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INFLUENCE OF END PLATES ON ROTATIONAL OSCILLATIONS OF A RECTANGULAR CYLINDER

R. Shmigirilov [1], A. Ryabinin [1]

[1] **Department of hydroaeromechanics, Faculty of mathematics and mechanics, St.Petersburg State University, 28 Universitetsky prospekt, Peterhof, 198504 St.Petersburg, Russia**

Abstract

Oscillations of rectangular cylinder elastically suspended in a air-flow were studied experimentally. The amplitude of oscillations measured at various cylinder lengths was shown to be affected by changes in incoming flow velocity and also by the presence or absence of end plates restricting the flow of air through the ends of the cylinder. Steady-state oscillation amplitude increases with an increase in cylinder aspect ratio. In the presence of end plates, the oscillation amplitude linearly depends on the Strouhal number. At the cylinder aspect ratio of five, the presence or absence of end plates on the cylinder has no effect on the oscillation amplitude.

Keywords: wind tunnel, steady oscillations, amplitude, end plates.

1 Introduction

The goal of this work is to study the effect of end plates used in an aerodynamic experiment on the rotational oscillations of an elastically suspended bluff body. Rotational oscillations are a significant hazard to suspension bridges [1]. End plates are typically installed to eliminate the flow of air through the ends. Thus the flow around short bodies with end plates is similar to the flow around elongated bodies. Long body cannot be directly tested due to the limited size of the test section of the wind tunnel.

In an aerodynamic experiment, end plates are affixed to the ends of the objects under study, such that the surfaces of the end plates are parallel to the mean flow velocity vector. End plates are used in experiments with wings [2], as well as in experiments with bluff bodies. An example of this approach is seen in segments of bridges [3, 4] and other bodies [5, 6, 7]. As a rule, end plates have a round or elliptical shape. The size of end plates is larger than the size of the model being studied. The presence of end plates changes various aerodynamic characteristics of models under study. Recently it was shown [8] that end plates significantly change the dependence of the coefficient of normal force of a square prism with a small aspect ratio on the angle of attack. This phenomenon leads to a decrease in the critical speed of galloping of an elastically fixed prism. In this work we studied the effect of end plates on aerodynamic characteristics of a rectangular cylinder placed perpendicularly to the flow velocity vector, by experimentally measuring the tension of the elastic spring on which the cylinder is suspended.

2 Experimental Method

Rotational oscillations of rectangular cylinders (parallelepipeds) are investigated. The thickness of the parallelepipeds d is equal to 20 mm, the width w is approximately equal to 100 mm. The length of the parallelepipeds l varies: 200, 500 and 700 mm, resulting in aspect ratios of the cylinders of 2, 5 and 7. Some experiments are performed with end plates. The diameter of each round end plate is equal to $d = 2w = 200$ mm.

Experiments are carried out in the wind tunnel AT-12 located on-premises Saint Petersburg State University. The wind tunnel has an open test section. The diameter of the outlet in the circular cross section of the nozzle is 1.5 m. The length of the test section is 2.25 m. The model is affixed in the test section with wire suspension. The diameter of the steel wire is 0.3 mm. The model can rotate around the horizontal axis that is perpendicular to the velocity vector of the air flow. A steel tail holder is affixed to the downstream end of the model. Two steel springs are attached to the holder (Fig. 1). A semiconductor strain gauge registers the tension of the lower spring.

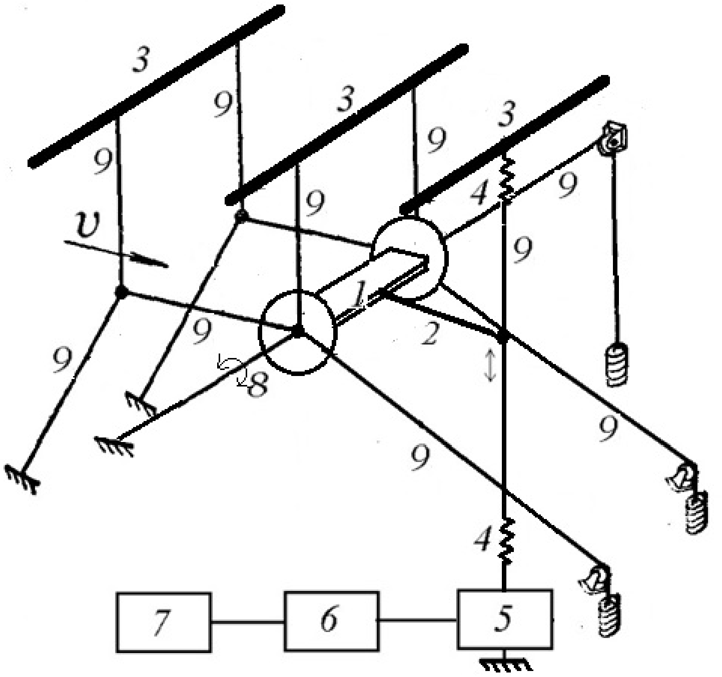

Figure 1: The sketch of the experimental setup: *1* — model with end plates, *2* — steel tail holder, *3* — immobile rods , *4* — springs, *5* — strain gauge, *6* — PC oscilloscope, *7* — computer, *8* — axis of rotation, *9* — wires.

PC-oscilloscope Velleman-PCS500A converts the analog signal of the strain gauge into a digital reading and transfers it to the control computer. Measurement frequency is 100 Hz or 1250 Hz. The duration of recording is 17 s at 100 Hz or 3.3 s at 1250 Hz. We observed that oscillation frequency does not depend on flow velocity. In the absence of flow in the test section, the oscillations of the cylinders on the elastic suspension are dampened, and the oscillation frequency remains the same as in the oscillations caused by the airflow. This means that aerodynamic forces are small in comparison with the elastic forces.

We propose that the tension of the spring in the extremes of the dependence of the signal on time is equal to the tension of the springs under the action of a constant load, causing a deviation equal to the amplitude of the oscillations. This assumption permits to relate the amplitude of the oscillations to the maximum or minimum tension force of the lower spring detected by the instrument. Two calibration experiments are carried out. In the first experiment, during the recording of the readings of the strain gauge, a known weight is suspended at the point of attachment of the tail holder to the wire. Based on the measurement results, a change in the readings of the device, caused by the known force, is determined. In another calibration experiment, a known weight is fixed at the end of the tail holder. The displacement of the load is measured. The ratio of the amplitude of tension oscillations of the lower spring to the amplitude of the model's rotational oscillations is determined.

The flow velocity in the test section was determined by the pressure drop on the wind tunnel nozzle.

3 Calculations

The signal processing technique is given in [9, 10]. Typical dependencies of the cylinder inclination on time are presented in the Fig.2

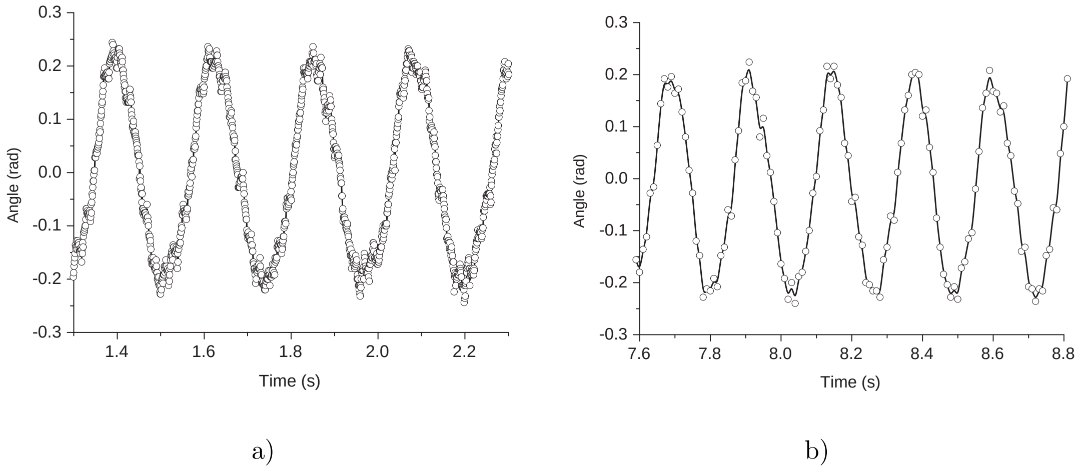

Figure 2: Dependencies of cylinder inclination on time: a) reading frequency 1250 Hz, b) reading frequency 100 Hz.

Approximately the amplitude of the rotational oscillations can be determined by graphs similar to those shown in Fig. 2. To do this, it is enough to measure the maximum and minimum values of the angle of inclination of the cylinder. Then we need to calculate the average value of the amplitude. However, the number of oscillation periods during the measurement is quite large and it is easier to apply the algorithm described below. The algorithm is a discrete variant of the Fourier transform. It allows us to approximate the data by a harmonic function of a given frequency.

The angle β_i measured at the time t_i is the sum of the periodic function $B\cos\omega t_i + C\sin\omega t_i$, constant E and an experimental error ξ_i. Experimental error is random variable with zero expectation:

$$\beta_i = B\cos\omega t_i + C\sin\omega t_i + E + \xi_i. \tag{1}$$

The oscillation period T and the angular frequency of oscillations $\omega = 2\pi/T$ are determined. Let n be the number of readings in one period, $i = 1, 2, 3, ..., n$. Multiplying formula (1) sequentially by $\cos\omega t_i$ and $\sin\omega t_i$ and calculating the arithmetic average over all readings in the period, we obtain as follows

$$\frac{1}{n}\sum_{i=1}^{n}\beta_i\cos\omega t_i = B\frac{1}{n}\sum_{i=1}^{n}\cos^2\omega t_i + C\frac{1}{n}\sum_{i=1}^{n}\sin\omega t_i\cos\omega t_i + E\frac{1}{n}\sum_{i=1}^{n}\cos\omega t_i + \frac{1}{n}\sum_{i=1}^{n}\xi_i\cos\omega t_i. \tag{2}$$

$$\frac{1}{n}\sum_{i=1}^{n}\beta_i\sin\omega t_i = B\frac{1}{n}\sum_{i=1}^{n}\sin\omega t_i\cos\omega t_i + C\frac{1}{n}\sum_{i=1}^{n}\sin^2\omega t_i + E\frac{1}{n}\sum_{i=1}^{n}\sin\omega t_i + \frac{1}{n}\sum_{i=1}^{n}\xi_i\sin\omega t_i. \tag{3}$$

The sums in equations (2) and (3) which contain only trigonometric functions can be calculated. Assuming that

$$\frac{1}{n}\sum_{i=1}^{n}\xi_i\sin\omega t_i = \frac{1}{n}\sum_{i=1}^{n}\xi_i\cos\omega t_i = 0, \quad \text{and} \quad E = \frac{1}{n}\sum_{i=1}^{n}\beta_i,$$

one can get the system of equations (4) and (5) for determinations of B and C:

$$B\frac{1}{n}\sum_{i=1}^{n}\cos^2\omega t_i + C\frac{1}{n}\sum_{i=1}^{n}\sin\omega t_i\cos\omega t_i = \frac{1}{n}\sum_{i=1}^{n}\beta_i\cos\omega t_i - \frac{1}{n}\sum_{i=1}^{n}\beta_i\frac{1}{n}\sum_{i=1}^{n}\cos\omega t_i, \tag{4}$$

$$B\frac{1}{n}\sum_{i=1}^{n}\sin\omega t_i\cos\omega t_i + C\frac{1}{n}\sum_{i=1}^{n}\sin^2\omega t_i = \frac{1}{n}\sum_{i=1}^{n}\beta_i\sin\omega t_i - \frac{1}{n}\sum_{i=1}^{n}\beta_i\frac{1}{n}\sum_{i=1}^{n}\sin\omega t_i. \tag{5}$$

For large n

$$\frac{1}{n}\sum_{i=1}^{n}\cos^2\omega t_i \approx 0.5, \quad \frac{1}{n}\sum_{i=1}^{n}\sin^2\omega t_i \approx 0.5,$$

$$\frac{1}{n}\sum_{i=1}^{n}\cos\omega t_i \approx 0, \quad \frac{1}{n}\sum_{i=1}^{n}\sin\omega t_i \approx 0, \quad \frac{1}{n}\sum_{i=1}^{n}\sin\omega t_i\cos\omega t_i \approx 0.$$

One can calculate the amplitude of rotational oscillation using expression $A = \sqrt{B^2 + C^2}$.

4 Results

We found that changes in readout frequency do not affect results. In almost all cases, oscillations with a constant amplitude are observed. An exception is the oscillation of a short cylinder $\lambda = 2$ at low air flow velocities v.

In Fig. 3 the dependence of amplitude of steady oscillations on Strouhal number Sh are presented.

$$\mathrm{Sh} = \frac{w}{Tv},$$

where T is the period of oscillation.

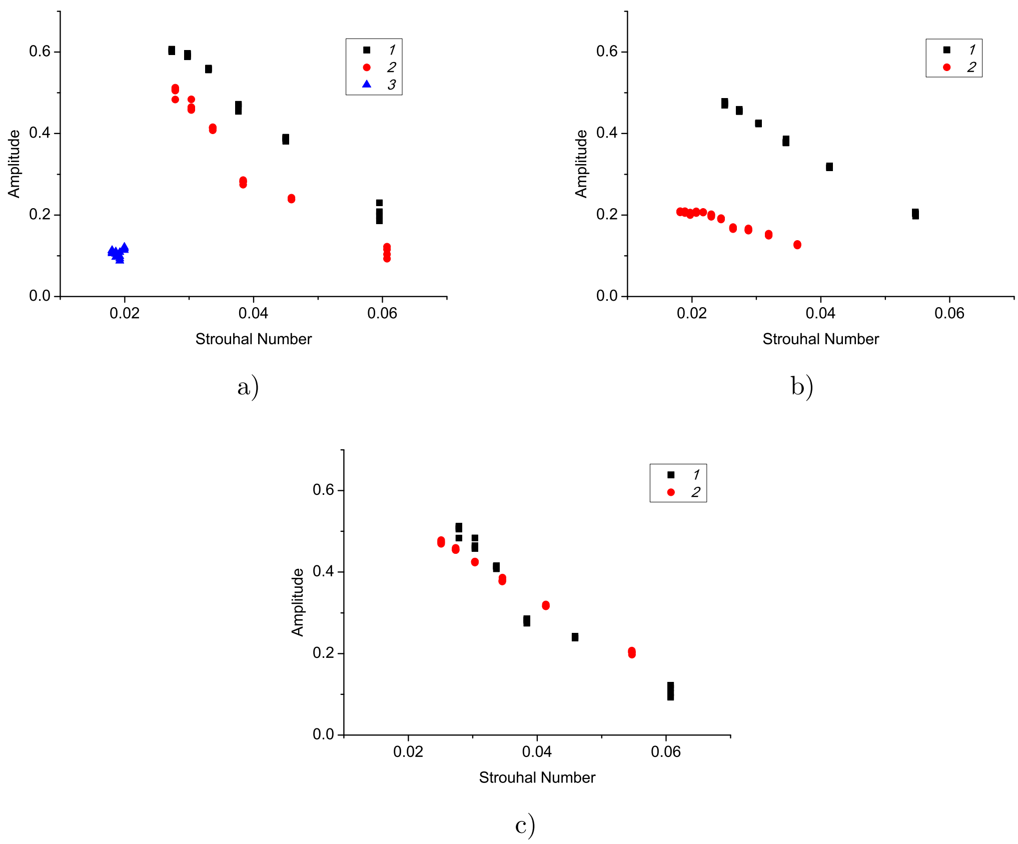

Figure 3: Dependencies of amplitude of oscillations on Strouhal number: a) without end plates, *1* - $\lambda = 7$, *2* - $\lambda = 5$, *3* - $\lambda = 2$; b) with end plates, *1* - $\lambda = 5$, *2* - $\lambda = 2$; c) comparison at $\lambda = 5$, *1* - without end plates, *2* - with end plates.

In all graphs, the amplitude of oscillations increases with a decrease in the Strouhal number. Graph a) shows that for a cylinder without end plates, the larger the elongation of the cylinder, the greater the amplitude of oscillations. Oscillation of the cylinder $\lambda = 2$ with a constant amplitude takes place only at a high velocity of air flow. Diagram b) shows the dependence of the amplitude of steady oscillations on the Strouhal number for cylinders with end plates. The range of Strouhal numbers, in which there are oscillations with constant amplitude for the cylinder $\lambda = 2$, increases significantly towards large Strouhal numbers. The dependence of the oscillation amplitude for a cylinder $\lambda = 5$ with end plates on the Strouhal number is nearly linear. Comparison of the dependencies of the amplitude on the Strouhal number is given in graph c) for cylinder $\lambda = 5$. The presence of end plates makes the dependence smoother. This phenomenon can be explained by the fact that under conditions where the end plates do not impede the flow of air through the ends of the cylinder, the vortex system behind the body has a complex character and is tuned with a change in the flow velocity.

5 Conclusions

Experiments with rectangular cylinders fixed on an elastic suspension with one rotational degree of freedom in the air flow show that the steady oscillation amplitude increases with increasing of the cylinder aspect ratio. Oscillations with a constant amplitude of the cylinder with aspect ratio $\lambda = 2$ are realized only at a sufficiently high flow velocity. The presence of end plates changes the dependence of the oscillation amplitude on the Strouhal number. For a cylinder with aspect ratio $\lambda = 2$, the range of flow velocities at which oscillations with a constant amplitude are observed is expanded. In this case, the amplitude is much larger than that of a cylinder without end plates. The difference in the amplitudes of oscillations of the cylinder with aspect ratio $\lambda = 5$ with end plates and without them is small. The dependence of the oscillation amplitude of the cylinder with end plates on the Strouhal number is nearly linear.

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