Dynamic Response of Moored Floats in Steady Currents

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ABSTRACT

Waters pumped up from oceans have been employed for Ocean Thermal Energy Systems for several years. Now attention is being given to the utilization of the nutrition value of the unpolluted waters from deep seas. For effective exploitation of deep waters for agricultural purposes or for industries dealing with marine products, it is important to uplift the water at minimum cost. One of the economical methods of uplifting the deep-sea water would be to use soft (flexible) pipes held at their tops using either floats or buoyancy-type platforms. A basic experimental study on the behavior of a moored-float, whose prototype corresponds to a large-scale floating structure like a tension-leg-platform, under the actions of current flow has been conducted. The response characteristics due to fluid drag and lift forces were investigated. The models were placed in a circulating water channel under unidirectional current flow. The response vibrations were recorded and analyzed. The results indicate that in-line components of responses increase with flow velocity due to higher fluid drag forces. The variation in the cross-flow components is much more complex and is influenced by eddies and other forms of turbulence. Also, the vortex-induced vibration involves a feedback mechanism in which vibration of the model and the vortex formation are coupled to each other.

1. INTRODUCTION

The area comprising of the so-called south-west islands of Japan i. e., region extending south from Satsuma Peninsula, including Okinawa has a warm climate and is usually subjected to severe typhoons. Consequently the agricultural farms and the marine related industries in many islands of this region are often affected. If it were possible, by some means, to uplift the water from the deep seas of this region, it would be a major contribution for the economic development of the area. The water at depths of more than about 100m has low-temperature, is rich in nutrition and is mostly unpolluted. But due to the high cost of constructing the facilities needed for the uplift, actual uplift in large quantities has not yet been a reality. One of the reasons of high cost is the design requirement for withstanding severe environmental conditions.

One of the economical methods for the uplift of waters from great depths would be using a soft (flexible) pipe. Figure 1 shows a proposal using this concept in which the water is lifted from deep seas to the shore using a soft pipe. The proposals for the structure (a) under installation and non-operation, (b) during the process of uplifting the deep water, and, (c) during non-operation under typhoons are shown. The soft pipe is held in position using floats moored to the sea bed. These floats are lifted or lowered depending on the requirements of the set-up as shown in the figure. Under typhoon conditions, the soft pipe is well-immersed in water for most of its length to avoid severe wave forces.

In addition to the wind and wave loads, there is Kuroshio current flowing in this region. Therefore current loading is one of the important factors for the design. Vortex shedding occurs for a structure under current flow when the Reynold's number exceeds a certain value. This in turn causes a variation of the lift and drag forces acting on the structure. The lift force oscillates with a frequency equal to the vortex-shedding frequency whereas the drag force oscillates with a frequency equal to twice the vortex-shedding

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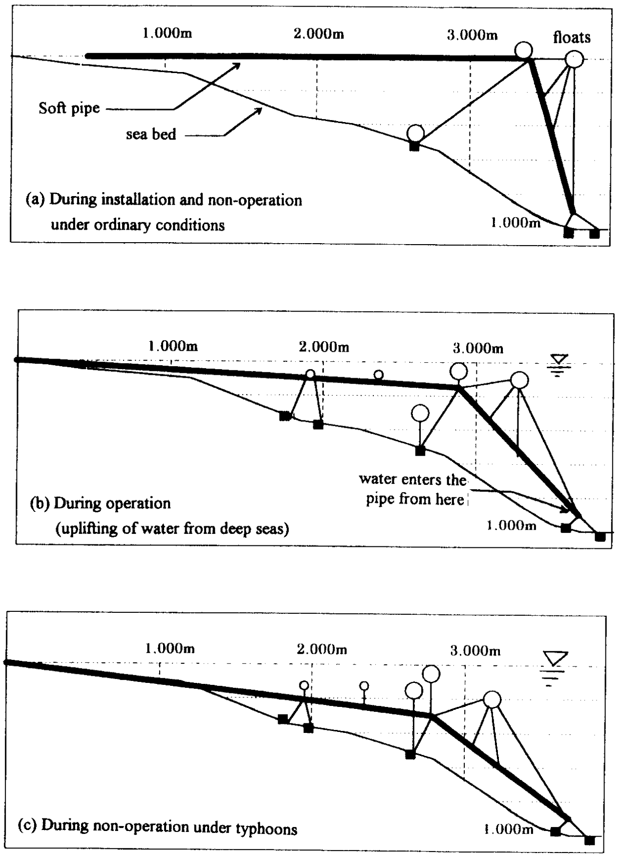


Figure 1 Example of a set up for uplifting nutrition-rich unpolluted waters from deep seas

frequency (Sumer and Fredsoe (1994)). When the structure is flexibly-mounted, it will undergo in-line vibration due to the action of oscillating drag force and cross-flow vibration due to the action of oscillating lift force. The writers investigated (Yoshihara et al, 1996, Venkataramana et al 1996) earlier experimentally the hydrodynamic forces due to current flow on offshore pipelines and submerged floating tunnel models which were held either rigidly (where the emphasis was on measuring the fluid drag and lift forces and computing the drag and lift coefficients for various types of models) or were flexibly-mounted using springs (where the emphasis was on measuring the response displacements due to the oscillating drag and lift forces).

In the present study, the objective is to investigate the response behavior of a moored structure which can serve as platform to install the soft-pipes for uplifting waters from deep-seas. Experiments are carried out in the laboratory using moored floats under current flow.

2. EXPERIMENTS

Experiments were carried out in the circulating water channel capable of generating unidirectional flows. The measuring section of this channel is 6m in length, 2m in width and 1m in depth with a maximum water velocity of 2m/sec.

Cylindrical floats made of ABS (Acrylonitrile, Butadiene and Styrene) resin were used as experiment models. Figure 2 shows the schematic diagram of a model moored to the sea bed using a steel mooring wire. The depth of water is 1m. Due to the buoyancy, the model is floating and is held in position by the mooring wire. In the figure, the symbols CH1 and CH2 represent the strain gauges attached to the wires to measure the tension variation. Table 1 shows the details of the four models used for the experiments. Models 1 and 2 have a mooring length of 1m whereas Models 3 and 4 have a mooring length of 90cm.

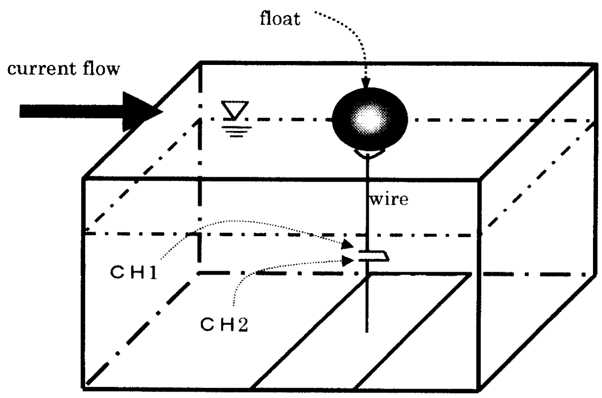


Figure 2 Schematic diagram of a float model

Table 1 Details of models

model	diameter (mm)	buoyancy (gmf)	mooring length (mm)
Model 1	93	300	1000
Model 2	140	1200	1000
Model 3	93	300	900
Model 4	140	1200	900

Figure 3 shows the details of the experimental setup. The response vibrations of the models were recorded using video cameras. The video camera, which

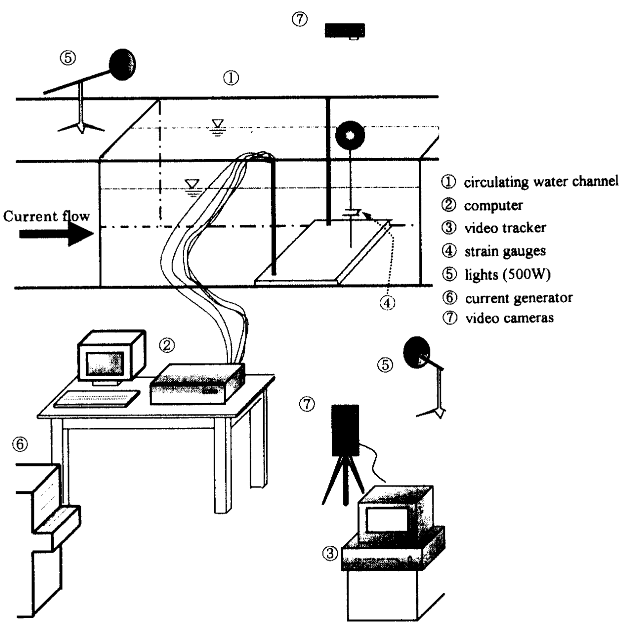


Figure 3 Experimental set up

was placed exactly above the models, was used for recording the in-line as well as cross-flow vibrations of the models whereas the one placed on the side recorded the in-line vibrations of the models as well as the vibrations of the mooring wire. In fact, traces of vibrations were recorded first using the video cameras, then these traces were analyzed using the video tracker to obtain the in-line and cross-flow vibrational components. Also using the strain gauges, variation in the strain in the mooring wire were recorded which were later converted into equivalent tension variations.

Firstly free vibration experiments were conducted by giving an initial displacement to the model and then releasing it from that displaced position. The decaying vibration pattern was recorded using video camera. Then forced vibration experiments were conducted for current velocities ranging from 0.1m/s to 0.8m/s at 0.1m/s intervals. When the response vibration of the model was fairly steady under current flow, its movement (or trace) was recorded using video camera. Using the video tracker, the trace was divided into in-line and cross-flow components, each consisting of 2048 discrete data, the time step of digitization being 1/30 sec. Then, the *rms* (root-mean-square) value of the displacement of the model, along the in-line (or cross-flow) direction was computed based on the 2048 discrete values of the displacements.

3. RESULTS AND DISCUSSIONS

Free-vibration experiments:

The models were given small displacements from their equilibrium positions, under no-current flow conditions, and then were released from these displaced positions. The decaying patterns of the responses were recorded using video cameras. Figure 4 shows the ex amples of response displacements during free-vibration experiments for the four models. The natural periods and damping ratios of the models are tabulated in Table 2.

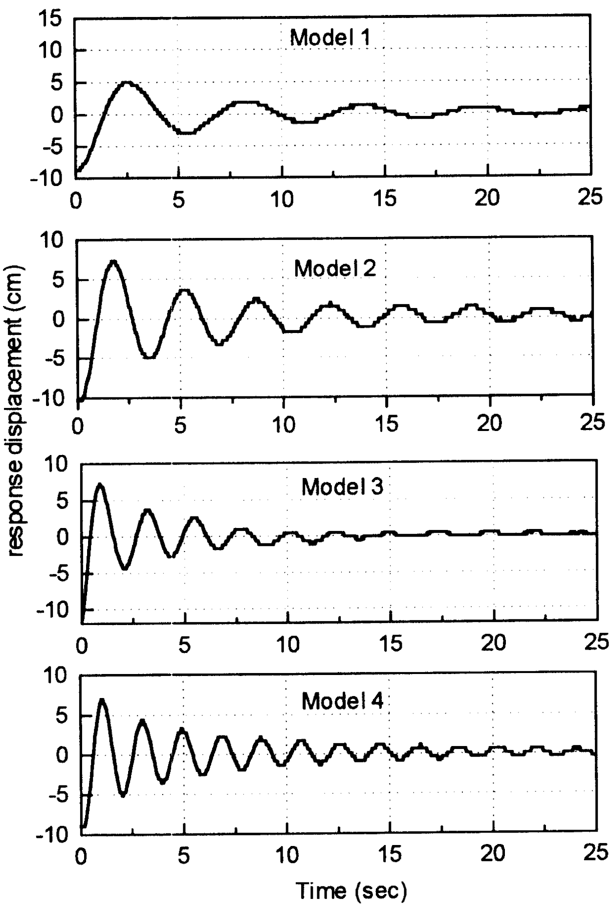


Figure 4 Examples of free-vibration response displacements

Table 2 Natural periods and damping ratios

model	natural period (sec)	damping ratios (%)
Model 1	5.61	4.7
Model 2	3.48	3.7
Model 3	2.28	3.6
Model 4	1.93	2.6

Forced-vibration experiments:

The time histories of the response displacement of the center of models in the in-line and cross-flow directions are shown in Figures 5 and 6 for the duration of about 60 seconds. The numbers inside the figures indicate the current velocities in meters per second. The in-line component of displacement increases with the increase in current velocity as expected due to the increase in fluid drag force. But their temporal variation is relatively small for any current velocity.

The variation in the cross-flow component of displacement, which is caused by oscillatory lift force, shows more complex characteristics with the increase in current velocity. Larger traces are observed for certain values of current velocities, which may be due to the synchronization of the vortex-shedding frequency at these velocities to the natural frequency of the models.

When there is not much interaction between the model and its wake, the vortex-shedding frequency is proportional to the current velocity. Also when the model is stationary and the flow is laminar, regular number of vortices are generated on the downstream side of the model.

For non-stationary structures such as the models of the present study, lift and drag forces due to these vortices influence the motion of the structure thus contributing a feedback effect i.e., causing the fluid-structure interaction. This effect is particularly severe when the frequency of generation of vortices i.e., the vortex-shedding frequency is closer to the natural frequency of the model. It may be possible that additional vortices may be triggered by the vibration of the model, which will be produced at or near the resonant frequency of the model and the lift forces may be several times higher than those anticipated on equivalent stationary bodies (Newman (1992)).

Further, when the flow is turbulent with fast current, vortices are generated in a random fashion and the model undergoes random vibration, as shown in Figures 5 and 6, due to oscillating lift forces with irregular frequency as well as amplitude.

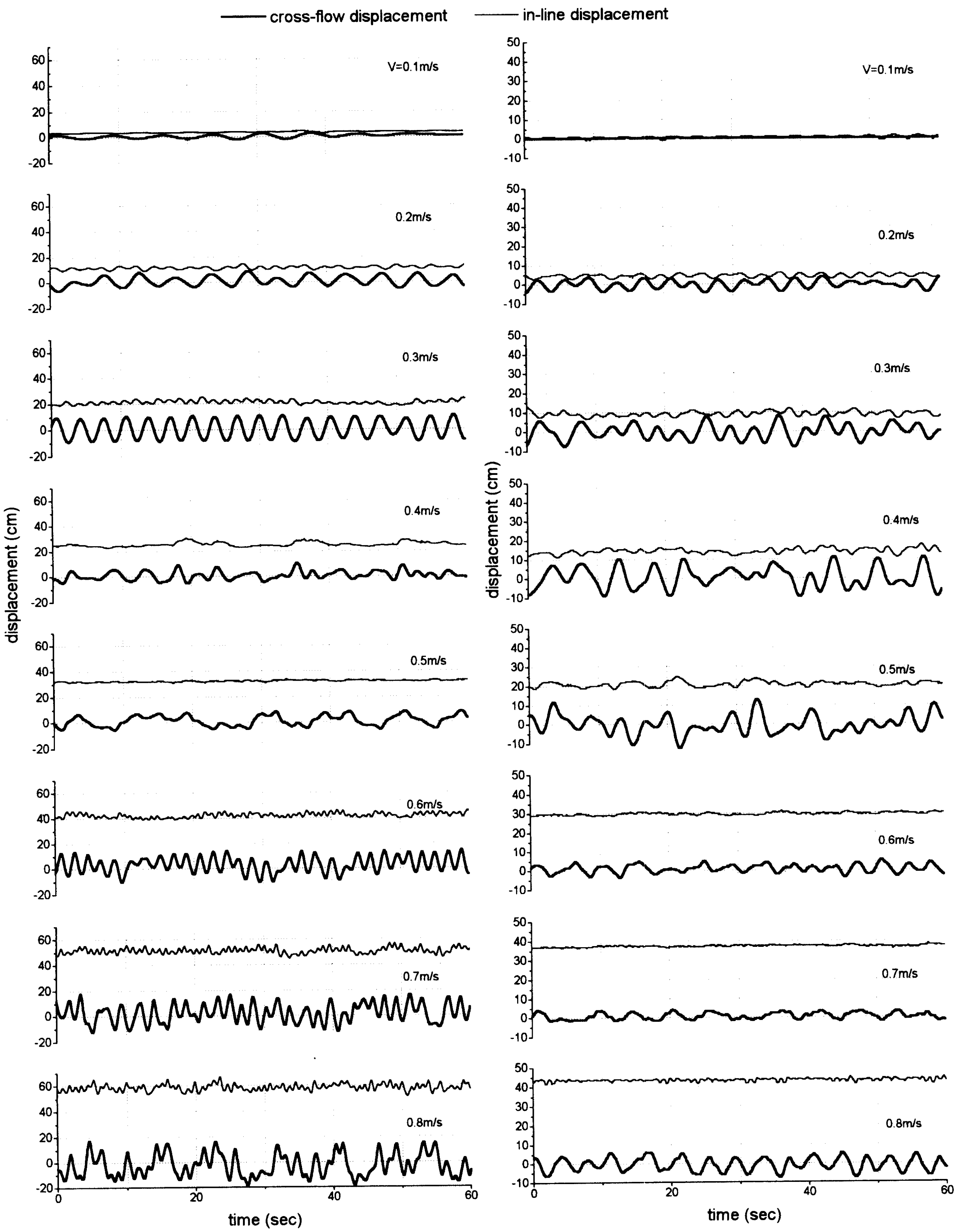
The Fourier spectra of time histories of cross-flow displacements were computed to identify the vibration frequencies corresponding to maximum amplitudes. Figure 7 shows the examples of these investigations for Models 1 and 2 whereas Figure 8 shows the same for Models 3 and 4.

Figure 9 shows the *rms* values of tensile forces in the mooring wires for different current velocities and various models. These were obtained from the strain data recorded through the strain gauges attached to the mooring wires and using a simple calibration test to convert the strains into equivalent tensile forces. The tensile forces increase with the increase in current velocities as expected. But for Model 2, there is a sharp increase in the values for higher current velocities. The reason for this behavior is not yet very clear.

One of the most interesting features of vortex-induced vibration is the occurence of "lock-in" phenomenon (for example, Nishio and Incecik (1995), Wu and Moe (1995), Wu (1995)). To illustrate this, the frequency ratio, which is the ratio of vibration frequency corresponding to maximum Fourier amplitude at each current velocity, and the natural frequency of the Models, is plotted against current velocity in Figure 10. For Models 2,3 and 4, for a considerably broader range of current velocity, the vortex-shedding frequency locks into the natural frequency indicating that the vortex-shedding interacts with the vibration of the model at these current velocities.

The *rms* values of the in-line and cross-flow displacements for about 60-second duration of the models were computed from the time history of the response displacements. They are plotted against current velocity in Figure 11. The cross-flow displacements show a peak for certain values of current velocity which is due to the proximity of the vortex-shedding frequency at that velocity to the natural frequency of the model. Also the cross-flow displacements are larger when the currents become faster. On the other hand, the in-line displacements increase with the increase in current velocity due to larger fluid drag forces.

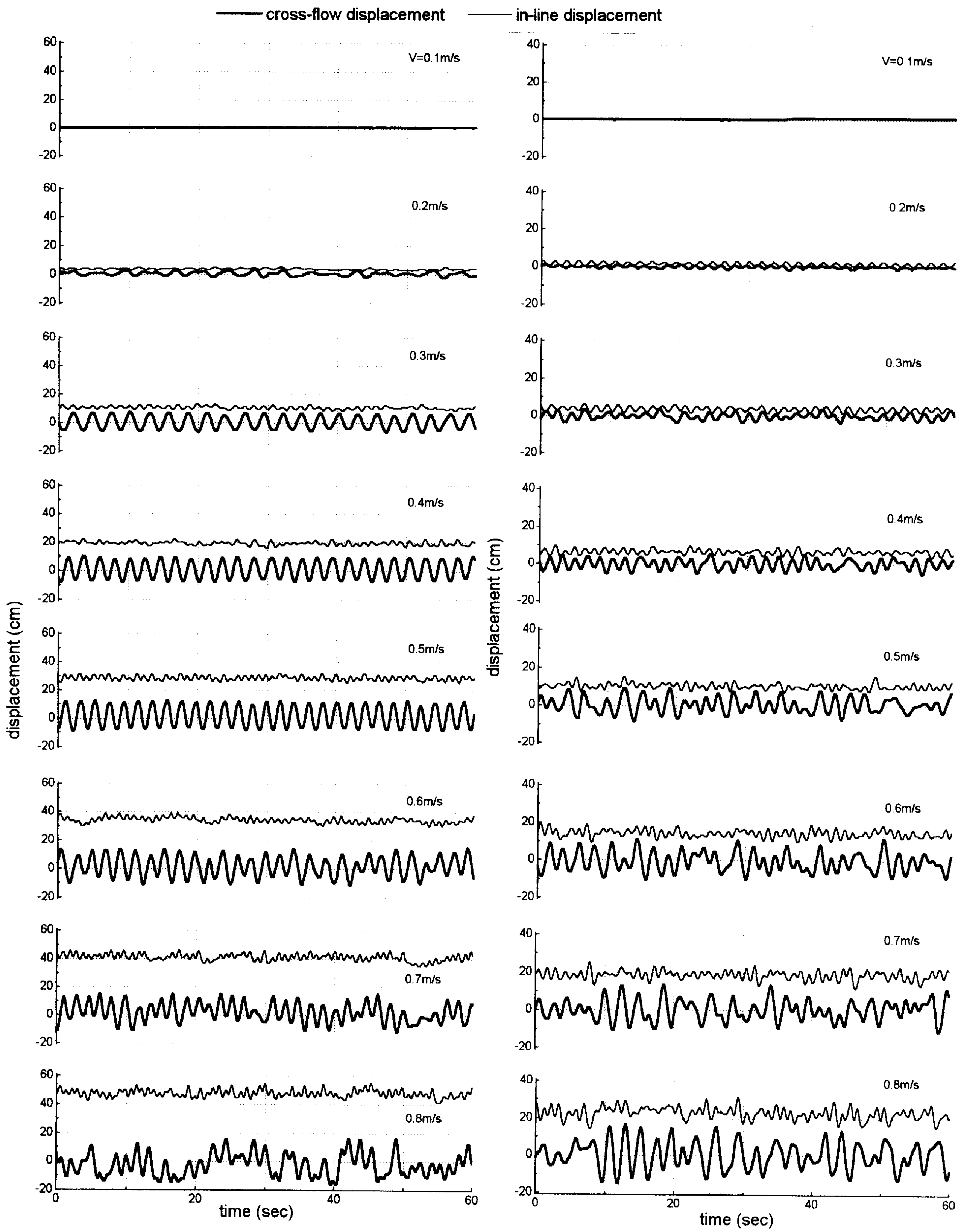
For steady current flows past offshore structures, the main measure of the frequency of lift forces is the Strouhal number S which is a function of the vortex-shedding frequency. In the present study, the time histories of cross-flow displacements were analyzed using Fast Fourier Transform as explained earlier and the frequencies corresponding to maximum amplitudes were located. Assuming that these correspond to vortex-shedding frequencies at each current velocity, Strouhal number was calculated. This Strouhal number is plotted as a function of Reynolds number for



(a) Response displacements of Model 1

(b) Response displacements of Model 2

Figure 5 Time histories of response displacements (Model 1 and Model 2)



(a) Response displacements of Model 3 (b) Response displacements of Model 4

Figure 6 Time histories of response displacements (Model 3 and Model 4)

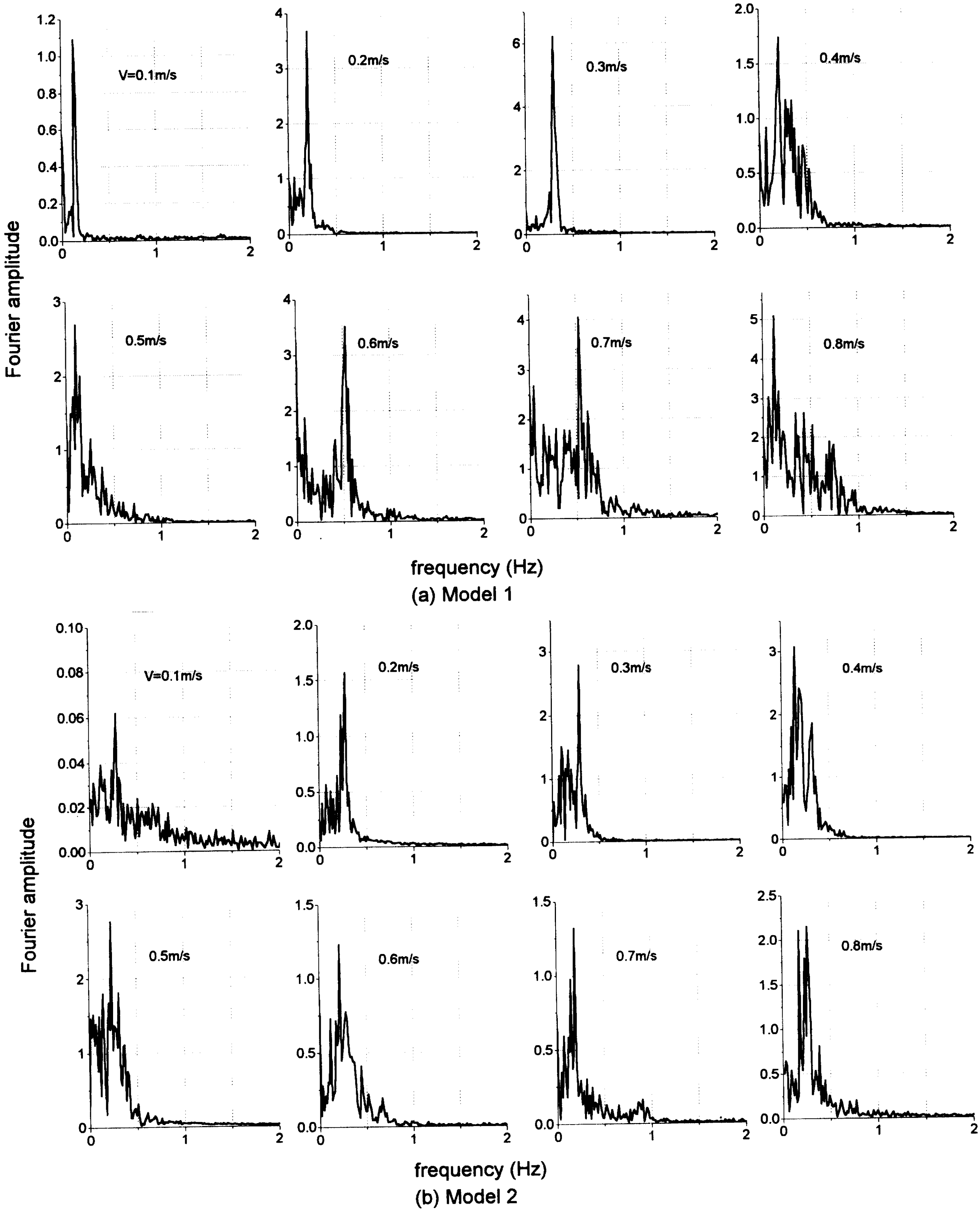


Figure 7 Fourier amplitudes of cross-flow displacements (Model 1 and Model 2)

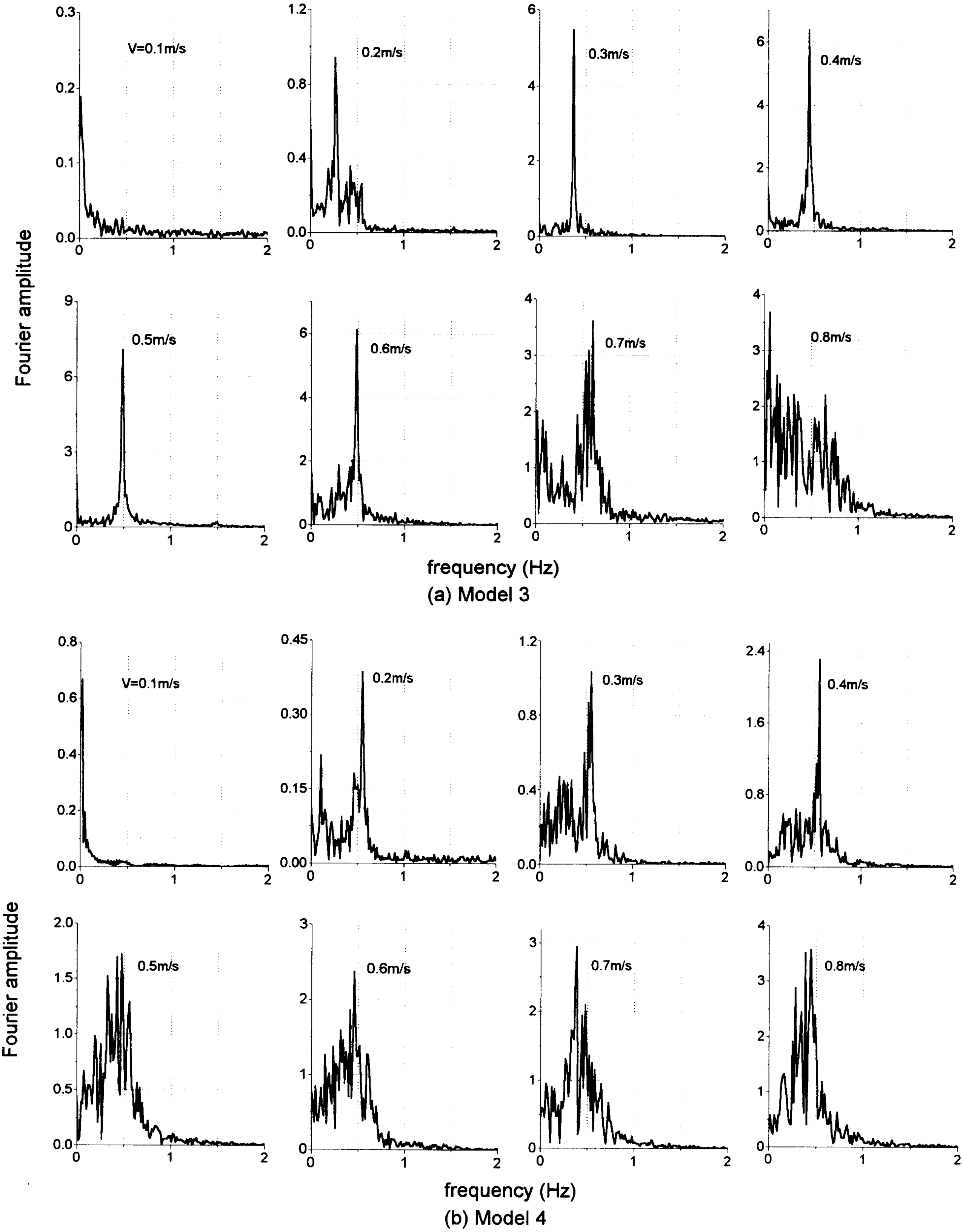


Figure 8 Fourier amplitudes of cross-flow displacements (Model 3 and Model 4)

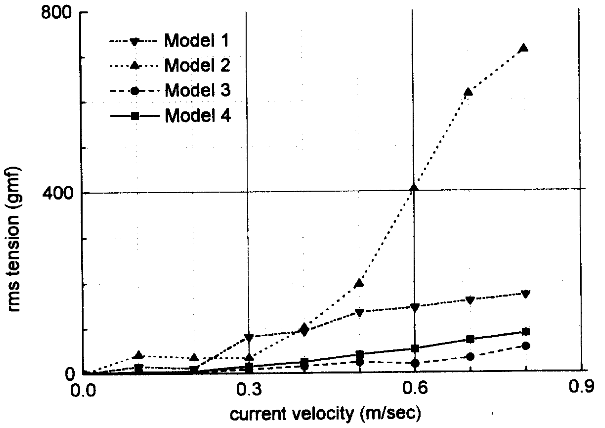


Figure 9 *rms* values of tensions in the mooring wires

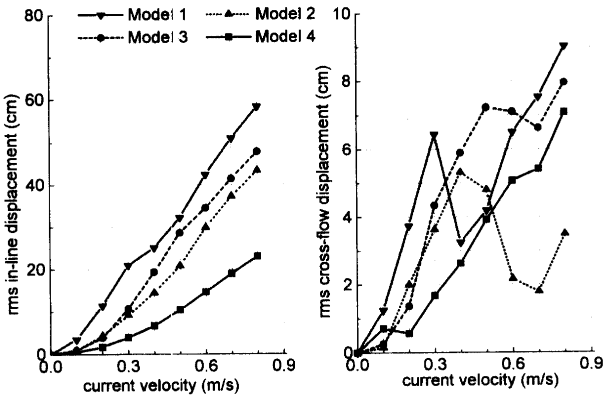


Figure 11 *rms* values of displacements (in-line and cross-flow responses)

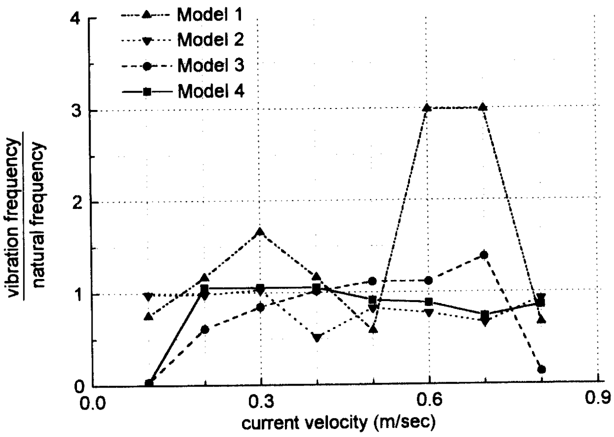


Figure 10 Frequency ratio (vibration frequency/natural frequency)

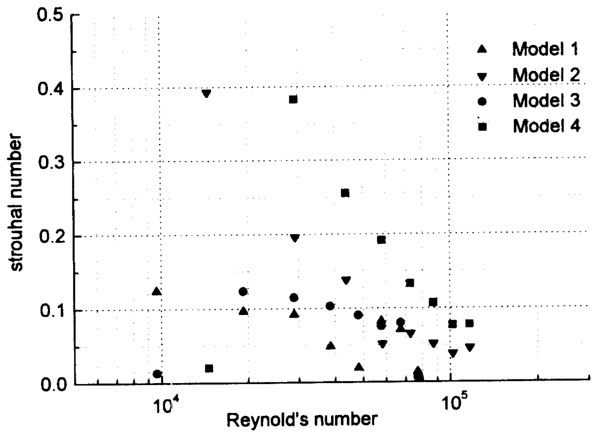


Figure 12 Strouhal number versus Reynold's number

Models 1 and 2 in Figure 12. It is known that for a stationary structure, Strouhal number takes fairly constant values (Yoshihara et al, 1996). But in the present case, the model is non-stationary and is free to vibrate since the bending stiffness of mooring wires is very low. It is seen that, the values of Strouhal number generally decrease with increasing Reynold's number.

4. CONCLUSIONS

A laboratory study on the vibrations of floats, moored to the sea bed, in steady current flow has been carried out. The main conclusions are summarized as follows:

1. The in-line displacements of response vibration of the models generally increase with flow velocity due to the action of higher fluid drag forces.
2. The variation of oscillating lift force and the oscillating cross-flow displacement is very complex and is significantly affected by the flow conditions around the models and by strong fluid-structure interaction effects.
3. When the natural frequency of the model is nearer to the vortex-shedding frequency, the values of cross-flow displacements, and hence the lift forces are maximum. Also, for a broad range of current velocities, the vortex-shedding frequency locks into the natural frequency indicating that the

vortex-shedding interacts with the model vibration at these current velocities.

4. For larger current velocities, the flow becomes highly turbulent around the models with irregular vortex-shedding and the models show patterns of severe random vibration.
5. It is concluded that the oscillatory lift force, rather than the drag force, may be a very important factor from design considerations for non-stationary structures such as the models considered in the present study.

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