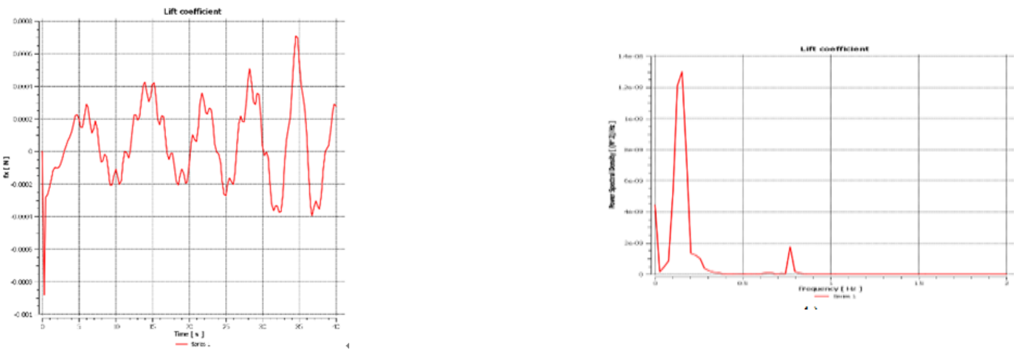
FIGURE 8 The velocity contours at different instants of time for cylinder TLP and variable cross-section TLP

In comparison to the uniform flow, for shear flow the time history curves of lift force for cylinder TLP and variable cross-section TLP change appreciably. For cylinder TLP, small oscillations are noticeable in every period. The interval of frequency for vortex shedding is wider than before. The vortex shedding is in the range of 0.2Hz-0.5Hz. For the variable cross-section TLP, there are two types of oscillations. The trend of large oscillations is the same as that of the cylinder TLP, but the frequency of every small oscillation is larger than that of cylinder TLP. Though the frequency of vortex shedding for variable cross section TLP is smaller than that of the cylinder TLP, the vortex shedding begins from 0.157Hz. The shedding is also found at a high frequency of 0.697Hz.



a) The time history curve of lift force b) The spectrum

FIGURE 9 The time history curve of lift force and its spectrum for cylinder TLP at 0.2y+0.2[0<y<1] (m/s)



a) The time history curve of lift force b) The spectrum

FIGURE 10 The time history curve of lift force and its spectrum for variable

From the Table 1 below, it can be seen that the frequency of variable cross-section TLP is always smaller than that of the cylinder TLP, although their average cross sections are equal and the volume of variable cross-section TLP is smaller than that of the cylinder TLP.

TABLE 1 The frequencies of TLP and variable cross section TLP at different velocities

	0.2(m/s)	**0.4(m/s)**	**0.2y+0.2[0<y<1] (m/s)**
Uniform cross-section (*D*=2m)	0.251Hz	0.498Hz	0.2Hz, 0.31Hz, 0.42Hz, 0.5Hz
Variable cross-section (*D*=1m-3m)	0.11Hz, 0.198Hz	0.352Hz	0.157Hz

4 Conclusions

This paper reports design of two types of TLP structures for simulation with uniform flow and shear flow. The velocity contours, lift force and drag force are illustrated to explain the results obtained. Following is the summary of final results:

1) For the two types of TLP structures studied, higher Reynolds number resulted in earlier vortex generation and higher energy storage in the vortex. Besides, the distance in-line between the adjacent vortexes is smaller at 0.4m/s than that at 0.2m/s. when velocity increases, the amplitude of lift force and also the frequency increase, which means that the frequency of vortex shedding is accelerated.

2) There are also several differences between the effects of the two types of TLP. The vortex is influenced by size of the section, that is the diameter of the vortex at the bottom is larger and the distance in-line between adjacent vortexes is more for the variable cross-section TLP than that for the cylinder TLP. Besides, a wider wake of variable cross-section is shown for the TLP. The time history curve of lift force shows that the frequency of variable cross-section TLP is smaller than that of the cylinder TLP for the same velocity though their average diameters are the same. In addition, low frequency vibration is observed in variable cross-section TLP.

3) When both types of TLP are subjected to shear flow, wake is different from the top to the bottom, and the vortex is generated earlier at the top. There are four peaks for cylinder TLP. The distribution of the peak value is amongst the uniform flow of 0.2m/s and 0.4m/s. Small oscillations arise in every period when variable cross-section TLP is subjected to shear flow. In the frequency spectrum curve, high frequency of lift force is found, but the main peak value is smaller than that of cylinder TLP.

This paper demonstrated that performance of variable cross-section TLP is better than the cylinder TLP with regard to the vortex-induced vibration. On the basis of results obtained in this study the variable cross-section TLP is recommended in engineering practice.

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