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Torsional aero-elastic oscillations of an elastically mounted circular cylinder

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Abstract. The object of this study is a system consisting of a rigid thin-walled cylinder of finite span, mounted on an elastic cantilever beam transversely to the direction of the subsonic air flow in a wind tunnel. The purpose is to identify and analyze the mechanisms of various types of aero-elastic resonant excitation of the system for the use in energy harvesting designs based on vortex-induced vibrations. The results of an experimental study are presented. In contrast to similar works with a similar configuration of the model that performs transverse translational oscillations, we discovered previously unexplored VIVs type in which the cylinder rotates around the cantilever support.

1. Introduction

Wind power is actively developing around the world and is one of the most promising areas of alternative energy. There are a number of fundamental shortcomings that limit the range of application of traditional rotary wind turbines: the presence of rotating parts, loss of efficiency in light winds and, at the same time, severe restrictions on the maximum allowable wind speed for the safe operation of wind turbines, low power density per unit swept area, generation of environmentally harmful infrasound background, etc. Therefore, intensive researches are underway for new ways of converting wind energy into electrical energy. One of these technologies is based on the resonance phenomenon, which leads to VIVs of elastically mounded cylinders [1], [2]. For example, if a system of electrodes and ceramic disks made of piezoelectric material is placed on them, then useful power can be extracted from the oscillations [3]. The mechanisms of energy extraction, as well as the analysis of existing piezoelectric generators of electric power, are qualitatively considered in the review [4].

In this work, an experimental study of resonant self-oscillations of a circular cylinder on a transverse flexible beam was carried out. In contrast to similar works with a similar configuration of the model that performs transverse translational oscillations [4]-[7], was discovered previously unexplored VIVs type in which the cylinder rotates around the cantilever support.

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2. Problem statement, object and research method

Let us consider the following configuration: rectangular elastic beam is rigidly embedded in a massive base so that in the unloaded state it occupies a horizontal position. The other end of the beam is rigidly embedded in an absolutely rigid circular cylinder with length $\boldsymbol{L}$, external diameter $\boldsymbol{D_{ext}}$, and internal diameter $\boldsymbol{D_{in}}$ (Fig. 1.).

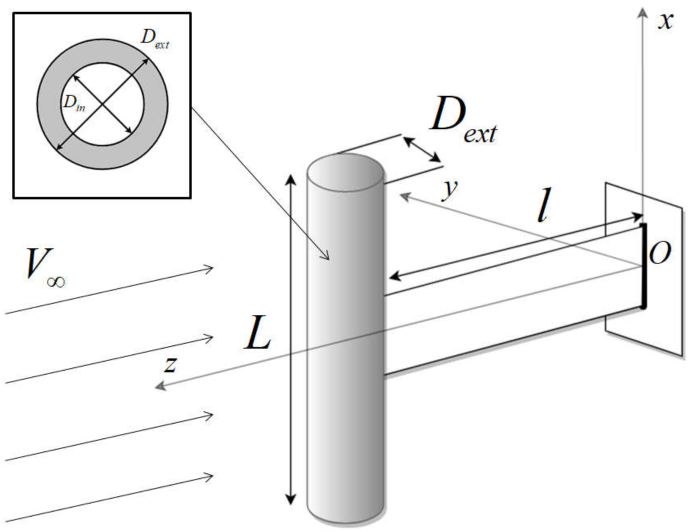
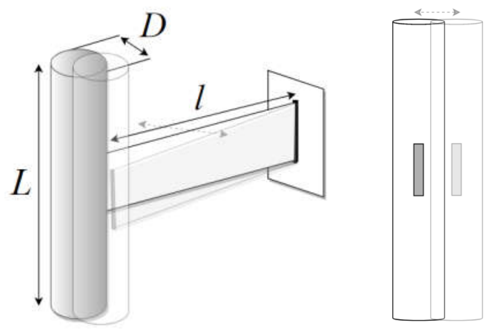


Figure 1. Circular cylinder on a transverse rectangular beam

Let us introduce a coordinate system as shown in Fig. 1. The circular cylinder can be displaced in the direction of the y axis and rotates in the y,z plane, and also rotates around the Oz axis. These motions cause the bending and torsional deformation of the beam, respectively. Thus, there are two predominant types of oscillations: bending and torsional (Fig. 2, 3). This system is excited by the uniform air flow moving opposite to the direction of the z-axis.



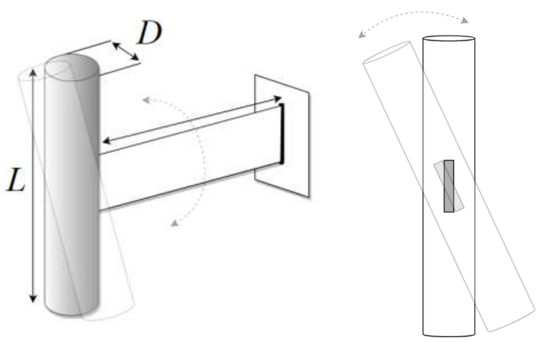
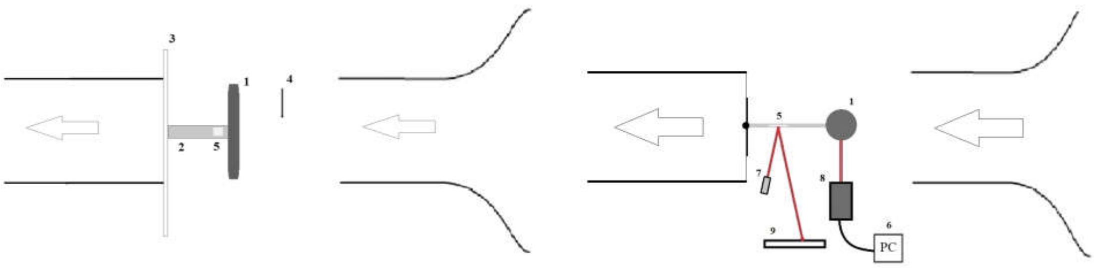


Figure 2. Bending oscillations **Figure 3.** Torsional oscillations

As the bending - type oscillations is a well-known phenomenon studied in detail by many groups, the main goal of the present study is the analysis of torsional oscillations, to our knowledge, previously unexplored.

3. Experimental equipment

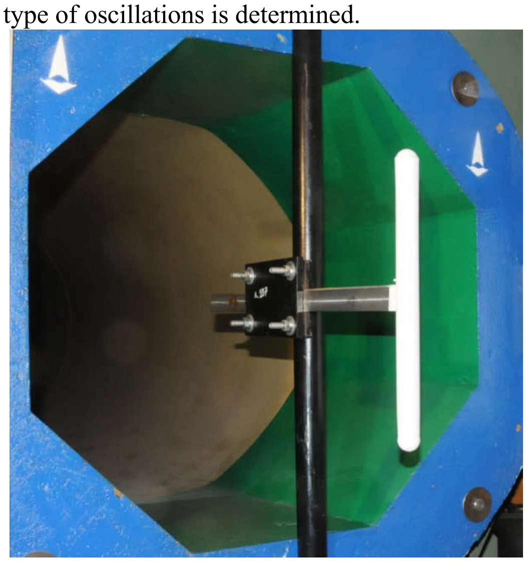
Experiments were performed in the Institute of Mechanics of Lomonosov Moscow State University in a wind tunnel A-10 with an Eiffel chamber and an open test section. The design of the model provides for changing the beam length to change the natural frequencies. To minimize the influence of the massive support, beam length is chosen in such a way that its length compared to the diameter of the cylinder was not less than 5 times.



(a) (b)

Figure 4. Experimental scheme; (a) – side view; (b) – top view;
1 – circular cylinder; 2 – rigidly embedded beam; 3 - rigid massive base; 4 – hot - film anemometer;
5 – mirror; 6 – PC; 7 – laser pointer; 8 – triangulation; 9 – screen

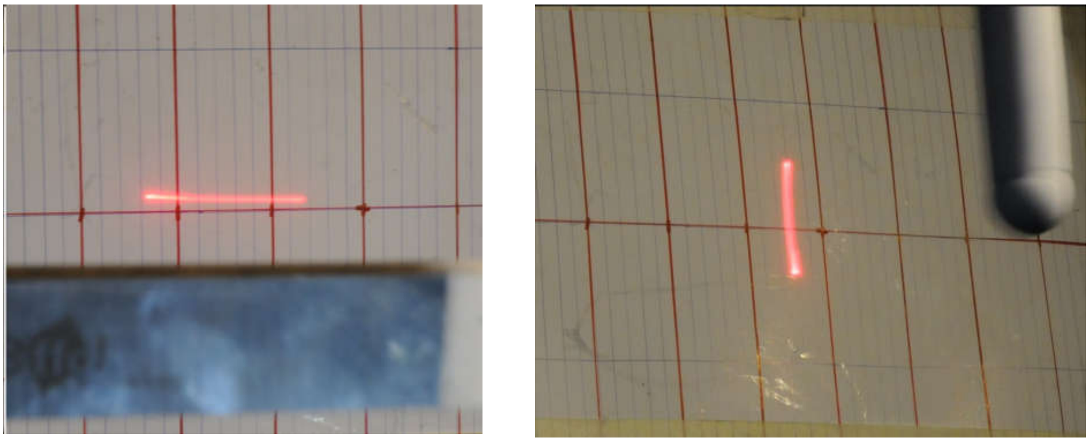
To measure the frequencies of natural oscillations and deviations from the equilibrium position of the system, a triangulation laser sensor RIFTEK RF603 is used (Fig. 4, 5 (b)). The sensor is located at the level of the top of the cylinder. A hot - film anemometer AR866 (Fig. 4, 5 (c)) is installed in the undisturbed flow to measure the flow speed in such a way that it does not affect the flow. To identify the type of oscillations, a mirror is installed on the elastic beam (see Fig. 4, 6.). According to the trace of the laser beam reflected from the mirror (horizontal - bending, vertical - torsional), the predominant type of oscillations is determined.



(b)

(a) (c)

Figure 5. Experimental equipment; (a) – circular cylinder on a transverse rectangular beam in a wind tunnel; (b) – triangulation laser sensor RIFTEK RF603; (c) – hot - film anemometer AR866;



(a) (b)

Figure 6. Laser trace reflected from a mirror mounted on a beam determines the type of oscillations: bending (a); torsional (b)

4. Scheme of the experiment

The experiment consists of three stages. The first stage consists in measuring the natural frequencies and damping rates of both types of oscillations without the flow, by disturbing the cylinder and recording the readings of the triangulation laser sensor of free oscillations. Each type of oscillation has its own way of bringing the cylinder out of equilibrium. For a bending type, the system should be deflected in a horizontal direction, for a torsional type, the cylinder should be rotated around its axis of rotation.

The second stage consists in gradually increasing the flow speed from the minimum possible velocity, and recording the readings of the triangulation laser sensor, taking into account the type of oscillations. Initially, with an increase in speed, the excitation of the bending type oscillations occurs. With a subsequent increase, torsional oscillations are excited. It should be noted that if the bending stiffness is too high, the bending oscillations are almost indistinguishable from the equilibrium state. The increase in speed is carried out until the system returns into a state close to equilibrium.

The third stage is a continuous decreasing of the flow speed. At this stage, the readings of the laser sensor are also recorded, but unlike the second stage, the recording is continuous, since this stage takes much less time compared to the second.

5. Experimental results

The constant physical parameters of the model are presented in Table 1. Measured with the triangulation laser sensor, the deviation versus time, as well as the spectrum of natural oscillations for beam length l=150mm are shown in Fig. 7, 8.

Table 1. Constant physical characteristics of model

Constant parameters				
Young's modulus of the beam material E, $Pa\ 10^9$	Shear modulus of the beam material G, $Pa\ 10^9$	Beam width a, $m\ 10^{-3}$	Beam thickness b, $m\ 10^{-3}$	Beam material density ρ, kg/m^3
224	82	33	3	8820
Cylinder material density ρ_0, kg/m^3	Cylinder external diameter D_{ext}, $m\ 10^{-3}$	Cylinder internal diameter D_{in}, $m\ 10^{-3}$	Cylinder length L, m	
2500	30	28	0.345	

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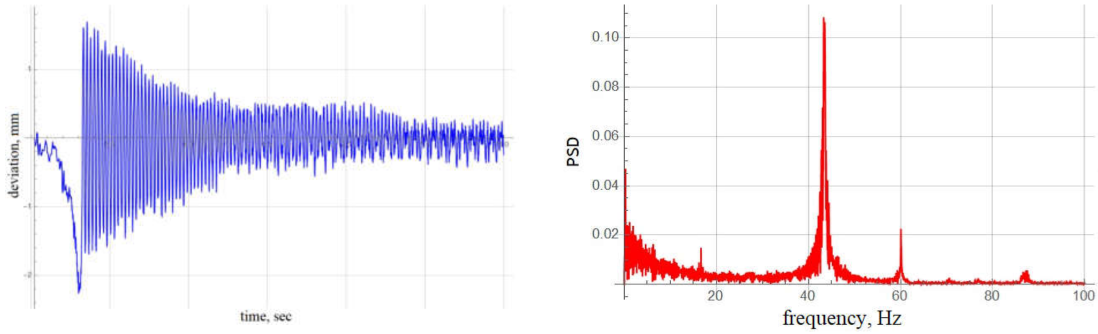
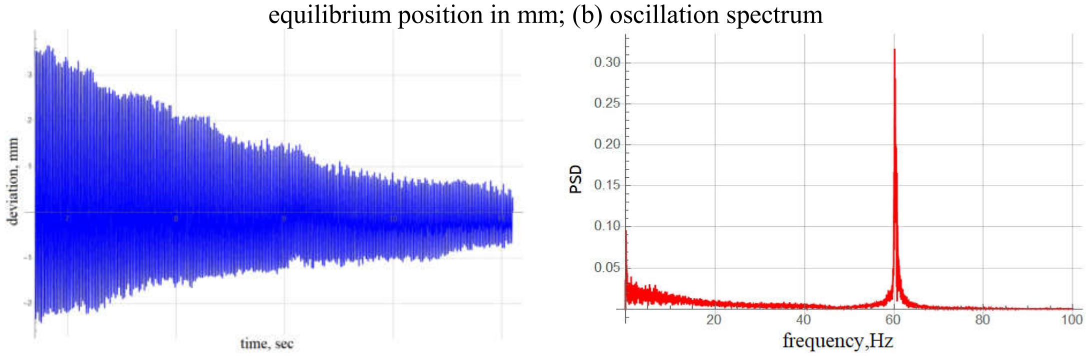


(a) (b)

Figure 7. Natural oscillations of bending type at V=0 m/sec, *l*=150mm; (a) deviation from the equilibrium position in mm; (b) oscillation spectrum



(a) (b)

Figure 8. Natural oscillations of torsional type at V=0 m/sec, *l*=150mm; (a) deviation from the equilibrium position in mm; (b) oscillation spectrum

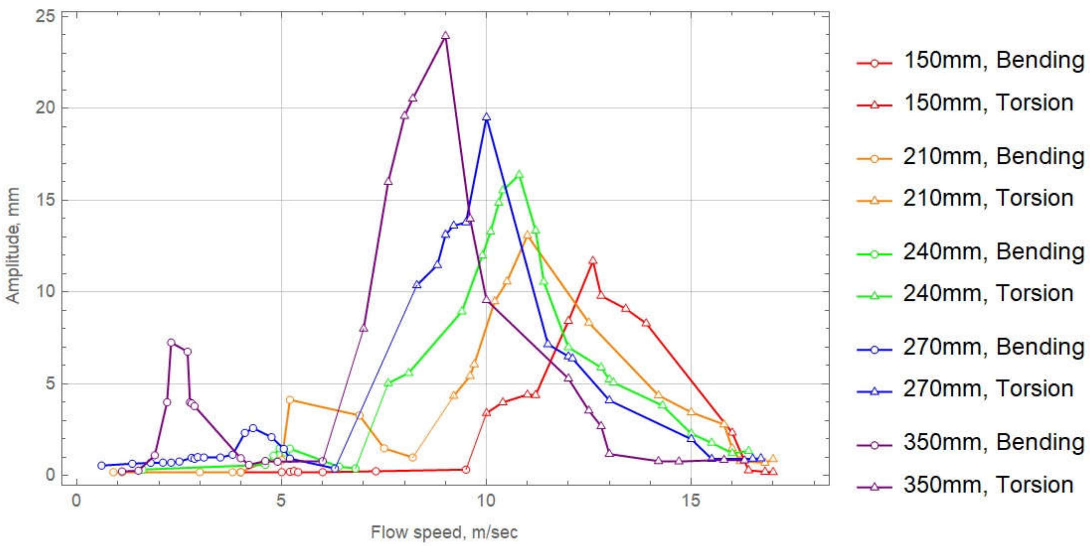
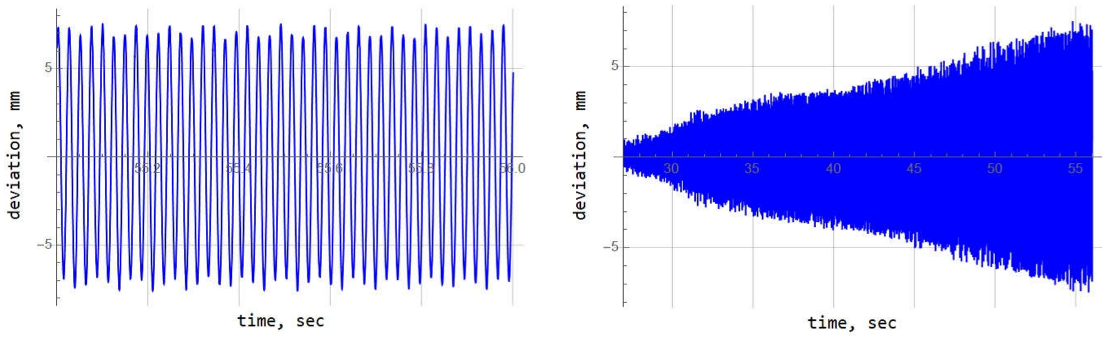


Figure 9. Oscillation amplitude (in mm) versus flow speed for various beam lengths



(a) (b)

Figure 10. Torsional type oscillations excitation at V=7.0 m/sec, *l*=350mm

As a result of experiments series with an air flow around the model the oscillation amplitudes versus the flow speed for various beam lengths was plotted (Fig. 9). The Reynolds number range based on cylinder external diameter corresponding to the response region was $5\times10^3..25\times10^3$. According to the indications of the laser reflection trace, the existence of bending and torsional self-oscillations corresponding to the resonance was proved. Initially, with an increase in speed, the excitation of the bending type oscillations occurs, with a subsequent increase, the oscillations turn into the torsional (Fig. 10). Thus, it has been established that for various natural frequencies of the system, which are determined by the beam length, there is an excitation of torsional oscillations. A set of cylinder oscillation amplitudes ratio A/D_{ext} and self-oscillation frequency f^0/f^* versus reduced velocity are shown in Fig. 11. In the present experiments, the maximum oscillation amplitude A/D_{ext} = 0.80 was obtained. It can be seen from the Fig.11 for a torsional resonance state that the characteristic reduced speed range is 6.9..7.35, which is corresponds to Strouhal number 0.144..0.136. In Table. 2, the dependences of the Strouhal numbers are given at a speed corresponding to the maximum amplitude of oscillations for both types of oscillations.

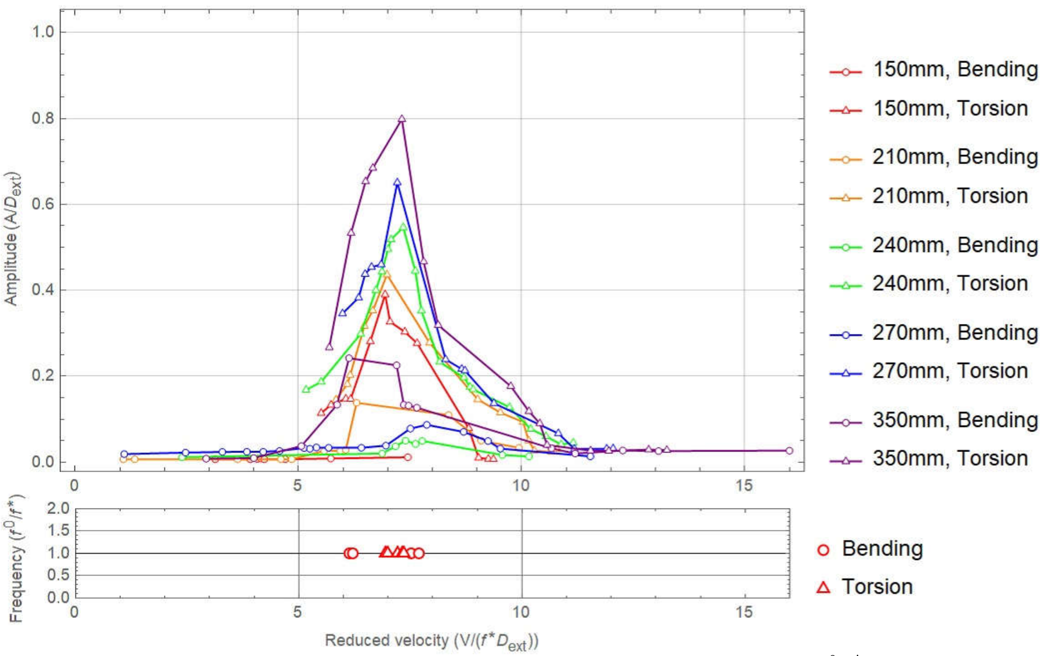


Figure 11. Oscillation amplitude ratio A/D_{ext} and self-oscillation frequency f^0/f^* versus reduced velocity

Table 2. – Strouhal numbers for both types of oscillations

l, mm	*150*	*210*	*240*	*270*	*350*
Torsional Strouhal number, $Sh_{tors.}$	0.144	0.143	0.136	0.1386	0.1366
Bending Strouhal number, $Sh_{bend.}$	-	0.161	0.133	0.13	0.163

In Fig. 12, to demonstrate the occurrence of different oscillations types, the deviation from the equilibrium position versus time during continuous decreasing of the flow speed for a beam length of 240 mm is shown. The excitation of torsional oscillations occurs first; next, with a decrease in the flow speed, the bending oscillations are excited. The red and blue parts of the graph correspond to torsional and bending oscillations, respectively.

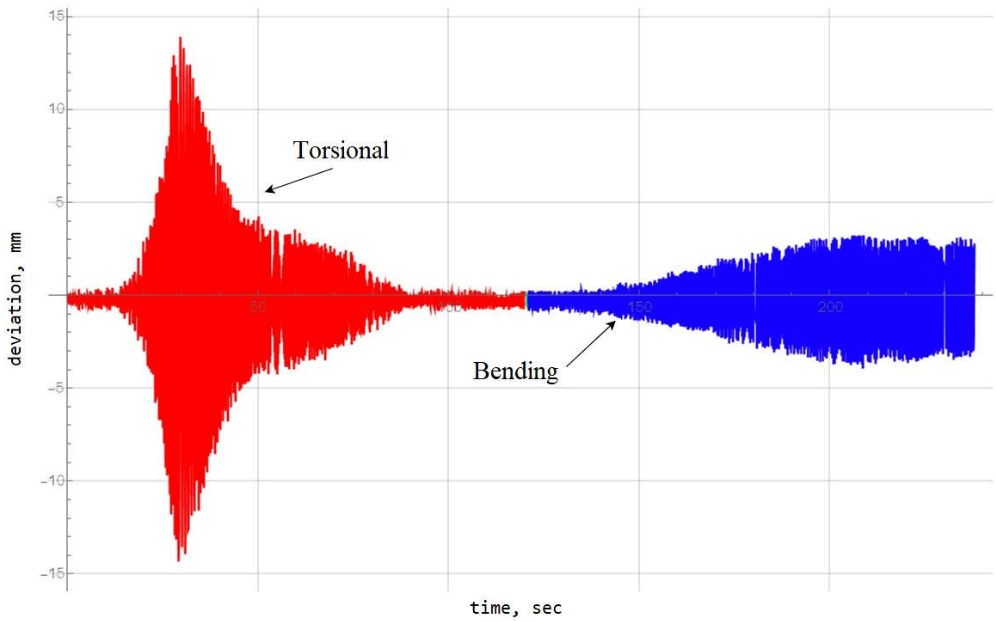


Figure 12. Deviation from the equilibrium position (in mm) versus time (sec) when decreasing the flow speed for a beam length of 240 mm. The red and blue parts of the graph correspond to torsional and bending oscillations, respectively.

6. Conclusions

The bending and torsional self-oscillations corresponding to the resonance with the von Karman vortex street are experimentally revealed. Torsional oscillations are discovered for the first time and, to our knowledge, were not observed before in VIV studies. It is shown that in the resonance torsional oscillations the higher oscillation frequency, the larger amplitude and a wider range of speeds are observed compared to similar parameters for bending oscillation. The effect of the beam length on the oscillation amplitude for both types of oscillations is studied. It has been established that for a given range of the beam lengths the maximum amplitude of torsional vibrations increases with an increase in the length of the beam.

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