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Discussion

Frequency lock-in and phase synchronization of vortex shedding behind circular cylinder due to surface waves

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ABSTRACT

The influence of harmonic surface wave on non-regular Karman Vortex Street is investigated. In our experiments, Karman Street arises behind a vertical circular cylinder in a water flow and harmonic surface waves propagating upstream. It is found that surface waves can modify regimes of shedding in Karman Street: frequency lock-in and synchronization of vortex shedding can arise. Intensive surface waves can excite symmetric vortex street instead of chess-like street, and completely suppress shedding behind the cylinder. It is shown experimentally that such effects occur if frequency of harmonic surface wave is approximately twice higher than the frequency of vortex shedding. Region of frequency lock-in is found on the plane amplitude–frequency of surface wave.

1. Introduction

Experiments on Karman Street demonstrate that the phenomenon of vortex shedding resonance and frequency lock-in is observed when a cylinder is placed in a mean flow with a time periodic component superimposed upon it, or when a streamlined cylinder is oscillating harmonically. In these cases vortex shedding exhibits a particularly strong influence of external perturbations providing modification of wake characteristics in the vicinity of the cylinder. Modifications include the appearance of a number of vortex modes synchronized with the artificially created oscillations. Synchronization may be achieved at frequencies of oscillation f_e equal to the frequency of shedding f_{sh}, and also for subharmonic resonance $2f_{sh} = f_e$ or super harmonic resonance $f_{sh} = f_{en}$, $n = 2, 3, 4 \dots$.

Influences of traversal oscillations of cylinder were investigated [1–3] for frequency of shedding f_{sh} close to the frequency of external forcing f_e. The main attention was paid to increase of lifting forces [1,2] and to the changes of the mode of vortex shedding. In [3], modes of vortex formation were categorized depending on how many localized vortices appear in the wake during a time interval equal to the period of the external forcing. It was also found [4] that frequency modulated cross-flow oscillation of the cylinder can lead to the destabilization of the Karman street and broadening of the velocity pulsation spectra in the vortex wake.

Influence of longitudinal oscillations of cylinder was investigated in papers [5,6]. It was shown that in this case, frequency lock-in occurs then shedding frequency is twice lower than the frequency of external oscillations: $2f_{sh} = f_e$. This result was obtained also in numerical simulations [7]. Classification of vortex modes generated behind the cylinder for different amplitudes and frequencies of longitudinal oscillations is given in [8].

It was found in physical experiments and numerical simulations that the time-periodic component superimposed upon mean flow at a certain degree is equivalent to the longitudinal oscillations of the streamlined cylinder. For example, in papers [9] studding vortices around an oscillating cylinder and in [10] studding vortices around a fixed cylinder in pulsating flow, the same shedding mode corresponding to generation of four vortices per period was observed. In other words, for the vortices appearing near a cylinder, the relative motion of fluid and cylinder is important.

The papers cite above relate to the case of homogeneous currents: hydrodynamic flows do not have free boundaries and surface waves do not occur in these systems. Meanwhile, in many cases, the vortex street behind the cylinder occurs in the water flow with a free surface. For example vortex wake occurs in the vicinity of wind farm masts in the coastal zone, where there strong tidal currents are observed. It should emphasized that the influence of surface waves on the characteristics of vortex wake has not been practically studied, although the papers cited above show that such effect could be substantial. It should be noted that, in the papers [11,12] Karman Street behind vertical cylinder is investigated in shallow water flow with free surface. Shallow water means that di-

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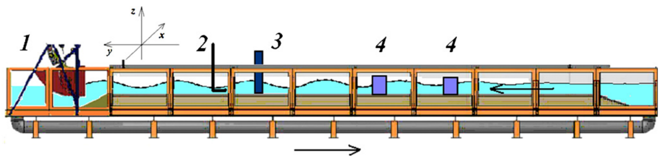

Fig. 1. Experimental sketch: "1" refers to the wave maker, "2" refers to the ADV, "3" refers to the location of the cylinder streamlined by the flow, "4" is for honeycombs; arrows indicate directions of current.

ameter of the cylinder is much more than the water depth. These experiments were performed for the laboratory modeling of geophysical and environmental processes in the Earth's atmosphere and ocean. The impact of waves on the structure of vortices was not investigated. This particular problem will be studied in the present paper. We're going to study the features of frequency lock-in and timing of vortex shedding in the Karman Street when the external forcing is due to the surface waves.

It should be noted that the surface harmonic waves produced in the vicinity of a vertical cylinder time periodic field with spatial structure is more complex than the field arising from periodic harmonic currents or harmonic vibrations of the cylinder. Surface waves have vertical and horizontal components, and the spatial structure of the surface wave field depends on the relationship between the wavelength and the water depth. Therefore, in the study of the appearance of synchronization, we have to analyze this phenomenon for different ratios between the wavelength and the depth of the water flow.

The paper is organized as follows. Section 1 describes the experimental scheme. Section 2 is devoted to the study of the frequency lock-in and phase synchronization on the basis of time series processing. Section 3 presents the results for the visualization of the flow behind a cylinder at different amplitudes of surface waves. Discussion and conclusions are presented in Section 4.

2. Experimental setup

The experimental study is conducted in the wave flume of the Laboratory of Continental and Coastal Morphodynamics, in Caen. This flume (Fig. 1) has a length of 18 m, a width of 0.5 m, while the water depth can be varied from 0 to 0.4 m. Waves of different spectrum and amplitudes are generated in the flume under conditions of deep water and shallow water. To generate surface waves in the flume, a computer controlled wavemaker is used.

Experimental facilities allow us to investigate the propagation of surface wave on the background of a steady current. This current is generated by means of power pump, as indicated in Fig. 1. In order to reduce the intensity of turbulent fluctuations created by the pump and for the purpose of reducing wave reflection, two honeycombs with a thickness of about 10 cm each are installed in the channel, as shown in Fig. 1, opposite to the wave-maker. Waves are excited at the end of the channel by the wave maker and they propagate upstream (from the left to the right, see Fig. 1). The experiments are implemented with traveling waves because the honeycombs led to a significant decrease in the amplitude of the reflected waves. During our experiments two round cylinders with a diameters d of $d_1 = 4$ cm and $d_2 = 10$ cm are used as models of masts. The depths of flow H are correspondingly $H_1 = 0.25$ m and $H_2 = 0.4$ m, Froude number $Fr_{1,2} = U_{1,2}/(gH_{1,2})^{1/2}$ and Reynolds number $Re_{1,2} = U_{1,2}d_{1,2}/\nu$ (U is for flow velocity, d is for cylinder diameter, ν is for kinematic viscosity) at which the measurements were respectively: $Fr_1 = 0.1$, $Fr_2 = 0.045$; $Re_1 = 6.410^3$, $Re_2 = 10^4$. Cylinders are placed strictly vertically on the channel axis.

To study the evolution of free surface displacement along the channel resistive probes are used. In the meantime, the characteristics of the hydrodynamic fields are measured thanks to Acoustic Doppler velocimetry (ADV). This measuring device is placed at a distance of several diameters from streamlined cylinder down the flow and measures the three components of velocity: V_x (transverse velocity), V_y (longitudinal velocity), V_z (vertical velocity), as shown in Fig. 1.

These velocity components are caused by different modes: by vortices formed behind the cylinder (hydrodynamic mode) and by surface wave. The two-dimensional surface waves propagate along the channel contributing to the components V_y, V_z. If we assume that the vortices formed behind the cylinder have only the vertical component of the vorticity, they contribute only to components V_x, V_y. Obviously, for such high Reynolds numbers that are achieved in the experiments, turbulent vortices occur in the cylinder wake. That is why it is impossible to neglect the impact of hydrodynamic mode into the component V_z, but this impact sufficiently smaller than the impact into components V_x, V_y.

For visualization of vortex dynamics, the flow was seeded with sand particles (10 μm) into the flow ahead of the cylinder. Using a horizontal light sheet (photodiode 532 nm with spherical lens) it was possible to visualize the cross section of the flow in the x–y plane. The size of the visualization domain stands for 40×30 cm. Image recording is performed by high-speed camera with a frame rate of 100 Hz.

3. Subharmonic frequency lock-in and phase synchronization

The study of sub-harmonic frequency lock-in for the vortex wake of a cylinder was conducted in two series of experiments, for Reynolds numbers of $Re = 6 \times 10^3$ and 10^4. Subharmonic frequency lock-in is manifested in the fact that under the action of surface waves with a frequency f_e, in the wake of a cylinder periodic or quasi-periodic oscillations having a half frequency $f_e/2$, appear. In general case this frequency does coincide with Strouhal frequency f_{Sh}. It should be noted that the surface waves generated by computer-controlled wavemaker has a very narrow frequency spectrum. On the other hand, vortex street at Reynolds numbers $Re = 6 \times 10^3$ and $Re = 10^4$ is a turbulent flow. Before exploring frequency lock-in, some experiments were conducted to study the turbulent fluctuations in hydrodynamic flow. We compared the level of turbulence and the mean flow profile in the channel for two cases: honeycombs were absent and honeycombs were used. The measurement results are shown in Fig. 2.

Measurements have shown that the maximum level of turbulence was observed in the vicinity of the channel bottom, that is associated with the generation of turbulent eddies in the boundary layer. The honeycombs reduce turbulent pulsations by half (Fig. 2a). Using of honeycombs changes also average velocity profile: reduction of the turbulence level causes the velocity profile to become more uniform over depth (Fig. 2b).

Turbulence level up to several percent may significantly affects the frequency lock-in, so for data processing, specific criteria has been developed by taking into account effects of random forces. Effect of surface waves on a vortex street led to the appearance of oscillations in the wake with a peak at half the frequency $f_e/2$, and the finite width of the spectral peak. Only when sufficiently large amplitude of the surface wave is excited, the spectrum of velocity fluctuations has with a narrow frequency peak at a half frequency $f_e/2$. It is therefore necessary to use criteria by which one could determine if frequency lock-in occurs or does not occur. As such criteria, we chose the width of the spectral peak: if the width of the spectral peak at the level of 5 dB (0.7 of peak value) is less than 3% of $fe/2$, we have classified this regime as frequency lock-in. If the spectral component with frequency is clearly visible, but the width of the peak was more than 3 percent, that such a regime we called a partial lock-in.