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파랑 중 원형 단면 세장체의 응답에 관한 실험적 연구

Experimental Study on Responses of Circular Cross-Section Slender Body on Waves

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Experimental Study on Responses of Circular Cross-Section Slender Body on Waves

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Abstract

The demand of oil and natural gas globally increases, resource development area is moving in deep sea. Floating and flexible offshore structures such as Semi-submersible, Spar, and FPSO have been widely used. Core equipment of floating offshore structures is composed of a number of slender bodies. These flexible structures are possibly to receive damage by marine environment such as waves and current. Moreover, flexible risers are easily damaged by the exciting force due to the motion of the floating body. These structures move in three-dimensions, because inline and transverse responses occurred by various forces. Thus, research and many experiments for the dynamic behavior analysis of the slender body are being carried out.

Generally, risers used in the development of oil and gas resource are composed of a steel pipe. However, the OTEC risers are not possible to use a steel pipe, using a flexible material such as polyethylene. To conduct the optimal design of flexible offshore plant, there is a need for dynamic behavior analysis of the slender bodies those are manufactured by various materials. In this study, used the three-dimensional motion measurement device to analyze the displacement of riser models induced external force factors; forced oscillation by riser linked to forced oscillation device in the current and regular wave condition.

KEY WORDS: Slender cylinder 원통형 세장체; Model test 모형실험; Forced oscillation 강제 동요; Regular wave 규칙파; current 흐름

CHAPTER 1. INTRODUCTION

1.1 Background

The demand of oil and natural gas is globally increasing; the existing resources on coastal oil field is rapidly exhausting that results fossil fuel development to move on deep sea recently. Fixed marine structures have been mainly used in shallow water. According to development water depth has become deeper, the cost of constructing a fixed marine structure significantly increased and physical defects caused by external forces on marine environment threatened structural stability. Floating or flexible offshore structures such as Semi-submersible, Drill-ship and FPSO(Floating Production Storage & Offloading) were designed to solve these problems. (Jung, 1999; Patel, 1989)

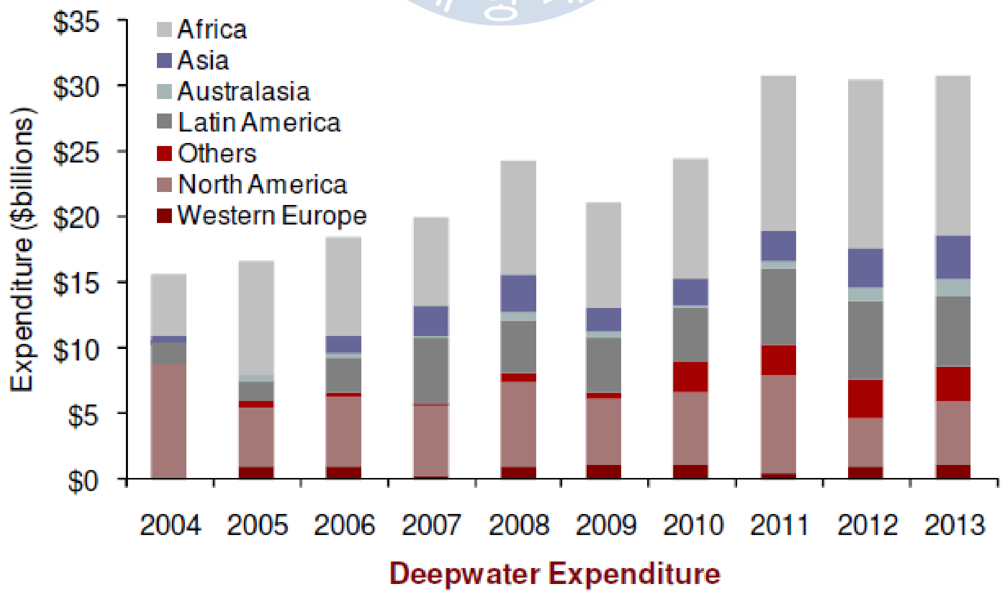


Fig. 1.1 Trend of deepwater expenditure about oil

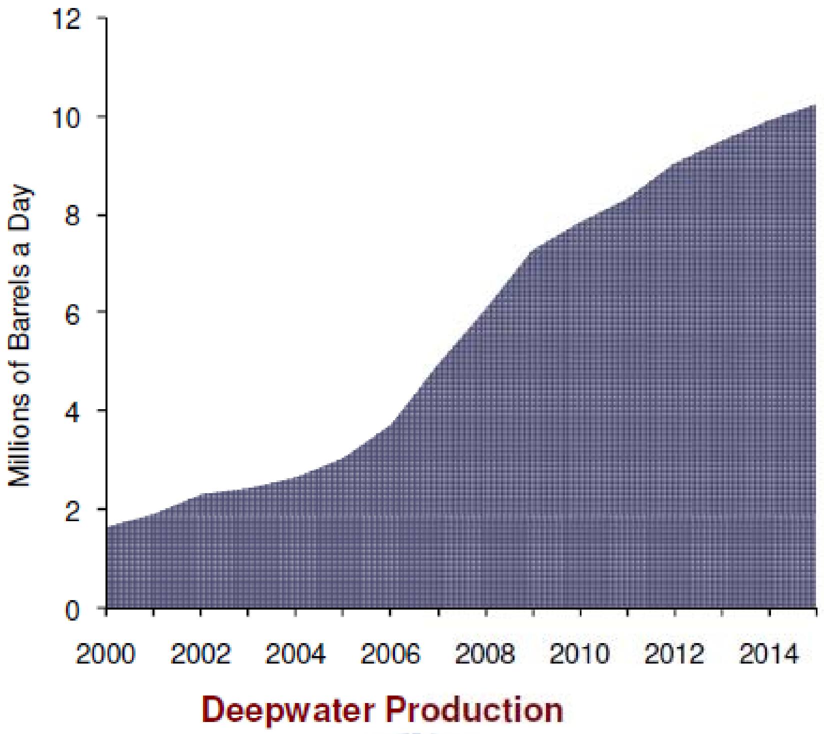


Fig. 1.2 Trend of deepwater production about oil

Researches have been continuing on one of core equipment consisting a flexible offshore structure, a very long slender body. Typically riser that used in the oil exploration and production of deep sea, mooring line for station keeping of structures, and pipe to intake water on Ocean Thermal Energy Conversion(OTEC) system.

Offshore structures are exposed on continuous hydraulic load by marine environment like waves and current inducing fluctuating motion of offshore structure. In this moment, excitation force is acting on bridged risers because flexible offshore structures move in the direction of three-dimension, according to elastic responses which are produced by fluids heading on inline and transverse direction to flexible offshore structure. (Chucheepsakkul et al., 1995; Park, et al., 2002; Lee, et al., 2013; Jung, 1999) Therefore, considerable dynamic studies and experiments for analyzing behavior of the slender body in marine environment are being carried out. In order to perform the model test of the slender structures, is very difficult to satisfy the geometric and dynamic similarity. So various experimental methods have been studied and developed. (Hong, et al,. 2002)

Generally, risers used in the oil and gas development are manufactured of steel. About water intake system in the deep sea, riser must be able to supply deep sea water of fine quality. So OTEC risers are not possible to use a steel pipe carrying oil and gas, but using a flexible material such as polyethylene. To conduct the optimal design of flexible offshore plant, there is a need for dynamic behavior analysis of the slender bodies those are manufactured by various materials. (Chena, et al., 2009; Jung, et al., 2004)

1.2 Recent research

External forces in ocean environment induced by waves and currents are eternally acting on flexible offshore structure those loads potentially lead structural defects of them. Due to the fact that researches for optimizing flexible offshore structure design were conducted in case of investigate slender model tests and figured out what immediate external forces make flexible offshore structure to behave in direction of flow. (Lee, et al., 2013).

Stabilizing riser applied on seabed mineral resources production becomes mightly important topic of research. About one of performed researches, slender model test was conducted based on riser on board Tension-Leg Platform(TLP) which has less heave motion. (Kwon, 2013). Unlike purpose of petroleum resource production, researches of riser using buoyancy system that extracts deep sea water have been in operation. One such example would be the structural analysis of riser on board OTEC system. And presuming behaviour of riser model under the different water depth and current velocity distribution. (Jung, et al., 2004).

In field of numerical analysis, study of stabilizing riser is consistently in operation by using simulation technique. Numerical analysis program has been developed to build database of flexible marine riser's three dimensional motion responses. Investigated availability of numerical analysis program through results of force oscillation model test. (Hong, et al., 2004). In sort of studies are still in operation about vortex shedding that has a large impact on motion of riser. Performed the motion analysis of deep-sea riser induced vortex shedding by using finite element method and how transverse motion response comes out according to reduced velocity. (Park, et al., 1999).

1.3 Objective of the dissertation

In this study, analyzing inline & transverse elastic responses of the slender body for various external force environment was conducted. Materials of model were chosen of Acryl, Polypropylene and Teflon; the modulus of elasticity is different each other. Experiment was performed with using the two-dimensional ocean engineering basin, the forced oscillation device and the current generation device are equipped in the Ocean Systems Engineering Laboratory(OSEL). Used the three-dimensional motion measurement device to analyze the displacement of riser models induced external force factors; forced oscillation by riser linked to forced oscillation device in current and regular waves condition.

CHAPTER 2. THEORETICAL BACKGROUND

2.1 Modulus of elasticity

Modulus of elasticity is a value that indicates the stiffness of the solid material mechanics. This factor is defined as the ratio of stress and strain. Stress-strain diagram can be used to determine the modulus of elastic from the slope of the linear region.

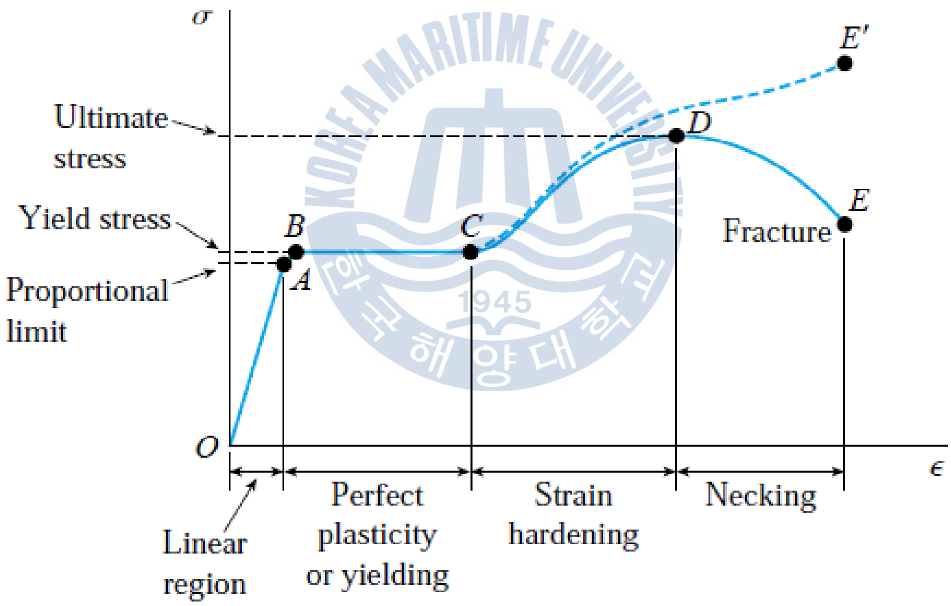


Fig. 2.1 Stress-strain diagram

The ratio of stress and strain is a constant within the proportional limit. This constant relationship is commonly known as Hook's law that proportional constant is corresponded to modulus of elasticity, signifies a linear slope within proportional limit.

$$\sigma = E\epsilon \tag{2.1.1}$$

Thomas Young proposed to use the ratio of the stress and strain to measure the stiffness of the material in 1970. This ratio is the Young's modulus or modulus of elasticity, Young's modulus is as follows.

$$E = \frac{\sigma}{\epsilon} = \frac{F/A_0}{\Delta l/l_0} = \frac{Fl_0}{A_0 \Delta l} \tag{2.1.2}$$

Unit of the modulus of elasticity is Pa, F is acting load, A_0 is the width of the cross-section of the material, Δl is the length variation of the material, l_0 is the original length of the material.

2.2 Natural frequency of experimental models

Grasping natural frequency of a model is highly significant to analyze elastic responses of slender structure acting on vary forced ocean environment. This study compared data from theoretical calculation and excitation experiment to figure out natural frequency of models.

Fixed a model support on forced oscillation device and let its cylinder part was free as cantilevered uniform beam. Formularized the circular natural frequency of this model as follow equation.

$$\omega_1 = 1.875^2 \sqrt{\frac{EI}{mL^4}} \tag{2.2}$$

Where w_1 is first circular natural frequency, E is the modulus of elasticity of the material, I is the moment of inertia of the cylinder cross-section, L is the length of the cylinder. And m is the mass per unit length of the cylinder, $m = (m_c + m_a)/L$, m_m is the mass of the material, m_a is the added mass, $m_a = \rho \pi r^2 l$, ρ is the density of water, r is the radius of the circular cylinder and l is length of the cylinder under water.

Table 2.1 displays circular natural frequency and natural period of each slender model as result of the equation 2.2 & experimental measurements.

Table 2.1 Natural frequency and period of models by theoretical calculations & experimental measurements

	Acryl	Polypropylene	Teflon
Calculated circular natural frequency ω_{C1} (rad/s)	18.97	14.06	7.34
Calculated natural frequency f_{C1} (Hz)	3.02	2.24	1.17
Calculated natural period T_{C1} (s)	0.33	0.45	0.86
Experimental circular natural frequency ω_{E1} (rad/s)	15.07	11.08	5.52
Experimental natural frequency f_{E1} (Hz)	2.4	1.76	0.879
Experimental natural period T_{E1} (s)	0.417	0.567	1.138
Error rate (%)	20.6	21.2	24.8

According to Table 2.1, values of natural frequency and period seem about the same tendency but it has a little distinction caused by added mass & damping effects. In this study conducted to analyze experimental result of natural frequency.

2.3 Vortex shedding effects & Dimensionless number

Vortex shedding is an oscillating flow that takes place when the water flows a cylinder body at certain velocities. In this phenomena, vortices are created at the back of the body and detach periodically from either side of body. According to Fig. 2.2, the fluid flow past the cylinder creates alternating low pressure vortices on the downstream side of cylinder due to fluid's viscosity. If vortex shedding matches the natural frequency of the structure, it can begin to resonate, vibrating with harmonic oscillations driven by the energy of the flow which is defined as Vortex Induced Vibration(VIV). VIV is must be considered in terms of design flexible offshore construction.

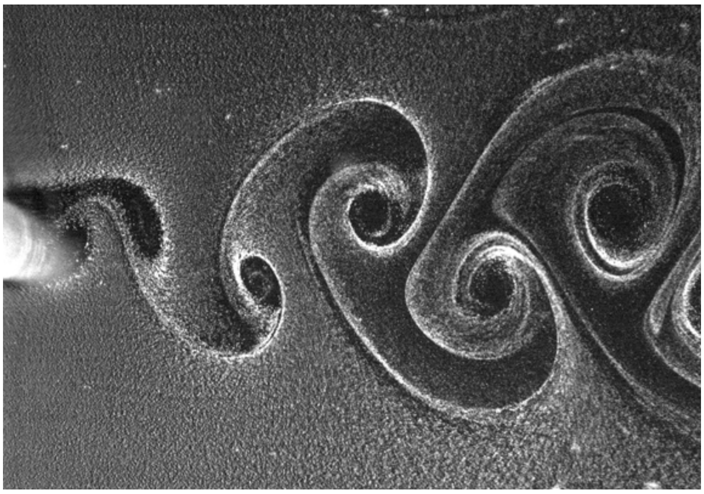


Fig. 2.2 The vortex around circular section

Dimensionless number aids to figure out which ocean forced environment causes vortex shedding to come out. In this study, there are two dimensionless numbers to apply, Reynolds number(*Re*) and Keulegan-Carpenter number(*K.C*).

$$Re = \frac{UD}{\nu} \tag{2.3.1}$$

Where U is the flow velocity, D is the diameter of the cylinder and ν is the kinematic viscosity of the fluid. The *Re* regimes of vortex shedding from a circular cylinder are given in Fig. 2.3.

In the Fig. 2.3, at very low *Re*, below about Re=5, the fluid flow follows the cylinder contours. The first separation occurs at Re>5. In the range $5 \leq Re < 40$, a fixed pair of vortices forms in wake of the cylinder. As *Re* is further increased, the wake becomes unstable and one of the vortices breaks away. Vortices are shed alternately at both side of cylinder and the wake has an appearance of a vortex street. For the range of the *Re*, $40 \leq Re < 150$, the vortex street is lanimar. Between Re=150 and 300, transition to turbulence occurs in the wake region. The *Re* range $300 < Re < 1.5 \times 10^5$ is knows as the subcritical regime. In this range, the laminar boundary layers separate at about 80° aft of the nose of the cylinder and the vortex shedding is strong and periodic.

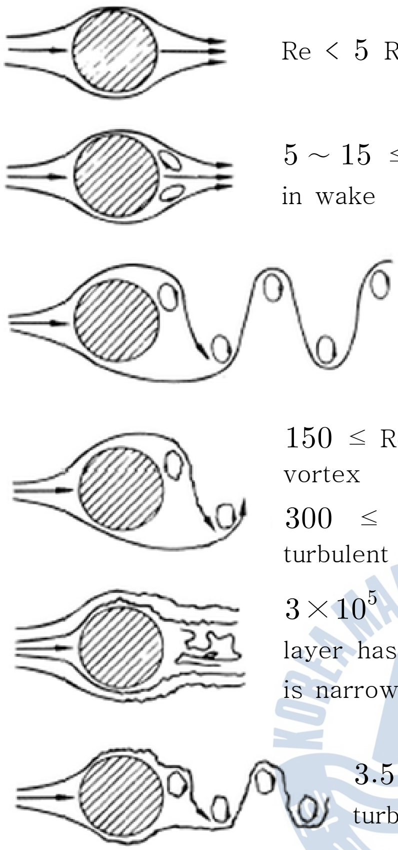


Fig. 2.3 Regimes of fluid flow across smooth circular cylinders

In this study, *Re* about experimental forced environment distributes in range of $300 < Re < 1.5 \times 10^5$. Transverse displacement is observed in direction of heading angle(inline) influenced by vortex shedding that actually happen on experiment.

Used $K.C$ number to figure out tendency of vortex shedding on water surface in sequence. And the vortex shedding produces lift forces transverse to the direction of flow that can induce substantial transverse vibration. $K.C$ number as follow equation.

$$K.C = \frac{U_{\max} T}{D} \tag{2.3.2}$$

Where U_{max} is the maximum horizontal fluid particle velocity, T is the wave period and D is the diameter of the cylinder. The $K.C$ regimes of vortex shedding from circular cylinders in oscillating flows are given in Fig. 2.4. When $K.C$ is low, below 3, a symmetric pair of vortices are formed in wake nearby a cylinder and its lift forces are minimal. When is greater than or equal to 3 and less than 8, one of the vortices in the pair becomes stronger and pairs of vortex become asymmetric formation. Lift forces increase at that time. In the range $8<K.C<13$, pairs of vortex are alternately shed into wake during half-cycle of flow oscillation. And then vortex shed out behind a cylinder. For the range $13<K.C<20$, multiple pairs of vortices are shed in each flow oscillation cycle and breakup about 45° to the direction of flow oscillation. In state of quasi-steady vortex shedding when $K.C>26$, the symmetric of vortices keep to wander and lift forces are acting on direction of both cylinder edges.

Range of $K.C$ about experimental forced environment is greater than 13. Transverse motion response is observed while vortex shedding producees lift force.

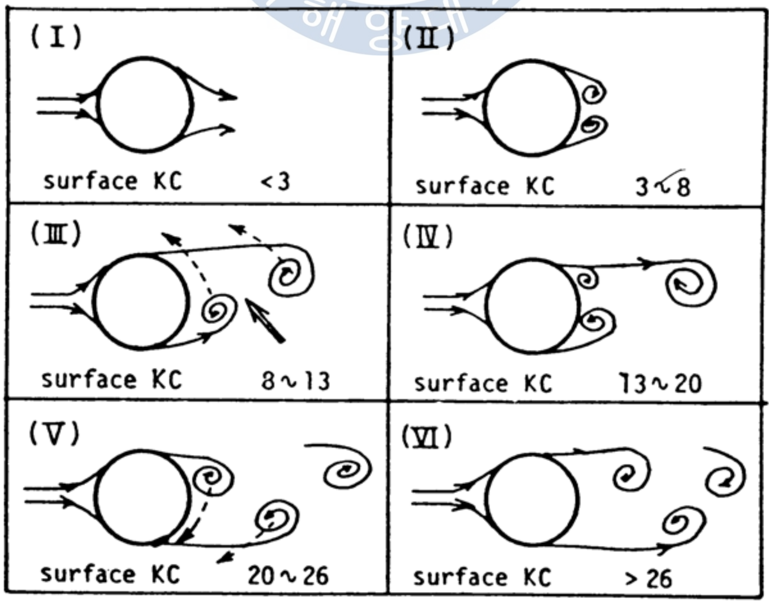


Fig. 2.4 Vortex shedding patterns around a vertical cylinder in waves as functions of $K.C$

Shedding frequency is required to analyze phenomena of vortex shedding. Natural frequencies of model and vortex shedding would be resonated when they are matched or multiplied, they resonate(lock-in). An equation for vortex shedding frequency as follow.

$$f_s = \frac{S_t U}{D} \tag{2.3.3}$$

Where f_s is the vortex shedding frequency, S_t is the Strouhal number, U is flow velocity and D is the diameter of the cylinder. Strouhal number is the function of the Reynolds number as Fig. 2.5

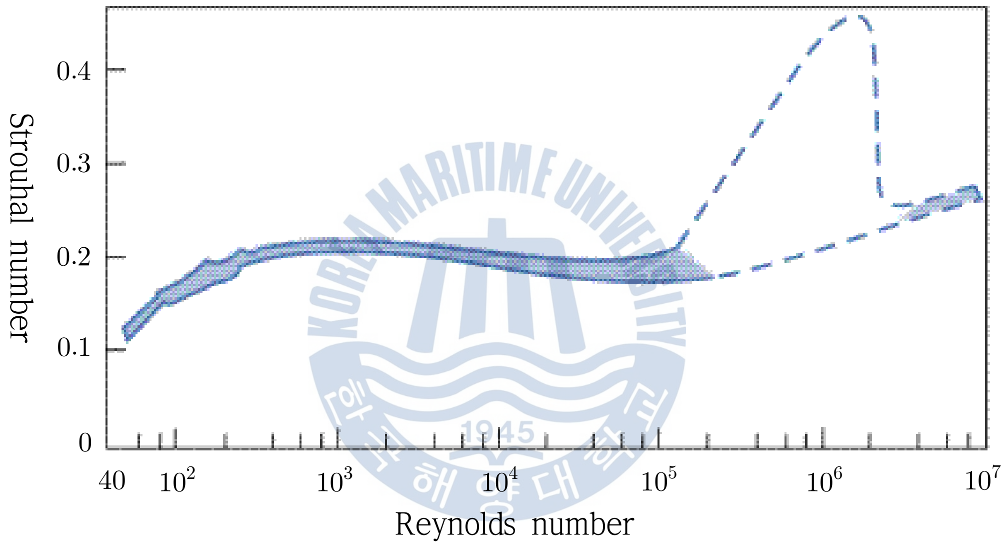


Fig. 2.5 Strouhal number & Reynolds number relationship for circular cylinders

CHAPTER 3. EXPERIMENTAL METHODS & MODELS

3.1 Experimental equipment

3.1.1 Two-dimensional ocean engineering basin

The experimental study is conducted on two-dimensional ocean engineering basin, which dimensions are 25 m×1 m×1.3 m(L×B×D). Basin belongs to Ocean Systems Engineering Laboratory(OSEL), Korea Maritime Ocean University(KMOU). The main function of piston wave generator equipped on basin is to generate wave its period up to 0.5 to 3.0 sec. The wave generator is able to produce types of regular and irregular wave which is applicable on ISSC, ITTC and JONSWAP wave energy spectrum. This study deals regular waves only.

Fig. 3.1 Two-dimensional ocean engineering basin

3.1.2 Forced oscillation device

Forced oscillation device travels on straight lines of X, Y, and Z axis. Also it oscillates in direction of θ. Forced oscillation device is able to synchronize the motions of all 4 degrees or move on each direction. Forced oscillation device is operated by rack and pinion system that allows to travels along x-axis by performing maximum speed as $1.5\,m/s$, its positive and negative acceleration as $0.5\,m/s^2$ and traveling distance is approximately 18 m. Experiment is conducted while model is settled on right position that device.

Fig. 3.2 Forced oscillation device

3.1.3 Current generation device

Current generation device is equipped inner two-dimensional ocean engineering basin. Horizontal circulating pump system which is able to control flow direction by valves and change current velocity by managing revolution of pump. The maximum current velocity is 0.4 m/s.

Fig. 3.3 Current generating device - Pump

3.1.4 Servo type wave height meter

Servo type wave gauge contacts water surface with an electrode pin and earthing conductor that has no interference between gauge and wave so measuring accurate wave height is possible. Servo type wave gauge measures the maximum or minimum wave height as 150 mm. Settle gauge in the middle of location between wave generator and a model.

Fig. 3.4 Servo type wave height meter

3.1.5 Acoustic Doppler Velocimetry(ADV)

Used Acoustic Doppler Velocimetry to measure flow velocity. A range of measuring flow velocity from 1 mm/s to 2.5 m/s and its error approximately ±1 %. As Fig. 3.5, detection part of Acoustic Doppler Velocimetry forms of three-forked legs that have to be closer about 5cm to the range of measuring flow velocity.

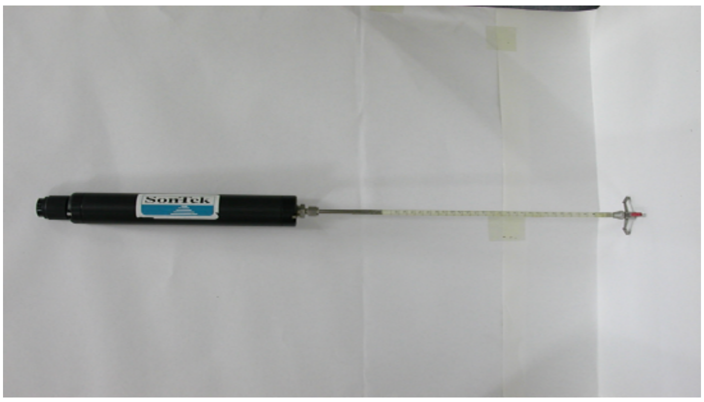


Fig. 3.5 Acoustic Doppler Velocimetry

3.1.6 Three-dimensional motion measurement device

Used three-dimensional motion measurement device to analyze the responses of elasticity of Slender cylinder model. Tracking motion of slender cylinder model is achieved by capturing reflecting marker displaced on model at regular intervals. Captured information of motion by five CCD(Charged-Couple Device) cameras and MCU-24(Multi Camera Unit-24) is classified of X, Y, and Z displacements as Fig. 3.6. Operated DIPP-Motion program to reduce errors and revise disturbance caused by reflectors.

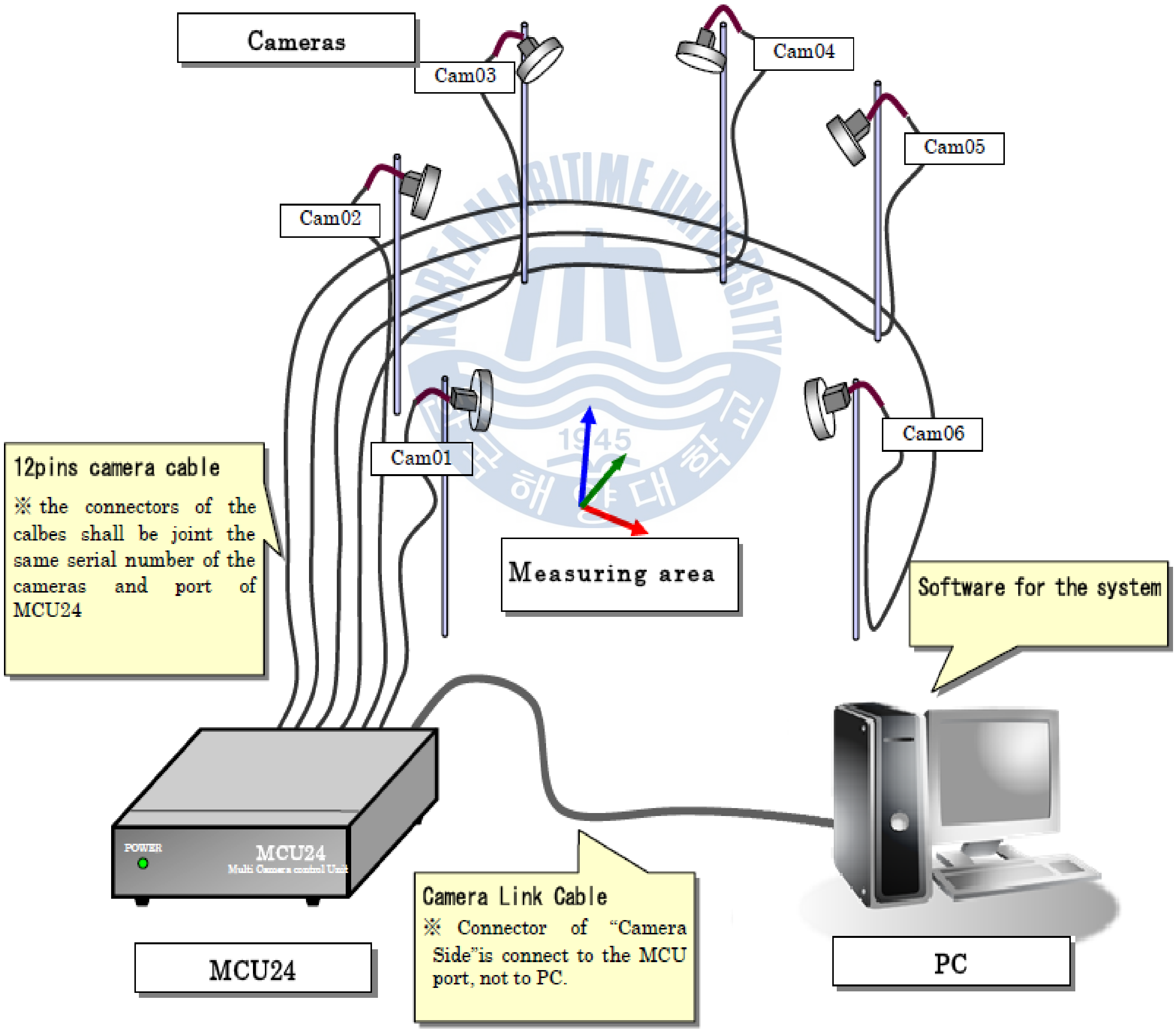


Fig. 3.6 Three-dimensional motion measurement device

3.2 Experimental models

As Fig. 3.7, models consist of 1cm width of disk and three different materials of slender structure as Acryl, Polypropylene(P.P), and Teflon those are characterized by own elasticity coefficient refer to Table 3.1. Reflective markers are placed on each model by 4cm intervals.

Fig. 3.7 Photo of slender body models

Table 3.1 Principal particulars of models

	Model I	Model II	Model III
Material	Acryl	Polypropylene (P.P)	Teflon
Length (m)	0.9		
Diameter (m)	0.01		
Mass per length in air (kg/m)	0.01019	0.00804	0.0188
Young's Modulus (Gpa)	2.943	1.57	0.491

3.3 Experimental methods and conditions

The experiment was conducted with three different slender models. Those mean modulus of elasticity also vary. Slender models were fixed to forced oscillation device in the two-dimensional ocean engineering basin; wave generator and forced oscillation device are established a synchronizing system which is able to control devices more accurately. A net-type wave absorber to minimize the influence of the reflective wave is placed on the end of the basin; as the Fig. 3.8 indicates, the experiment was performed by setting the model in the center of the basin. The five CCD cameras were used to detect minute displacement data of moving slender models. Since accurately performing the calibration procedure of the three-dimensional motion measurement device, the errors of the measurement data being minimized less than 1 mm.

A slender model is placed as in the Fig. 3.9, the experiment was conducted in six types of marine environment that distributes different external force conditions each case; First, the single forced oscillation is applied to models if external force is acting on the same current direction as wave incidence. Second case is single regular waves in applied to models. Third case is onset of single current to models. Fourth is the forced oscillation and regular waves are applied to the model. Fifth, the regular waves and current are applied to the model. Lastly, the forced oscillation, regular waves and current are applied to the model at the same time.

Table 3.2 and Table 3.3 show the experimental conditions of the external force environment. Table 3.2 shows that single external force is applied to the Acryl, P.P, and Teflon models. Table 3.3 shows that combined external force is acting on Teflon model. Each case of experiment was performed three times for reproducibility of the experimental phenomenons. Used a video camera to observe the singularities during experiment and utilize data to compare and analyze modulus of elasticities up to various types of external force conditions.

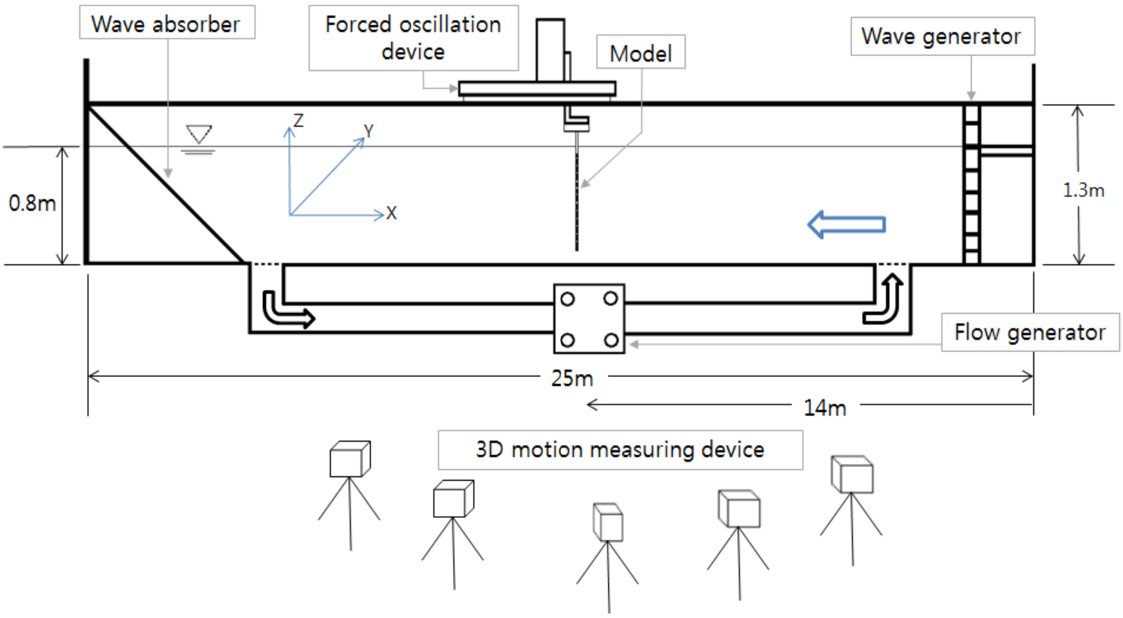


Fig. 3.8 Schematic of the experimental method

Fig. 3.9 Slender body model test in regular waves

Table 3.2 Experimental conditions for a single external force

Acryl, P.P, Teflon					
Forced oscillation	Period (sec)	3.0	4.0	5.0	
	Amplitude (mm)	250			
Regular waves	Period (sec)	0.8	1.0	1.5	2.0
	Wave height (mm)	80	100		
Current	Velocity (mm/s)	150			

Table 3.3 Experimental conditions for synthesized external forces

Teflon			
Forced oscillation	Period (sec)	3.0	
	Amplitude (mm)	250	
Regular waves	Period (sec)	1.0	1.5
	Phase difference	Case I, Case II	Case III
	Wave height (mm)	50, 100	
Current	Velocity (mm/s)	150	

3.4 Data measurement and processing

As mention earlier, fourteen points of the reflector are attached to the slender body model at 4 cm intervals; displacement of the X, Y, Z axis of the points was measured. As the Fig. 3.10, thirteen points of marker(reflector) was measured without top of models because it was difficult to measure displacement of the reflector located at the top of the model.

By using displacement data of each point to understand the tendency of the three-dimensionally moving slender models. Analyzing elastic responses in the direction of inline(X-axis) and transverse(Y-axis) was conducted. Difference of X-axis displacement from point 1 & 13 was expressed in the concept of relative displacement. The elastic responses of the inline were shown by using data of the relative displacement. The elastic responses of the transverse were shown by using the maximum displacement of the Y-axis of point 13.

Fig. 3.10 Photo of reflecting markers attached on a model for displacement measurement

CHAPTER 4. RESULTS & DISCUSSION

4.1 Three-dimensional behavior analysis

Measured the three-dimensional displacement data of models before comparing the elastic responses analysis of the inline and transverse up to vary experimental conditions.

Fig. 4.1 is displacement data of Teflon model in the forced oscillation. Device oscillated Teflon model in period of 3.0 sec and its amplitude is 250mm. The graph at the top left is a representation that the reflectors are attached to three-dimensionally moving model. The graph at the top right is a representation by projecting the 3D data to the XZ plane; graph at the bottom left, it was represented by projected on the XY plane. And the graph at the bottom right, it was represented by a projection on the YZ plane. The relative displacement in the XZ plane graph was represented by a maximum of '+' and '-' direction.

Fig 4.2 is displacement data of P.P model in the regular waves; wave period is 2.0 sec and wave height is 100 mm. Analyed motion responses of models in both inline and transverse direction.

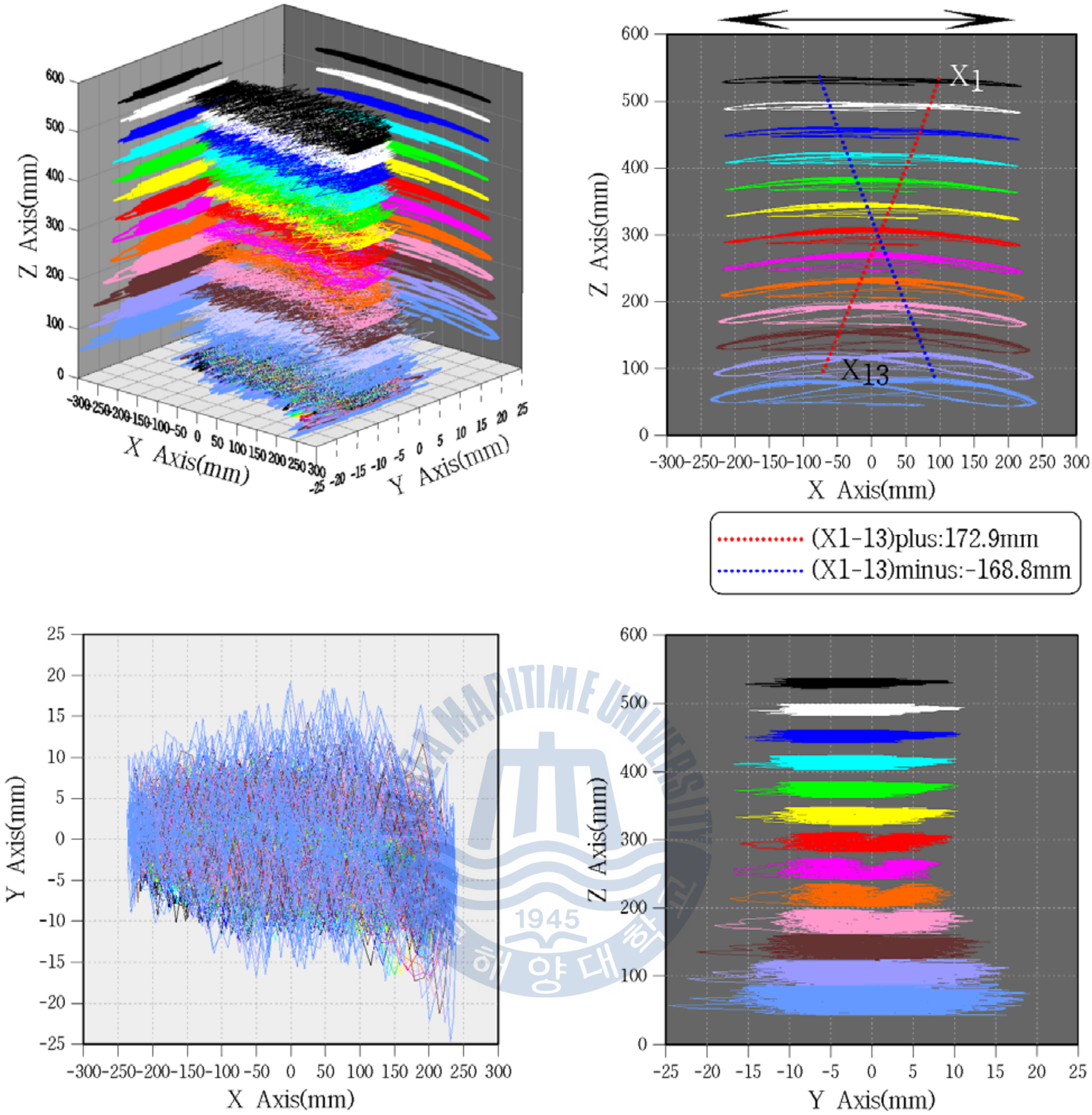


Fig. 4.1 Three-dimensional displacement data of the Teflon model in the forced oscillation (Forced oscillation period: 3.0 sec, amplitude: 250 mm)

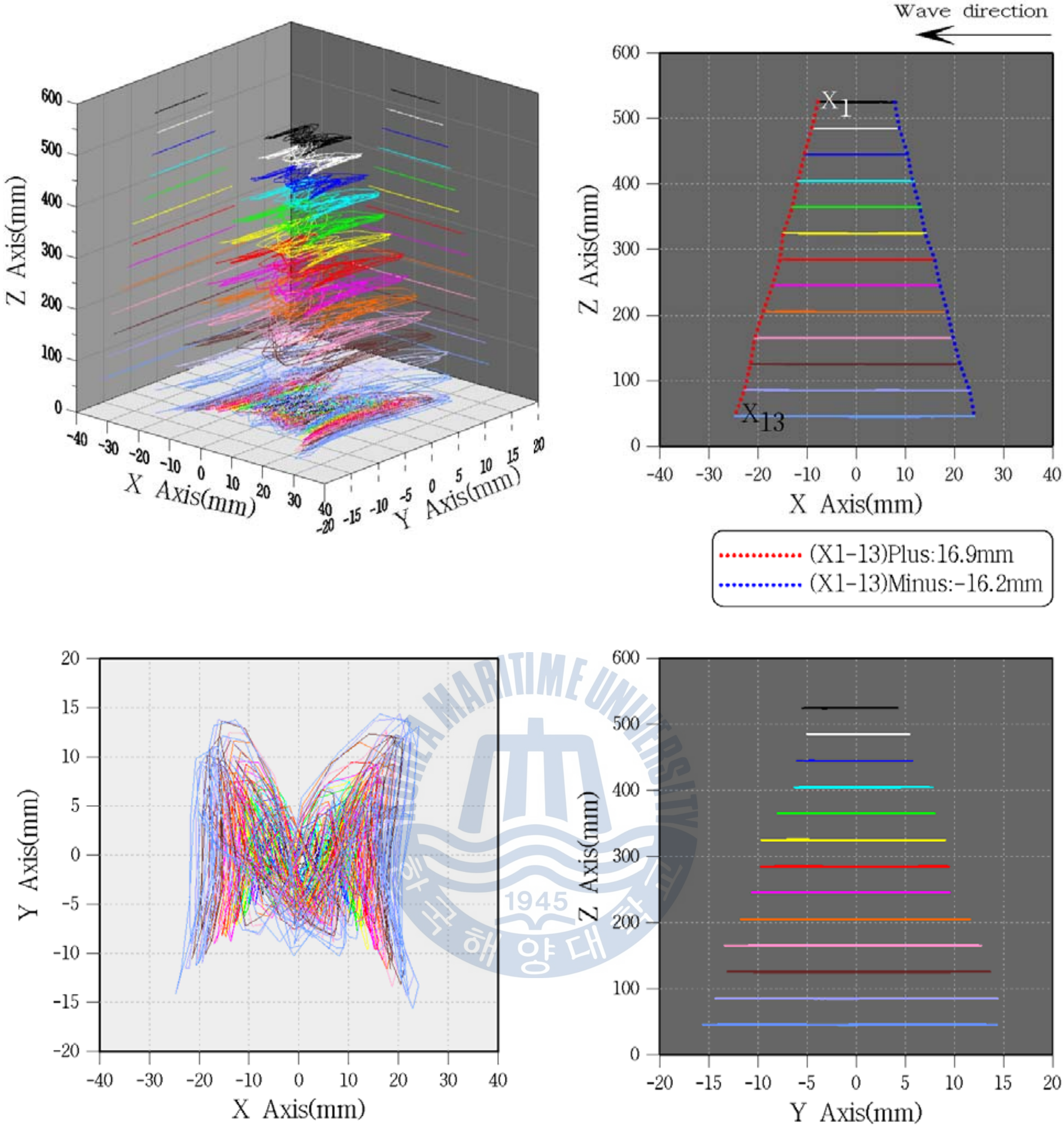


Fig. 4.2 Three-dimensional displacement data of P.P model in the regular wave (Wave period: 2.0 sec, wave height: 100 mm)

4.2 Elastic responses of the single external force environment for each models

In this section, the elastic responses from regular waves, current and oscillation acting on slender models in both inline and transverse drections.

Fig. 4.3 (a) and (b) are presented the trends of the elastic responses depending on the forced oscillation periods 3.0, 4.0, 5.0 sec.

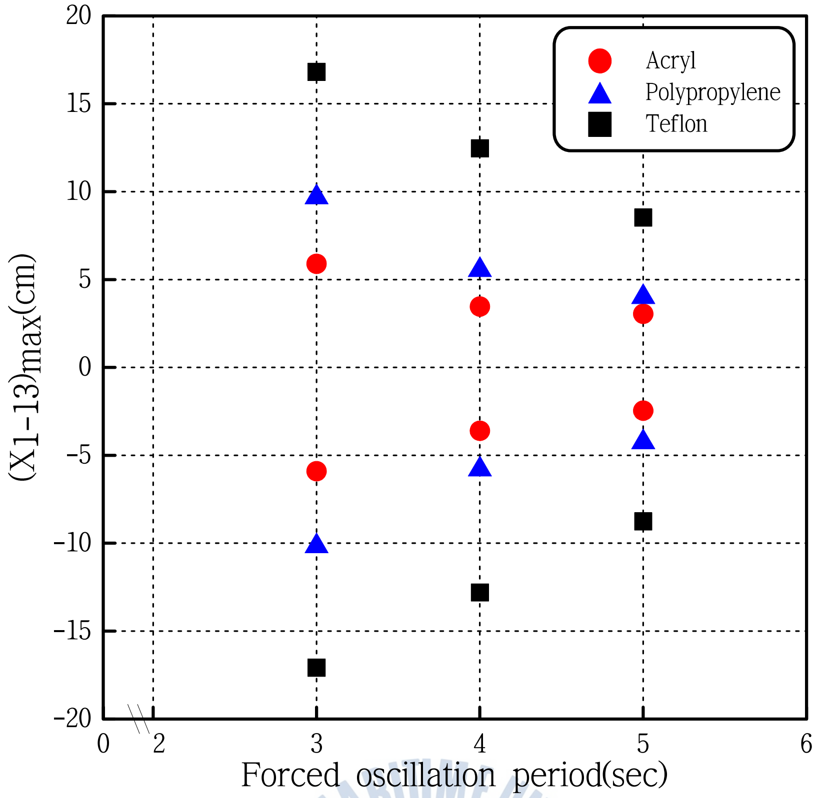
To begin with, in the Fig. 4.3 (a), we have noticed the symmetry of the relative displacement between the plus(+) and minus(-) direction in coordinates. Moreover, when the stiffness of the model is more mild and the period of the forced oscillation is shorter, the elastic responses of the inline are more increased.

Next, in the Fig. 4.3 (b), when period is 3.0 sec, Teflon that has the mild stiffness is presented the biggest responses. However, P.P has medium stiffness when period is 5 sec. Given these phenomenons, it seems a resonance as a resonance between natural frequency of the P.P model and vortex shedding frequency.

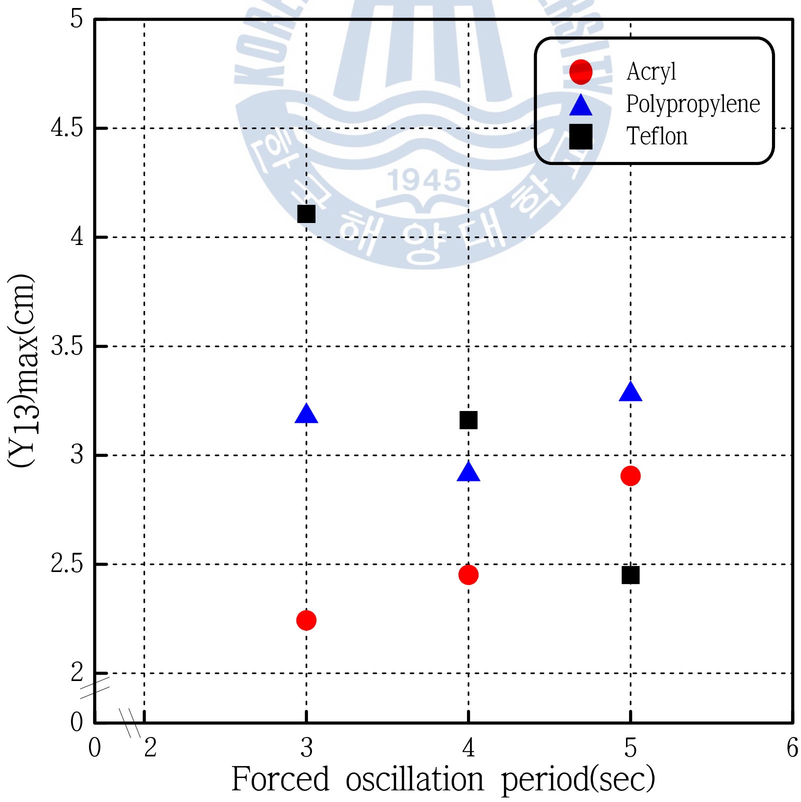
Fig. 4.4 (a) and (b) are presented the tendency of the elastic responses depending on the regular waves period 0.8, 1.0, 1.5, 2.0 sec and height 80, 100 mm. In the Fig. 4.4 (a), we have noticed the symmetry of the relative displacement between the plus and minus direction. When the stiffness of the model is more mild and the period of the regular wave is longer, the responses about the inline direction are bigger. While, transverse responses are increased totally by extending wave period; and particularly, responses of P.P has medium stiffness are more increased than Acryl and Teflon that have strong and mild stiffness.

The elastic responses about the current are presented in the Fig. 4.5. As with this graph, inline responses are increased when stiffness is mild. While, transverse responses are presented biggest when the model is P.P has medium stiffness. This phenomenon bears resemblance to trends of responses about forced oscillation and regular waves.

According to analysis of elastic responses in the single forced environment, investigation of offshore environmental condition has to be taken in precedence in order to select material for design a slender structure.

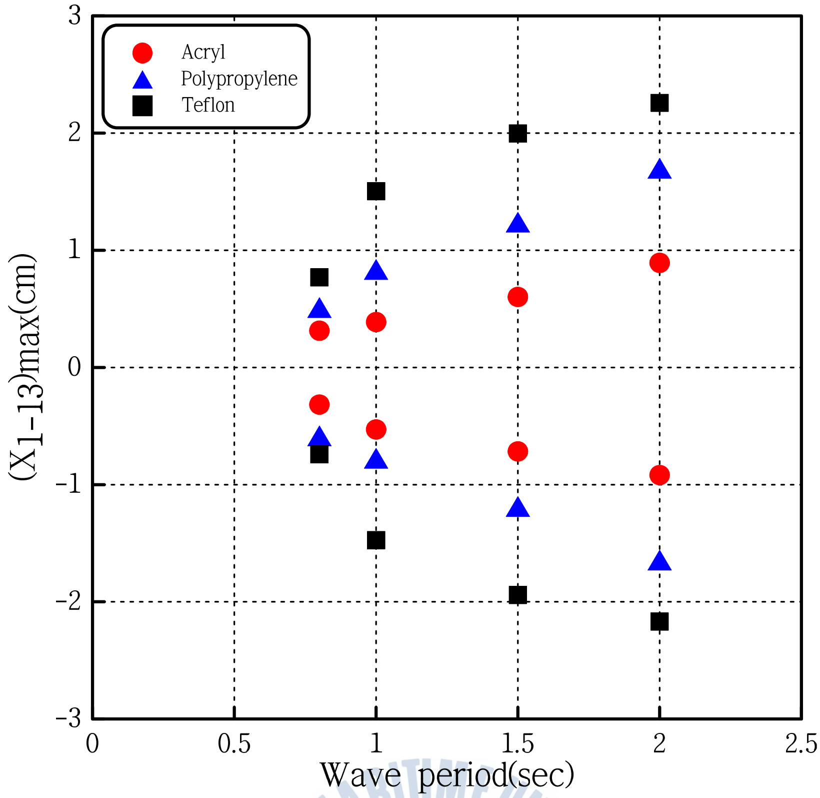


(a) Inline elastic responses

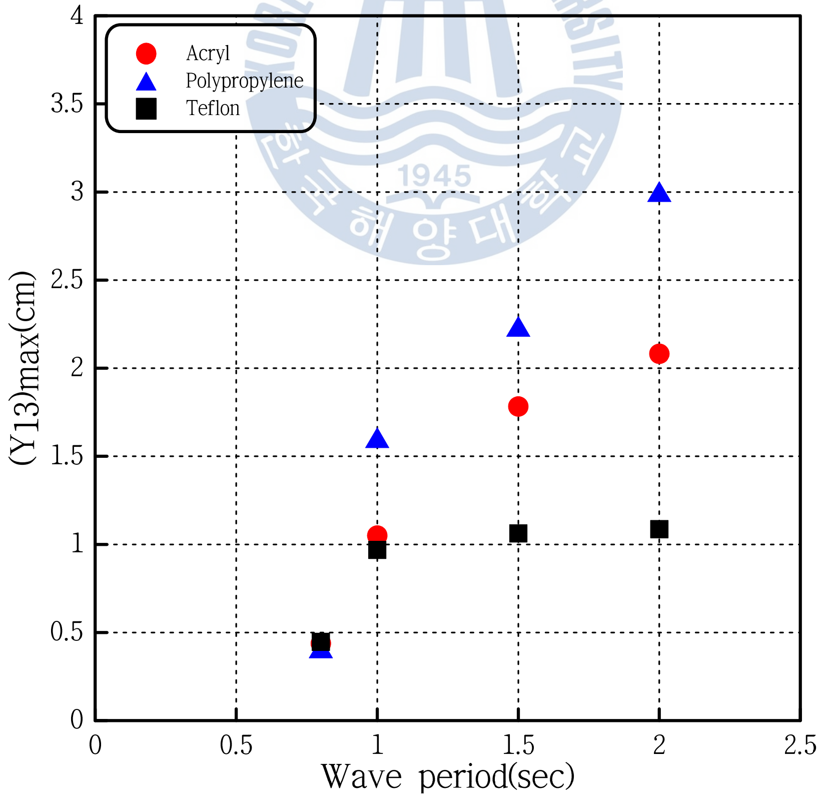


(b) Transverse elastic responses

Fig. 4.3 Elastic responses of the forced oscillation for models



(a) Inline elastic responses



(b) Transverse elastic responses

Fig. 4.4 Elastic responses of the regular waves for models

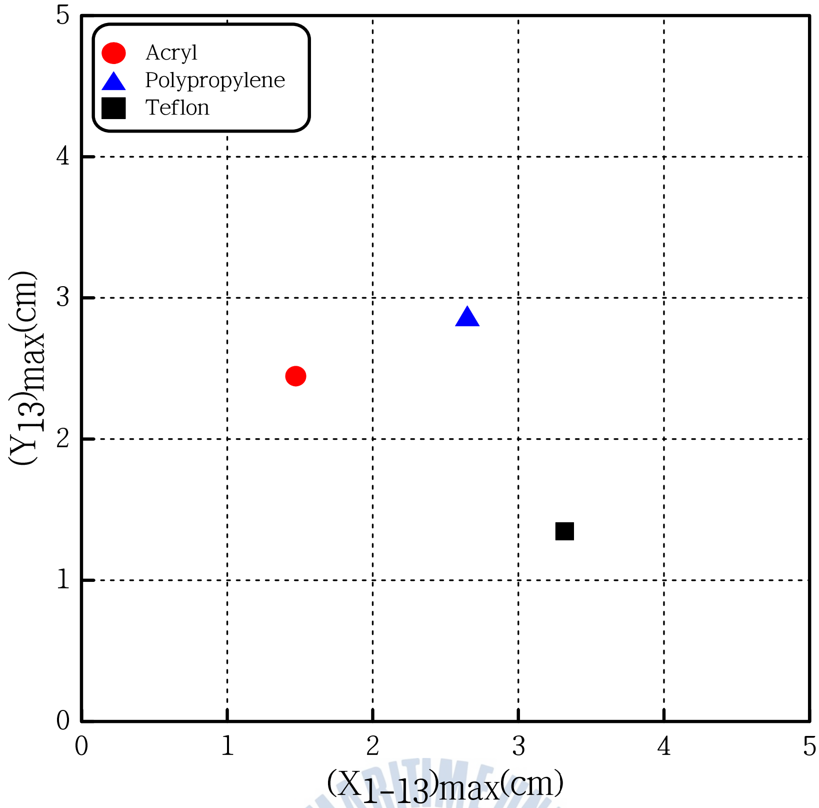


Fig. 4.5 Inline & Transverse elastic responses of the current for models (Current velocity: 150 mm/s)

4.3 Shedding frequency in current condition

As Fig. 4.6, domain of frequency is indicated by using displacement(Y13) in direction of transversely moving slender models. This graph signifies x-axis as natural frequency of slender model and y-axis as amplitude of motion. Color of lines display each material of model, a red line means Acryl, a blue line means P.P, and a black line means Teflon. It makes a little difference of shedding frequency between calculation and experiment. The range of shedding frequency calculated by equation (2.3.3) is about 2.85~3.3 Hz and in consequence of experiment is 2.75 Hz. In case of test Teflon model, the domain of shedding frequency is lower than calculation because it seems a Teflon model to move in direction of flow. However, experiment data that shedding frequency of Acryl and P.P model from experiment are within a range of calculated frequency value. So shedding frequency from model test is reliable in a measure. To support an experimental result, graph on Fig. 4.6 shows natural frequencies of each model are distinguishable with shedding frequency and resonant phenomenon(lock-in) does not occur.

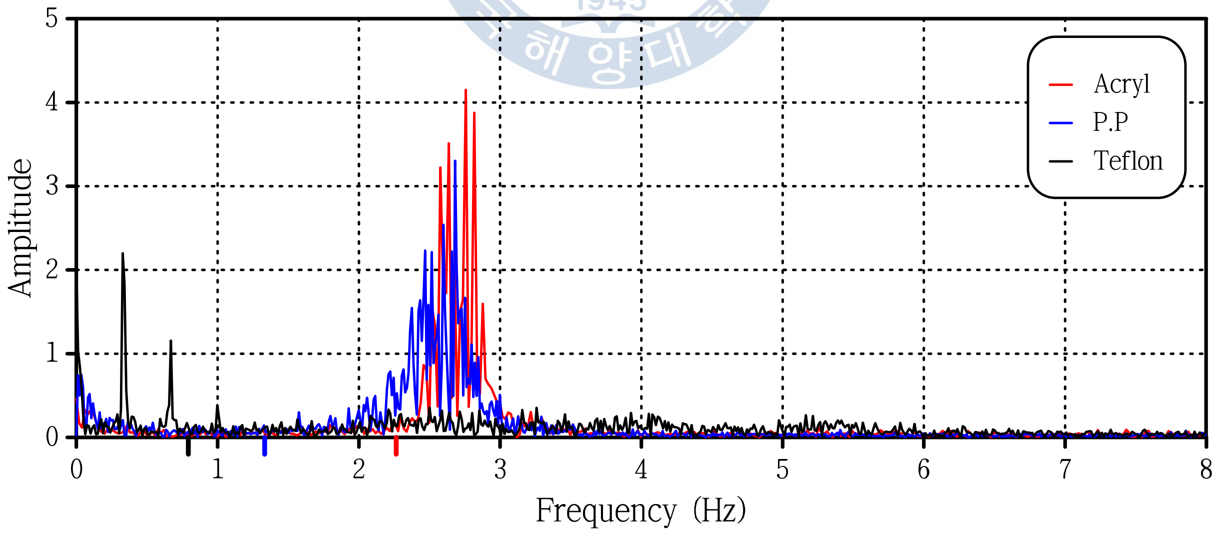


Fig. 4.6 Analyzing frequency domain relative to transverse elastic response of each slender model

4.4 Elastic responses of the synthesized external force environment for a Teflon model

In this section, inline and transverse elastic responses are analyzed when the synthesized external forces are applied to the Teflon model. When the external forces are synthesized, there are three cases. First, when the forced oscillation and regular waves have been synthesized; second, when the regular waves and current have been synthesized; third, when the forced oscillation, regular waves and current have been synthesized. The analysis were carried out for the elastic responses of the single external force and synthesized external forces.

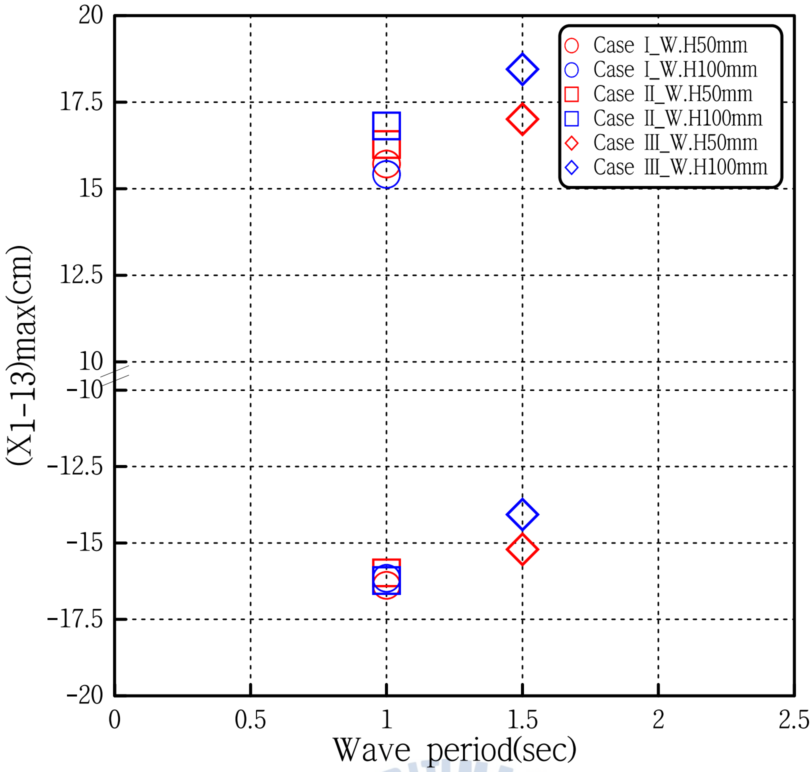
4.4.1 Elastic responses of the forced oscillation and regular waves for a Teflon model

Fig. 4.7 (a) and (b) are graphs of the elastic responses when the forced oscillation and regular waves are applied to the Teflon model; the forced oscillation period is 3.0 sec, the amplitude is 250 mm and regular waves period is 1.0, 1.5 sec and the wave height is 50, 100 mm. In these graphs, red and blue symbols mean the wave height 50, 100 mm.

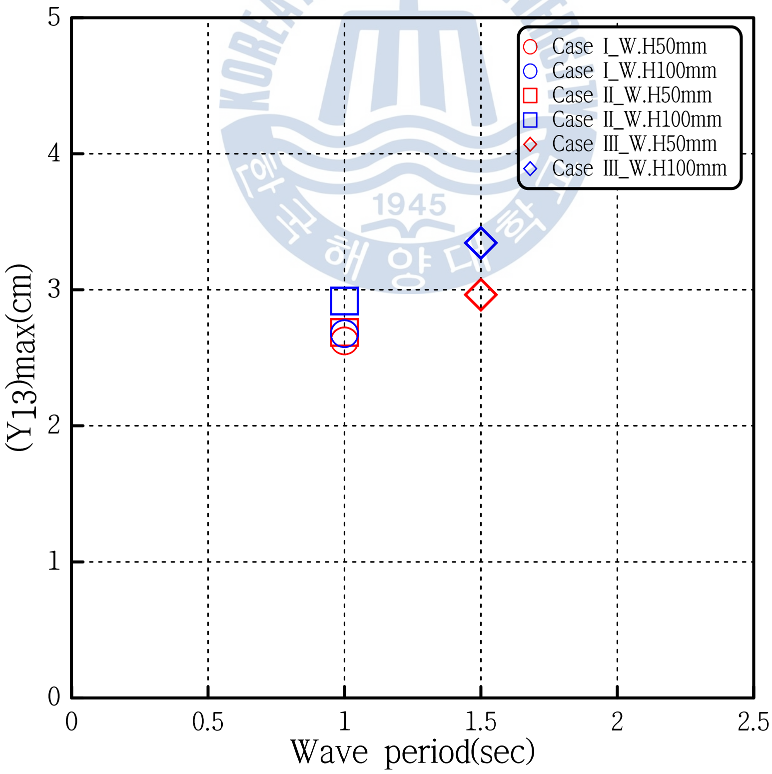
When the forced oscillation and regular waves are combined the phase difference is occurred as shown Fig. 4.8. To explain this graph, the graph of the top shows the phase of the forced oscillation; below two graphs indicate phase differences of 180° (Case I) and 0° (Case II) of the forced oscillation in wave period 1.0sec. And the graph of the bottom, means the phase difference 90° (Case III) of the forced oscillation in wave period 1.5sec. In the Fig. 4.7 (a) and (b), circular and rectangular symbols show the phase differences case I, II in the wave period 1.0 sec; diamond symbol means the phase difference case III in the wave period 1.5 sec.

The inline elastic responses of the synthesized the external forces are shown in Fig. 4.9 (a). In this figure, the dotted line of the purple means the responses of the single forced oscillation; '+' and '×' symbols are the responses of the single regular waves, and the remaining symbols are as mentioned above. When the forced oscillation and the regular waves are synthesized, depending on the phase, the interaction varies. In the Fig. 4.9 (a), as the wave height becomes large in the wave period 1.0 sec, the responses are increased. These can be shown in the interaction by the waves. However, when the wave period is 1.5 sec, the responses are not increased by the wave height becomes large. So, Elastic responses are difficult to be increased by the waves. Consequently, according to the phase of two external forces are encountered, the interaction can be varied. Due to the fact that elastic responses likely change because of interaction are not constant in accordance with a phase of two external forces encounter.

Fig. 4.9 (b) shows transverse elastic responses, and symbols of the figure are as described above. Synthesized elastic responses of two external forces are getting smaller than a single forced oscillation. This fact would be regarded as the due to interaction between both of the external forces. And the responses appeared differently according to the phase between the both external forces.



(a) Inline elastic responses



(b) Transverse elastic responses

Fig. 4.7 Elastic responses of the forced oscillation & regular waves for a Teflon model-I

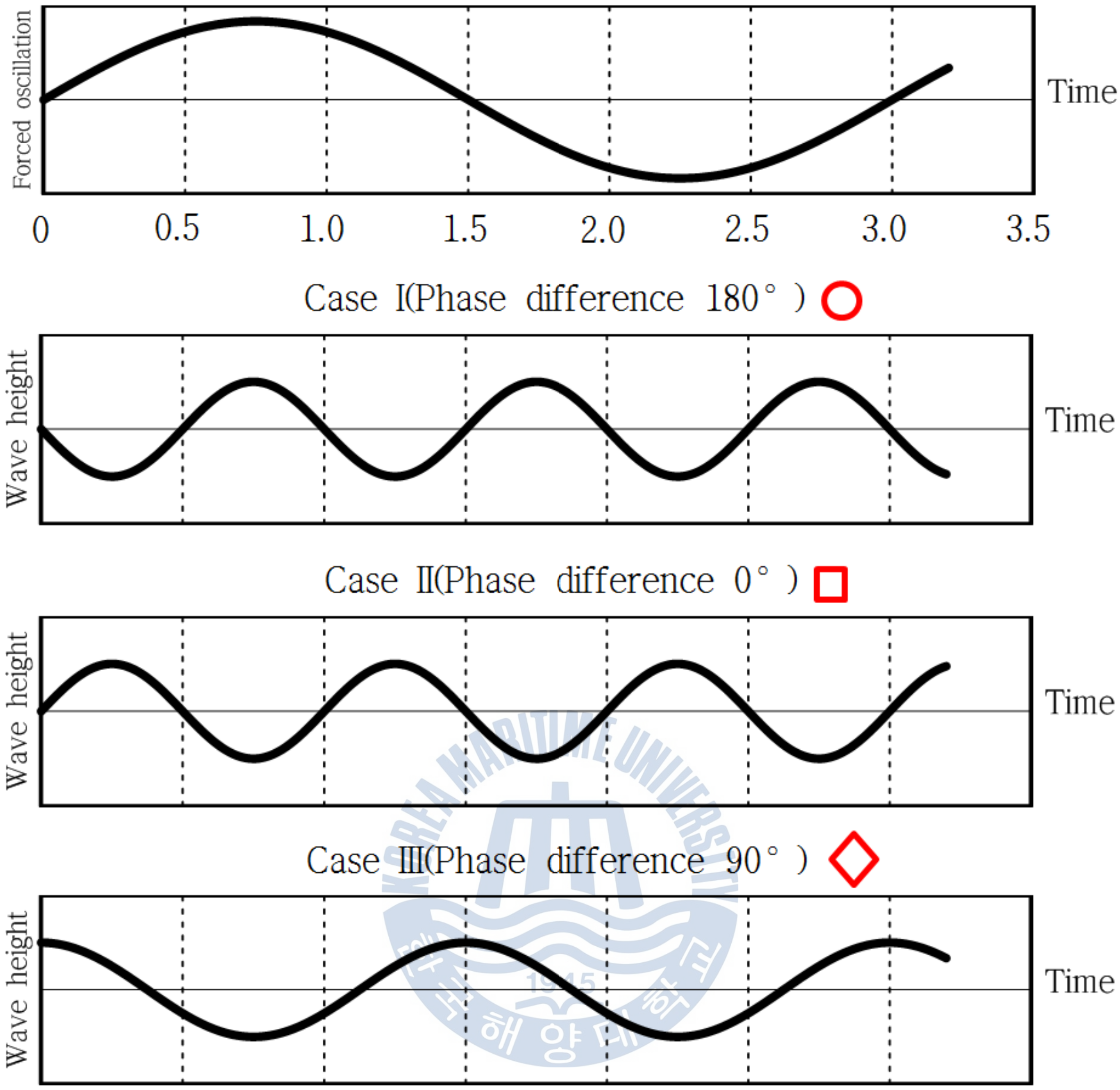
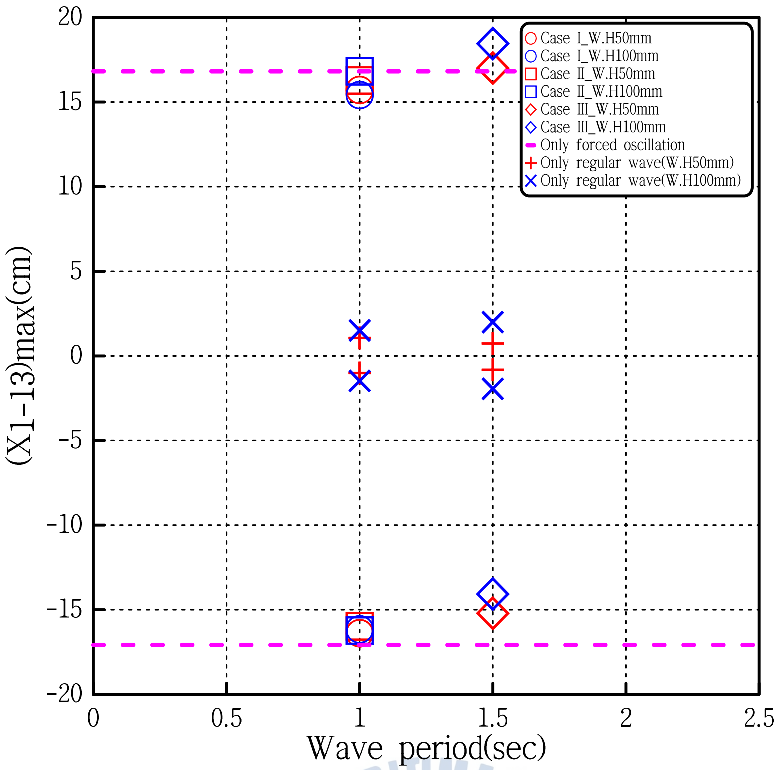
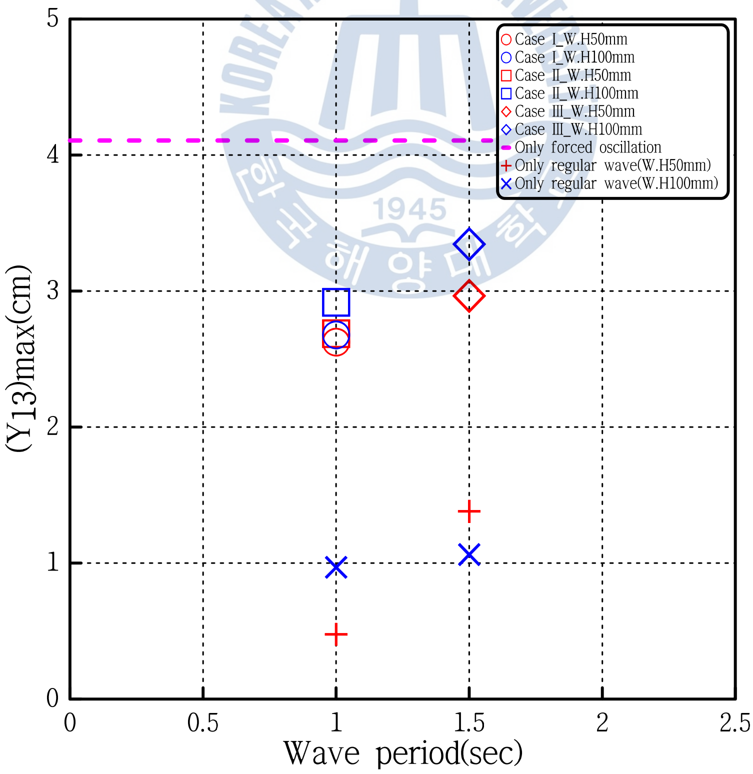


Fig. 4.8 Phase difference of the forced oscillation & regular waves



(a) Inline elastic responses



(b) Transverse elastic responses

Fig. 4.9 Elastic responses of the forced oscillation & regular waves for a Teflon model-Ⅱ

4.4.2 Elastic responses of the regular waves and current for a Teflon model

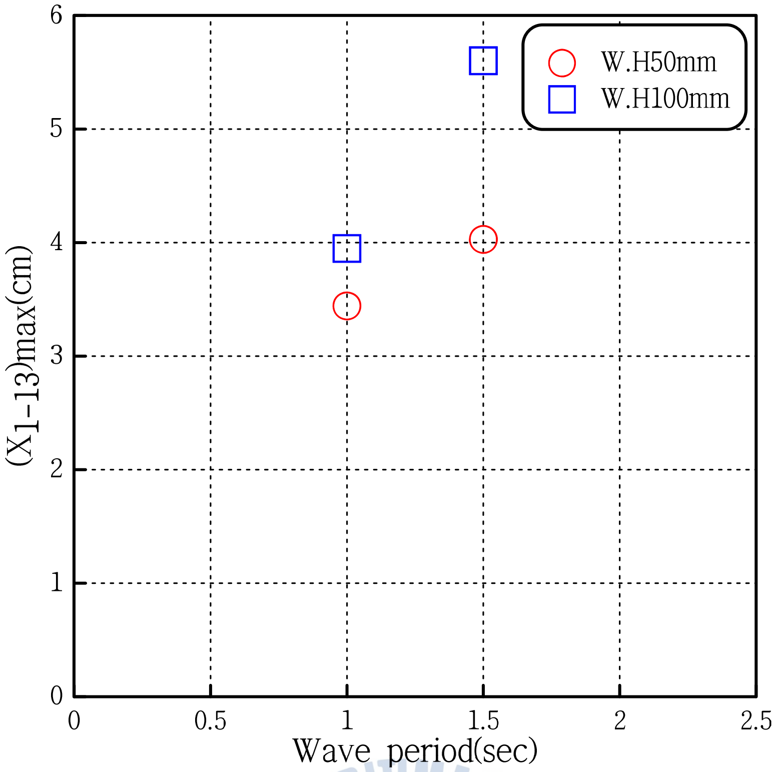
Fig. 4.10 (a), (b) are graphs of the inline and transverse elastic responses when regular waves and current are applied to Teflon model; regular wave period is 1.0, 1.5 sec, and the velocity of current is 150 mm/s. In this figure, red circle and blue square indicate the wave height 50, 100 mm.

The inline elastic responses of the synthesized and single external forces are shown in Fig. 4.11 (a). In this figure, '+' and '×' symbols are responses of a single regular waves; the dotted line of the green indicates the responses of the current, and the remaining symbols are as mentioned above.

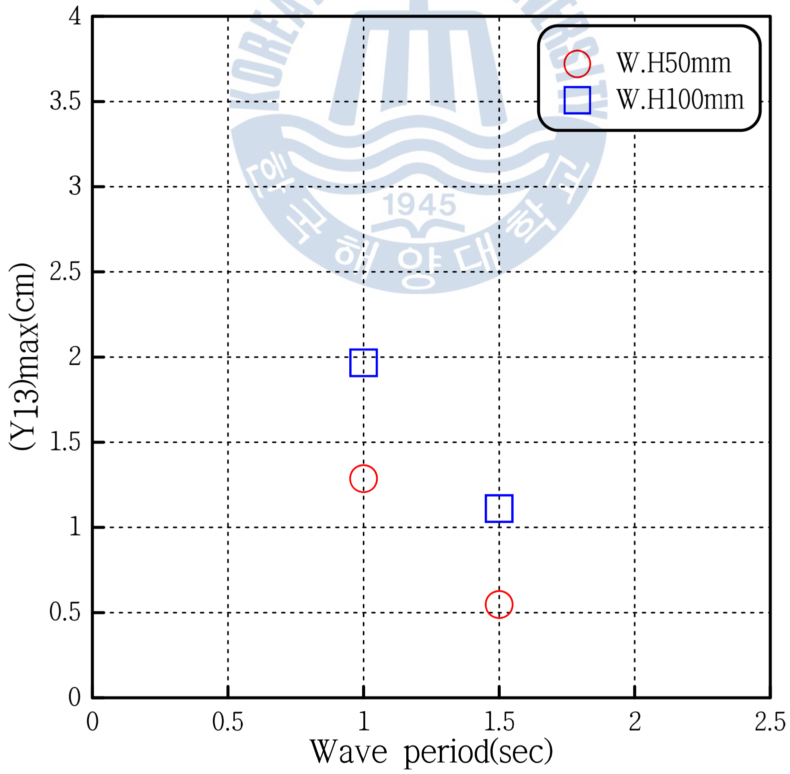
In this experiment, inline elastic responses overall increase when wave period becomes longer and wave height is higher. These phenomenon can be seen to be occurred for the interaction between both of the external forces.

Fig. 4.11 (b) shows the transverse elastic responses, symbols of the graph are as mentioned above. The responses of single regular waves increase as the wave period becomes longer. However, the responses of the synthesized external forces increase when wave period becomes shorter and wave height is higher. These phenomena are generated by the interaction between both of the external forces.

In comparing the Fig. 4.11 (a) and (b), it is possible to see inline and transverse elastic responses increase in different wave conditions. Therefore, it is necessary to design the flexible offshore structure in consideration of the wave environment of the installation area.

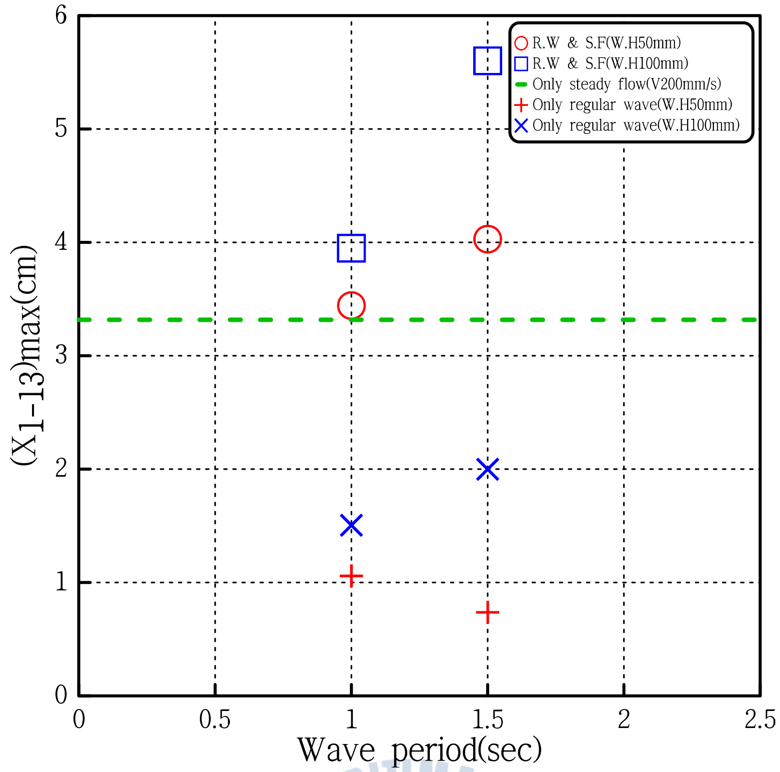


(a) Inline elastic responses

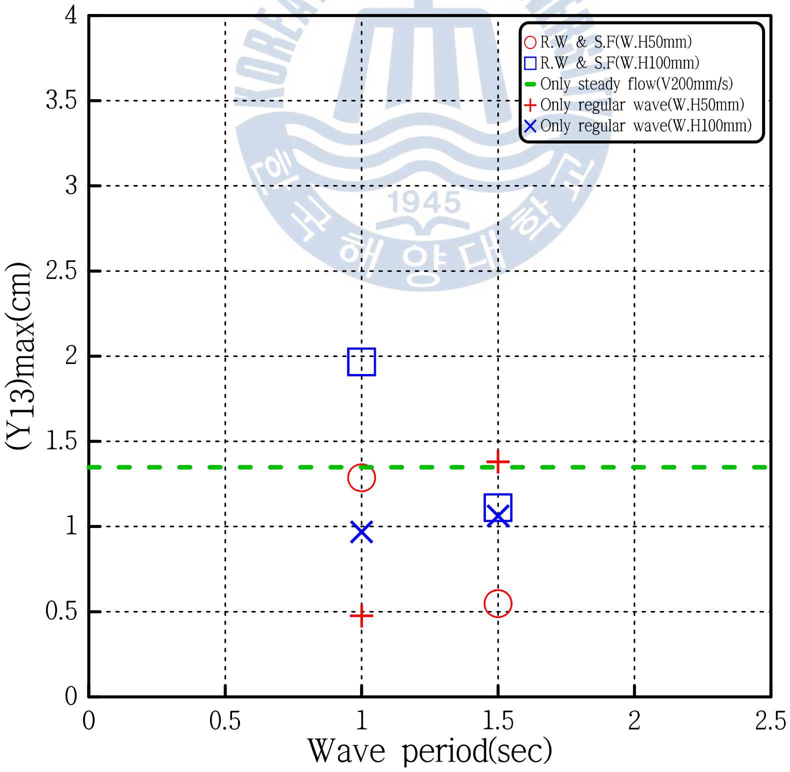


(b) Transverse elastic responses

Fig. 4.10 Elastic responses of the regular waves & current for a Teflon model-I



(a) Inline elastic responses



(b) Transverse elastic responses

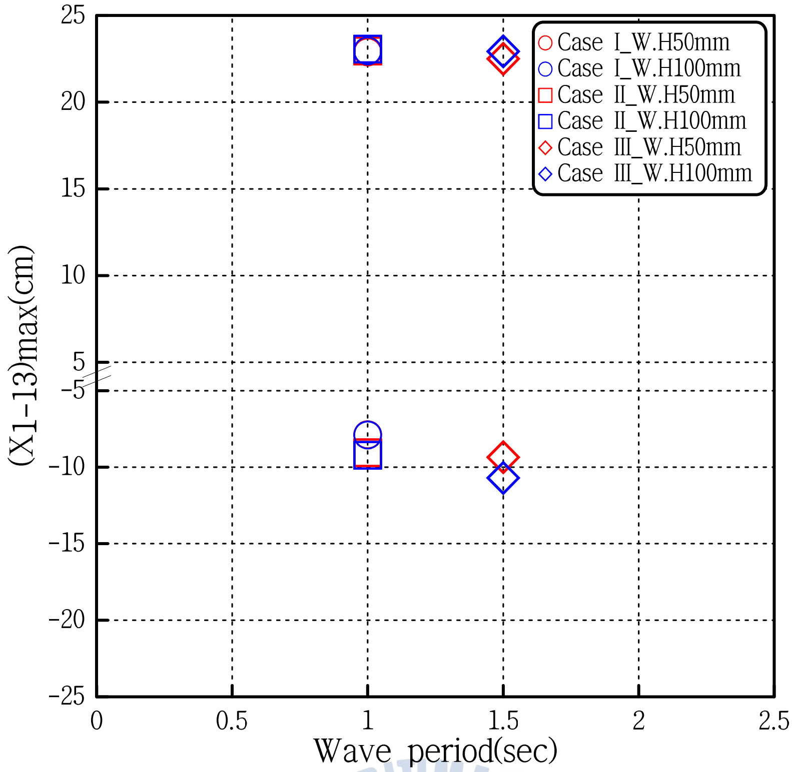
Fig. 4.11 Elastic responses of the regular waves & current for a Teflon model-II

4.4.3 Elastic responses of the forced oscillation, regular waves and current for a Teflon model

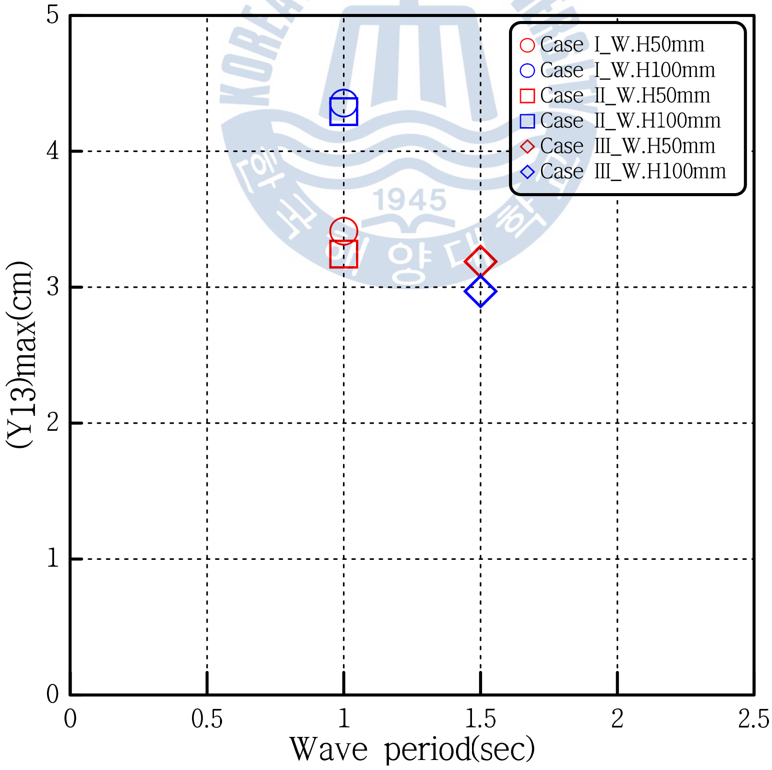
Fig. 4.12 (a), (b) are graphs of the elastic responses when the forced oscillation, regular waves and current are applied to the Teflon model; the forced oscillation period is 3.0 sec, the amplitude is 250 mm, and regular waves period is 1.0, 1.5 sec, the wave height is 50, 100 mm, and velocity of current is 150 mm/s. In the graphs, red and blue symbols mean the wave height 50, 100 mm. In this section, when the forced oscillation and regular waves are synthesized the phase difference is happened as shown Fig. 4.13 as mentioned the section 4.4.1. To explain Fig. 4.13, the graph of the top shows the phase of the forced oscillation; below two graphs indicate phase differences of 270° (Case I) and 90° (Case II) of the forced oscillation in wave period 1.0 sec. And the graph of the bottom, means the phase difference 270° (Case III) of the forced oscillation in wave period 1.5 sec. In the Fig. 4.12 (a) and (b), circular and rectangular symbols indicate the phase differences case I, II in the wave period 1.0 sec; diamond symbol means the phase difference case III in wave period 1.5 sec

The inline elastic responses of the synthesized the single external forces are shown in Fig. 4.14 (a). In the figure, the dotted line of the purple means the responses of a single forced oscillation; '+' and '×' symbols are the responses of the single regular waves, the dotted line of the green indicates the responses of the current and the remaining symbols are as mentioned above. In terms of the elastic responses for synthesized external forces, influences of wave period and height are small. Overall similar responses occur because of the interaction between the three external forces. And responses for each external forces may seem to occur in a linear superposition.

Fig. 4.14 (b) indicates transverse elastic responses, and symbols of the figure are as mentioned above. Transverse responses to the synthesized external force environment become smaller due to the interaction between the external forces. And those responses are different from the inline responses, the linear superposition has not occurred.



(a) Inline elastic responses



(b) Transverse elastic responses

Fig. 4.12 Elastic responses of the forced oscillation & regular waves & current for a Teflon model-I

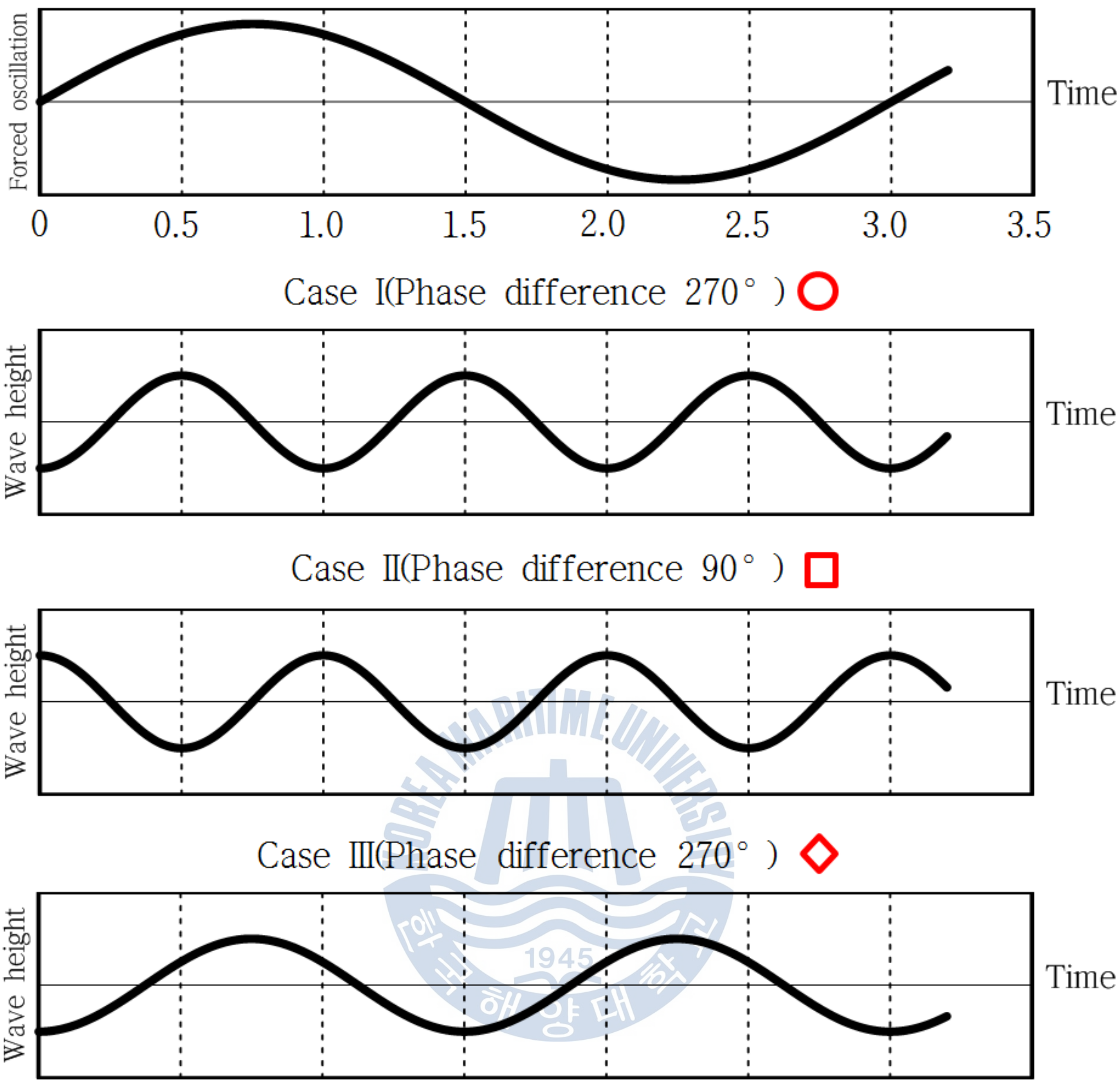
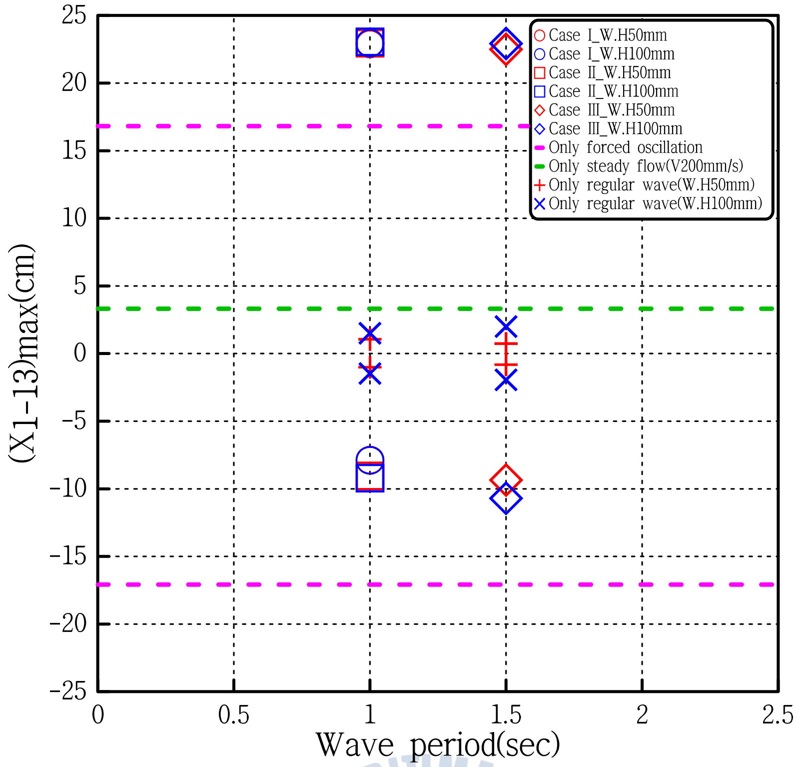
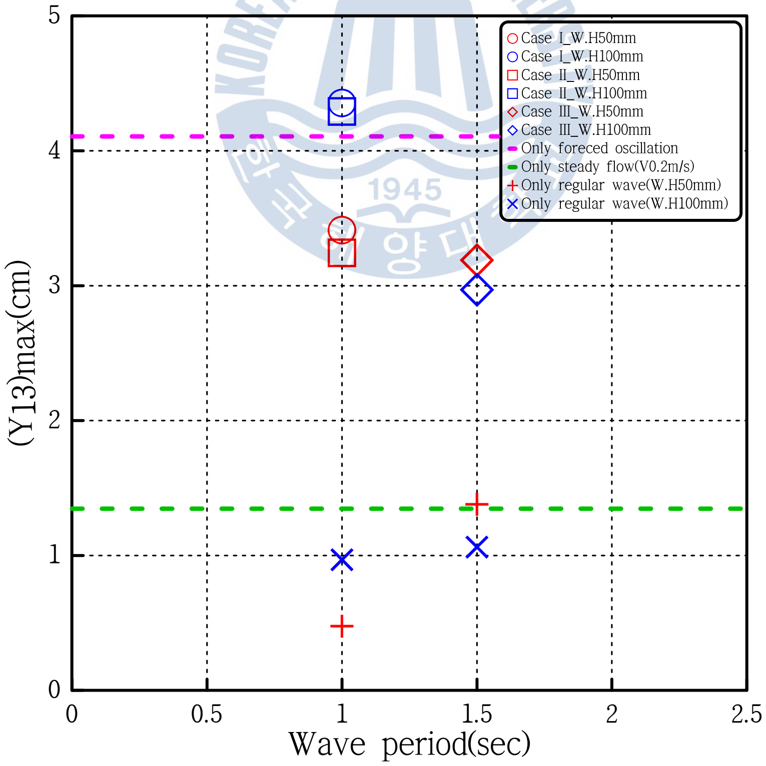


Fig. 4.13 Phase difference of the forced oscillation & regular waves



(a) Inline elastic responses



(b) Transverse elastic responses

Fig. 4.14 Elastic responses of the forced oscillation & regular waves & current for a Teflon model-II

CHAPTER 5. CONCLUSION

In this study, experimental analysis were conducted about the elastic responses of the slender models those stiffness were distributed by comparing different materials in a variety of external force and environmental conditions.

1. Inline elastic responses tend to increase when amplitude of the forced oscillation is high by single environmental condition factors if long period of external force is acting on low stiffness model. When the forced oscillation period is 3.0 sec, inline responses of Teflon model are about 17 cm, P.P as 10 cm, and Acryl as 6 cm.

2. Transverse elastic responses about the single environmental condition factors are presented the increasing or decreasing trend according to existence of the resonance phenomenons. In waves conditions of several forced environment, three slender models showed transverse responses as 0.5 cm in wave period 0.8 sec. When wave period is 2.0 sec, transverse responses of P.P as 3 cm, Acryl as 2 cm and Teflon as 1 cm.

3. When the forced oscillation and regular waves effect on each model simultaneously, inline responses would be different up to combined environmental conditions induced model oscillation by interaction of external forces that effects on transverse responses being somewhat decreased. Inline responses are measured 15 to 19 cm. About transverse responses, 2.5 to 3.5 cm are measured which range is less than 1 cm in forced oscillation condition.

4. Generally, inline and transverse responses tend to increase or decrease depending on composing vary environmental conditions. About inline

responses, there are 1 to 2 cm of difference. Difference of transverse responses is up to 1.5 cm. Analysis using simulation technique would be required to investigate experimental result in sequence.

5. Considered in these results of analysis about elastic responses, when a slender structure is designed, it is profitable to employ proper materials depending on the environmental conditions of a specification.

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감사의 글

연구의 즐거움을 느끼게 해 주시고, 학문적으로 많은 가르침을 주신 조효제 교수님과 정정열 교수님께 감사드립니다.

본 논문을 세세히 심사해 주시고 제가 모르고 있었던 것을 아낌없이 가르쳐 주신 이승재 교수님께 감사드립니다.

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