공학석사 학위논문

예인선의 운동변화에 따른 예인되는 FPSO의 침로안정성 평가를 위한 실험적 방법

Experimental method for assessing course stability of FPSO towed by a tug-boat with change of motion

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Experimental method for assessing course stability of FPSO towed by a tug-boat with change of motion

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Abstract

This paper presents the experimental investigation of course stability and towing stability of a floating production, storage, offloading(FPSO) towed by a tug-boat with change of motion. In the conventional experiment to assess tug operations, the towing stability of the towed vessel has been evaluated under the condition that the tug-boat moves only in a linear direction. In this study, experiments were conducted by using the conventional method to investigate the towing characteristic of FPSO unit. The results of conventional method has been compared the other research and stability criteria in order to validate. Furthermore, a model test method was developed to evaluate the towing stability and course stability of FPSO unit for the change of motion of the tug-boat. The motion of the tug-boat was modeled as lateral sinusoidal motion with a parametric change of its frequency and amplitude. The classification of stability was classified into towing stability and course stability considering the motion of the tug-boat. The measured physical quantities are the motion of the FPSO and tension of the towline. The experimental results were analyzed from the perspective of the classified towing stability and course stability of the FPSO. Based on the analysis results, we proposed an additional model test procedure for evaluating the course stability. Furthermore, the necessity of the developed experimental method is demonstrated by comparison with the results of the conventional experimental method.

초 록

본 연구는 예인선의 운동 변화에 따라 예인되는 부유식 생산 저장 하역 설비의 예인안정성과 침로안정성에 대한 실험적 연구를 수행했다. 예인 작업을 평가하기 위한 기존의 실험기법은 예인선이 직진 운항되는 조건에서 예인되는 부유체의 예인안정성이 평가되었다. 본 연구에서는 부유식 생산 저장 하역 설비의 예인특성을 조사하기 위해 기존의 실험기법을 활용하여 실험을 수행하였다. 기존 실험기법을 활용한 결과는 선행연구와 예인안정성 범주와 검증을 위해 비교하였다. 또한 예인선의 운동 변화에 따른 부유식 생산 저장 하역 설비의 예인안정성 뿐만 아니라 침로안정성 평가를 위해 모형시험 기법을 개발하였다. 예인선의 운동은 주파수와 진폭을 변수로 하여 사인운동으로 모델링 되었다. 예인선의 운동을 고려하여 예인안정성과 침로안정성으로 새롭게 안정성을 분류하였다. 측정 물리량은 부유식 생산 저장 하역 설비의 운동과 예인삭의 장력을 계측하였다. 실험 결과는 분류된 예인안정성 관점과 침로안정성 관점에서 분석하였다. 분석한 결과를 기반으로 침로안정성 평가를 위한 모델테스트 절차를 제안하였다. 또한, 기존의 실험 방법 결과와 비교하여 개발된 실험 기법의 필요성을 입증하였다.

KEY WORDS: Towing stability 예인안정성; Cousre stability 침로안정성; Towing system 예인시스템; Slewing motion 회두운동;. Tug-boat 예인선.

Chapter 1. Introduction

1.1 Background

With progress in the development of deep-sea resources, towing operations of floating production, storage, offloading(FPSO) systems have been increasing. Since floating structures are typically towed in the ocean, a towing system is used in which a towline is located at the stern of the tug-boat. It is important to secure the towing stability of the structure. As shown Fig. 1.1, towing operations without secured towing stability can lead to an unexpected planar motion of structures and marine accidents such as stranding or collision with other ships. Therefore, in order to prevent marine accidents while towing the structure to the installation site, it is essential to evaluate the towing stability in the initial design stage.(Kwon et al. 2014) Nevertheless, according to the statistical data in Fig. 1.2, the causes of accident such as collision or stranding have a significant part of the tug-boat marine accidents. Therefore, it is necessary to develop an evaluation method considering the motion of tug-boat since the conventional evaluation method is insufficient about the motion of tug-boat.

Fig. 1.1 Marine accidents of towing operation

(source : http://www.thephuketnews.com)

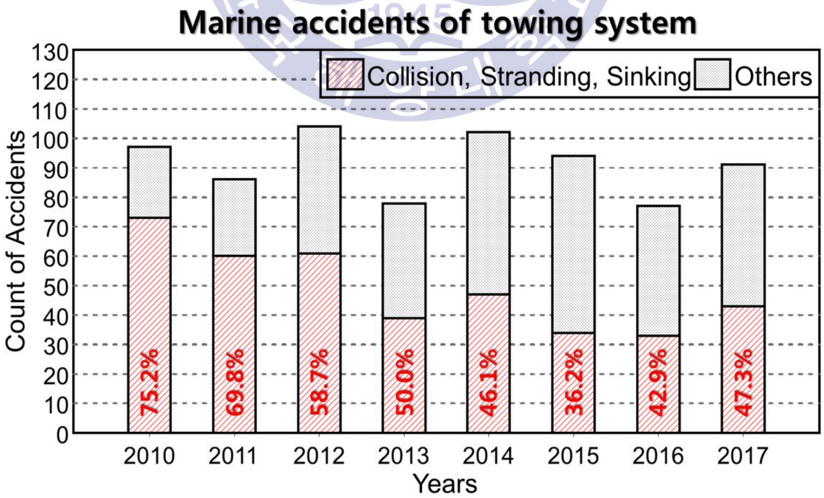


Fig. 1.2 Statistical data of marine accidents

(source : http://kostat.go.kr)

1.2 Literature review

The evaluation method of the towing stability is largely divided into three methods. The simplest method for evaluating the towing stability in the initial design stage is stability discrimination using the characteristic equation. Therefore, many studies have been performed on towing stability discrimination. However, the method faces difficulty in quantitative stability discrimination, and the result can depend on the accuracy of the hydrodynamic derivative.(Strandhagen et al. 1950; Bernitsas & Kekerdis 1985; Varyani et al. 2005)

Generally, the evaluation and prediction of towing stability have been studied through model tests and numerical analysis. Lee, S., & Lee, S. M. (2016) conducted the experiment on the towing stability of the barges accoridng to the change of bow shape. Yasukawa et al.(2006) performed a model test on two barges and compared the result with the result of simulation using the equation of maneuvering motion. Nam et al.(2014) performed an experiment to evaluate the towing characteristics of a barge during a multi-tug operation, and they verified and supplemented the results by numerical calculation. Latorre(1988) pointed out that the result of a model test is more stable because the model resistance is assessed bigger than the prototype resistance. Fitriadhy & Yasukawa(2011) conducted a model test to estimate the hydrodynamic derivative and studied course stability through a simulation based on a mathematical model.

The conventional experiments that have been performed in the previous studies did not consider buoys, which exist in the route during actual towing operations, or cases where it is necessary to avoid other unexpected structures. In general, experimental studies on towing stability have been conducted during straight motion of the tug-boat. However, actual towing operations may involve unexpected situations requiring a change of course. Fitriadhy et al. (2015) theoretically analyzed the motion of the slack towline when the tug-boat turns, and they verified it with an experimental analysis. In their experiment, a rotating arm was used to implement the turning motion, which is disadvantageous in that a model test using a rotating arm cannot be performed for a long time. In addition, the tug-boat may be affected by the motion of the towed vessel. Therefore, it is also necessary to evaluate the stability of the towed vessel with respect to the turning of the tug-boat.

1.3 Objectives and Scopes

In the present study, we conducted an experimental study, and it consist of two main parts. First, we observed the towing characteristics of the FPSO according to parameters by applying the conventional experimental method. The results of applying the conventional experimental method were compared with the results from towing stability discrimination formulas and other research. Second, we developed a model test method for evaluating the course stability for an FPSO by introducing forced motion of tug-boat, and we observed the effect of the FPSO's motion on the motion characteristics of the tug-boat. Furthermore, the results of the developed experiment were compared with those of the conventional experiment. Based on the comparison results, the towing stability and course stability of the FPSO were analyzed. Finally the necessity of the developed experimental method is demonstrated and a procedure to evaluate the course stability of an FPSO is proposed through the developed experiment.

Chapter 2. Stability criteria

2.1 Equation of towed FPSO motion

Strandhagen et al.(1950) proposed a stability discrimination formula based on the linear equation of floating structure motion. The towed vessel is very slow compared to the self-propulsion vessel. Therefore, horizontal plane motion dominate in the towed vessel. Among the different types of motion, sway and yaw motion most significantly affect the towing stability. Fig. 2.1 shows the coordinate system of the towing system. Equation (1) is the equation of motion for sway and yaw. The left-hand side of Equation (1) represents the inertial force associated with the acceleration, and the right-hand side contains the towline tension(T) and hydrodynamic force acting on the FPSO.

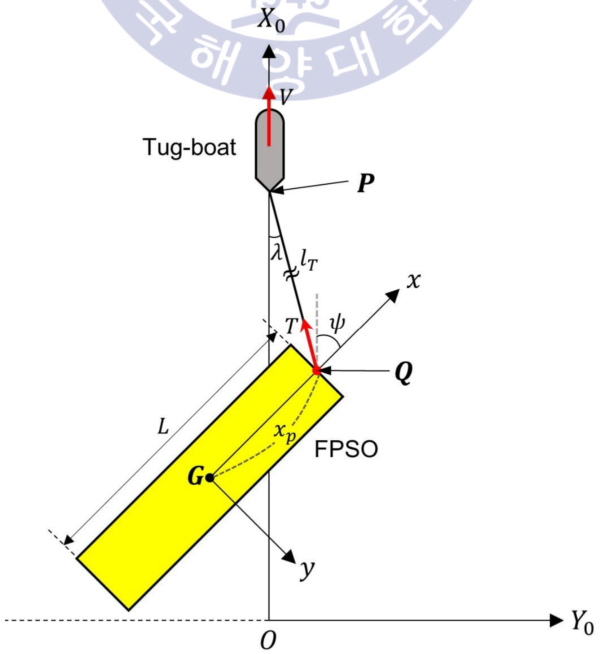


Fig. 2.1 Coordinate systems of tug-boat and FPSO.

$$(m+m_y)\dot{v}+(m+m_x)ur = Y_v v + Y_r r - T\sin(\lambda+\psi),$$
$$(I_{zz}+J_{zz})\dot{r}+(m_y-m_x)uv = N_v v + N_r r - Tx_p \sin(\lambda+\psi) \tag{1}$$

where, Y_v, Y_r, N_v and N_r are expressed only as linear terms through the Taylor series expansion.

The most reliable method is to conduct constrained model tests to get hydrodynamic derivatives of structure. However, in this study, the measurement of hydrodynamic derivatives using a circular water channel(CWC) was limited. Therefore, there is a method of using the empirical formular in addition to the model test. Although it is an empirical formular for commercial ships such as container ship or VLCC, Empirical formular is used for qualitative evaluation in this study. (Inoue & Kijima 1981) It is shown in Equation (2).

$$Y_v' = -\left(\frac{1}{2}\pi\Lambda + 1.4C_B\frac{B}{L}\right)\left(1+\frac{2}{3}\frac{\tau}{d}\right),$$
$$Y_r' = \frac{1}{4}\pi\Lambda\left(1+0.8\frac{\tau}{d}\right) - m_x'$$
$$N_v' = -\Lambda\left(1-\frac{0.27}{l_v'}\frac{\tau}{d}\right) \tag{2}$$
$$N_r' = -\left(0.54\Lambda - \Lambda^2\right)\left(1+0.3\frac{\tau}{d}\right)$$

where, L : length of ship B : breadth of ship, d : average draft, C_B : block coefficient, τ : trim, $\Lambda = 2d/L$, $l_v' = \Lambda/\left(\frac{1}{2}\pi\Lambda + 1.4C_B\frac{B}{L}\right)$

2.2 Towing stability discrimination formula

Equation (3) is derived from kinematic characteristics for points P, Q, and G in Fig. 2.1. (Strandhagen et al. 1950)

$$v + x_p + V\psi = l_T\dot{\lambda}, \tag{3}$$

Equation (1) and (3) can form a set of simultaneous equation with three variables, and each general solution is shown in Equation (4).

$$v = k_1 e^{\sigma t},\ \psi = k_2 e^{\sigma t},\ \lambda = k_3 e^{\sigma t} \tag{4}$$

The general solution is substituted in Equation (1) and (3) to derive Equation (5).

$$\begin{cases} (M_y\sigma - Y_v)k_1 + (mV - Y_r\sigma + T)k_2 + Tk_3 = 0 \\ -N_v k_1 + (I_z\sigma - N_r\sigma + Tx_p)k_2 + Tx_p k_3 = 0 \\ k_1 + (x_p\sigma + V)k_2 - l_T\sigma k_3 = 0 \end{cases} \tag{5}$$

where, M_y is $m + m_y$ and I_z is $I_{zz} + J_{zz}$. In order to satisfy Equation (5), k_1, k_2 and k_3 must be zero, which means that the determinant must be zero. Therefore, the characteristic equation such as Equation (6) can be derived:

$$\sigma^4 + A\sigma^3 + B\sigma^2 + C\sigma + D = 0, \tag{6}$$

where,

$$A = -\frac{N_r}{I_z} - \frac{Y_v}{M_y},$$

$$B = \frac{Y_v N_r - (Y_r - mV)N_v}{M_y I_z} + T\left(\frac{1}{M_y I_z} + \frac{x_p^2}{I_z l_T} + \frac{x_p}{I_z}\right),$$

$$C = \frac{T}{M_y I_z}\left\{\left(1 + \frac{x_p}{l_T}\right)(N_v - x_p Y_v) + \frac{1}{l_T}((Y_r - mV)x_p - N_r)\right\} + \frac{Tx_p V}{I}$$

$$D = \frac{TV(N_v - Y_v x_p)}{M_y I_z l_T}$$

When the Routh-Hurwitz method is applied to Equation (6), the necessary condition is that A, B, C and D must have positive signs, and the sufficient condition is that the sign of the first column of the Routh-Hurwitz table should be uniform. Stability discrimination by necessary condition is expressed in Equation (7) and (8):

$$x_p > \frac{N_v}{Y_v}, \tag{7}$$

$$T > \frac{l_T\{-N_v(mV - Y_r) - Y_v N_r\}}{I_z + M_y x_p(x_p + l_T)}, \tag{8}$$

Stability discrimination by the sufficient condition is expressed in Equation (9) and (10):

$$\frac{AB - C}{A} > 0, \tag{9}$$

$$ABC - C^2 - A^2 D > 0, \tag{10}$$

Equation (9) and (10) provide the criteria of towing stability in towing systems. This process followed the approach of Peters (1950). In addition, the added mass value is required to calculate necessary conditions of the stability discrimination in Equation (7) and (8) and to calculate sufficient condition in Equation (9) and (10). In order to obtain the added mass and added moment of inertia, we refer to the Clarke's estimation equation(Clarke 1983). Equation (11) is the result of a regression analysis of the results of various research institutes that have basin.

$$\begin{aligned} m_x' &= (0.03 \sim 0.05)m' \quad , \\ m_y' &= \pi\left(\frac{d}{L}\right)\left\{1.0 + 0.16C_B\left(\frac{B}{d}\right) - 5.1\left(\frac{B}{L}\right)^2\right\} \\ J_{zz}' &= \pi\left(\frac{d}{L}\right)\left\{\frac{1}{12} + 0.017C_B\left(\frac{B}{d}\right) - 0.33\left(\frac{B}{L}\right)\right\} \end{aligned} \tag{11}$$

where,

$$m', m_x', m_y' = m, m_x, m_y / \left(\frac{1}{2}\rho L^2 d\right)$$
$$J_{zz}' = J_{zz} / \left(\frac{1}{2}\rho L^4 d\right)$$

$L : length\ of\ the\ ship$
$B : breadth\ of\ the\ ship$
$d : draught\ of\ the\ ship$
$C_B : block\ coeffcient\ of\ the\ ship$
$\rho : water\ density$

2.3 Classification of towing stability and course stability

The structure that are towed by the towline behave by tension of towline and the hydrodynamic forces according to the shape of structure under the free surface. The stability of the planar motion of the structure was classified in the previous studies.(Latorre 1988; Kwon 2015) Fig. 2.2 is a stability classification with refer to Latorre(1988), and Fig. 2.3 is classification with refer to Kwon(2015). Since previous studies have considered the stability of the tug-boat straight ahead, they have used both technical terms without a clearly classification of course stability and towing stability. However, in this study, a clear classification was needed because lateral motion of the tug-boat was introduced.

In this study, towing stability and course stability were newly classified by refer to conventional stability classification. It is divided into the perspective of course stability and towing stability according to the motion of the tug-boat. Fig. 2.4 shows the stability classification according to the motion of the tug-boat. From the perspective of towing stability, it can see what kind of motion of the tug-boat should do to reduce the amplitude of the slewing motion of the towed vessel. On the other hand, from the perspective of course stability, it can see how well the towed vessel follows the path of the tug-boat.

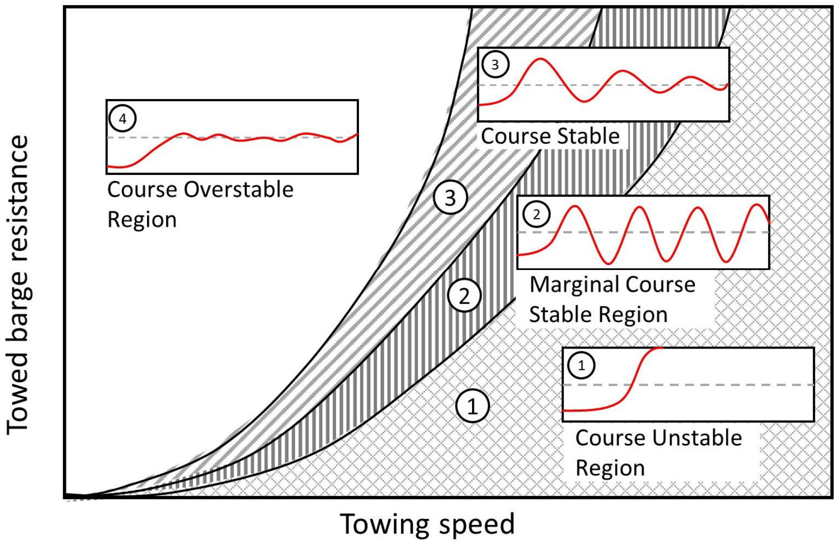


Fig. 2.2 Illustration of towed vessel course stability and resistance (Latorre, 1988)

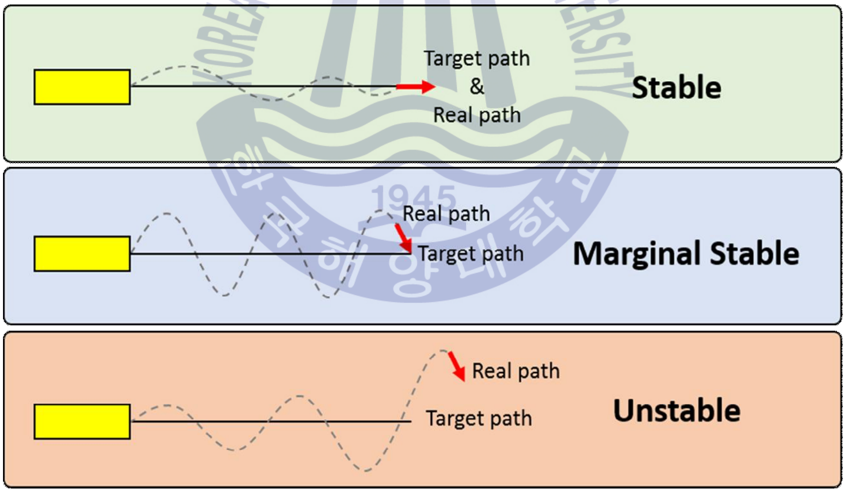


Fig. 2.3 Towing stability criteria of towed vessel (Kwon, 2015)

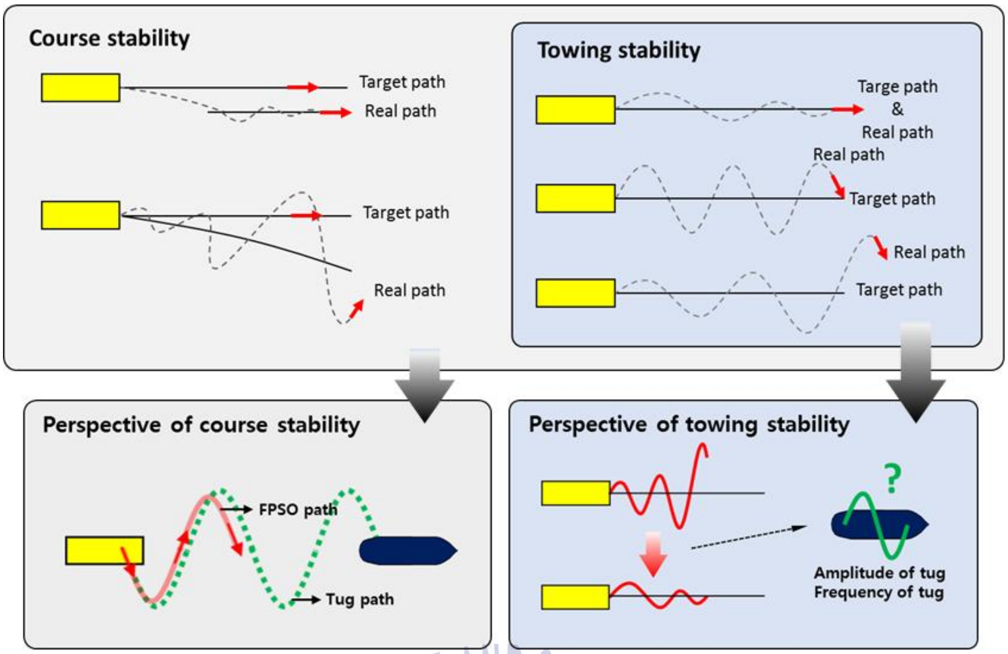


Fig. 2.4 New stability classification according to the motion of the tug-boat

Chapter 3. Experimental set-up

3.1 Circulating Water Channel

This study was conducted in circulating water channel(CWC) located at the Korea Maritime and Ocean University(KMOU). The observation area of the CWC has a width of 1.8m, depth of 1.2m, and length of 4.0m(Fig. 3.1). Prior to the experiment, the flow velocity was measured in each section of the CWC to secure the uniformity of the flow.

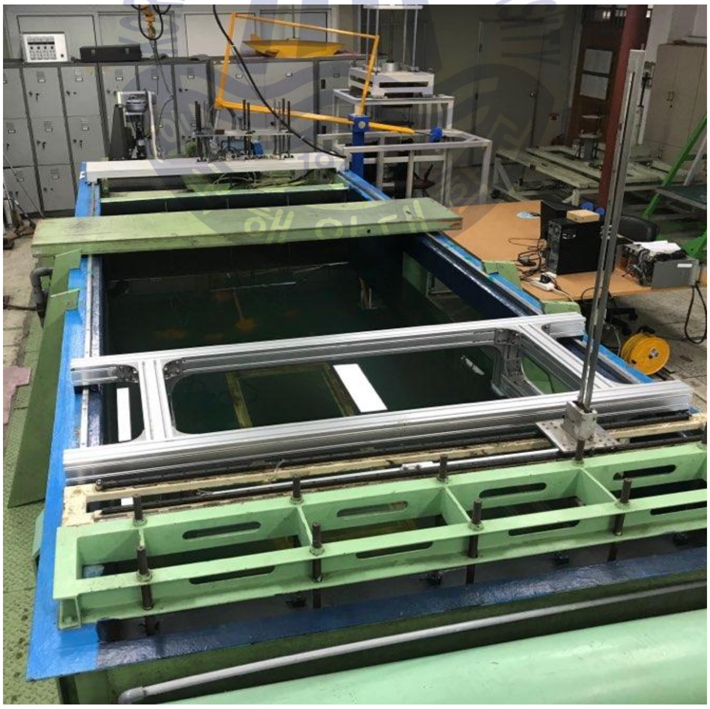


Fig. 3.1 Circulating water channel in KMOU.

3.2 Experimental equipments

Pitot tube and pressure transmitters were used to measure flow performance and flow velocity of the CWC. A differential pressure transmitter(Fig. 3.2) capable of measuring the maximum pressure difference up to 62.2mbar was used.

A 3-D displacement meter(Fig. 3.3) was used to measure the planner motion of the model, with reflective makers(Fig. 3.3) attached to the center of gravity, forward, and aft of the model. A 3-D displacement meter was composed of 5 cameras and the average error of measured displacement by calibration was less than 1mm.

In addition, a tension meter(Fig. 3.4) was used to measure the towline tension(T), and a polyethylene material was used to ignore the self-elasticity of the towline. The maximum measurable tension of the tension meter is 10N. In this study, it was placed at the upper end using a pulley system so as not to affect the weight per unit length of the towline.

The forced oscillation device(Fig. 3.5) was used to implement the motion of tug-boat. The motion of the tug-boat was modeled as lateral sinusoidal motion with parametric change of its frequency and amplitude.

Fig. 3.2 Differential pressure transmitter.

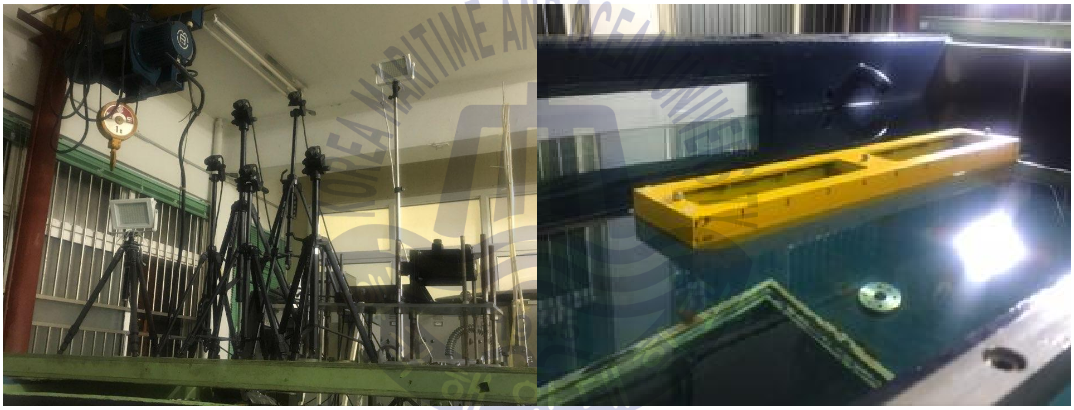


Fig. 3.3 3-D displacement meter and reflective marker

Fig. 4.4 Tension meter

Fig. 3.5 Forced oscillation device

3.3 FPSO model

In this study, The scale ratio of the model is 1/100, and a FPSO was made by the KMOU as a wood material for this research. Therefore, it has to measure the mass characteristics of the model. The weight inside the model was arranged using a moment-of-inertia measuring device so that the mass radius of gyration of the yaw was approximately 26% of the model length. The measured mass characteristics were compared with inclining test. The principal dimensions of the model are listed in Table 3.1. and Fig. 3.6 shows the actual model.

Table 3.1 Principal dimensions of the model ship.

Description	Magnitude		Unit
	Even keel	Trim by bow	
Length of model	1.2	1.2	$[m]$
Breadth of model	0.23	0.23	$[m]$
Depth of model	0.11	0.11	$[m]$
Draught	0.054	-	$[m]$
Displacement	14.34	14.84	$[kgf]$
Vertical COG (KG)	0.01945	0.02052	$[m]$
Mass radius of gyration k_{xx}	0.07359	0.07436	$[m]$
Mass radius of gyration k_{yy}	0.29943	0.30689	$[m]$
Mass radius of gyration k_{zz}	0.31784	0.32428	$[m]$

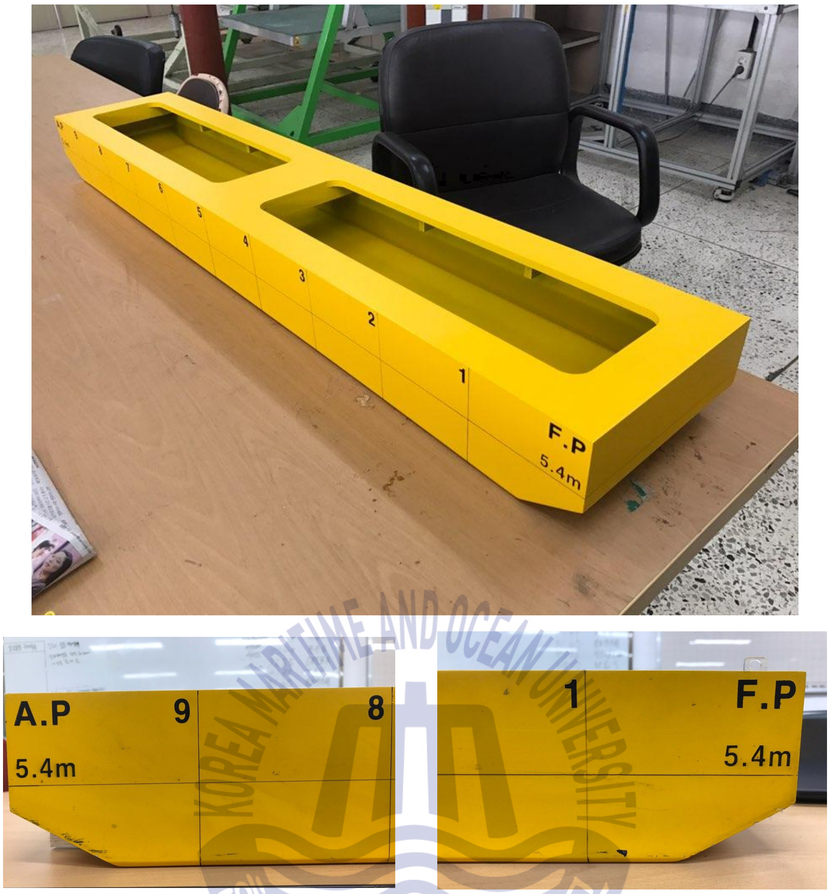


Fig. 3.6 Model ship

3.4 Conventional and developed experimental method

Fig. 3.7 shows the actual design of the towing system experimental apparatus. Fig. 3.8 shows the overall layout of the experimental equipment and the model. Fig. 3.8(a) is conventional experimental method and Fig. 3.8(b) is developed experimental method. In an actual towing system, the tug-boat may be affected by the interaction of the tug-boat and FPSO. Therefore, the pulley system in Fig. 3.8(a) was installed to implement the surge of the tug-boat according to the motion of the FPSO. In this case, the vertical displacement of the weight in the pulley system was less than 5% of towline length. Fig.3.8(b) shows the installation of a forced oscillation device for the lateral motion of tug-boat. The upper part of the pulley systems was removed, and the towline was fixed. In the conventional experimental method, the towing stability of the FPSO can be determined during the straight motion of the tug-boat. On the other hand, in the developed experimental method, the course stability of FPSO can be determined when changing the course of the tug-boat.

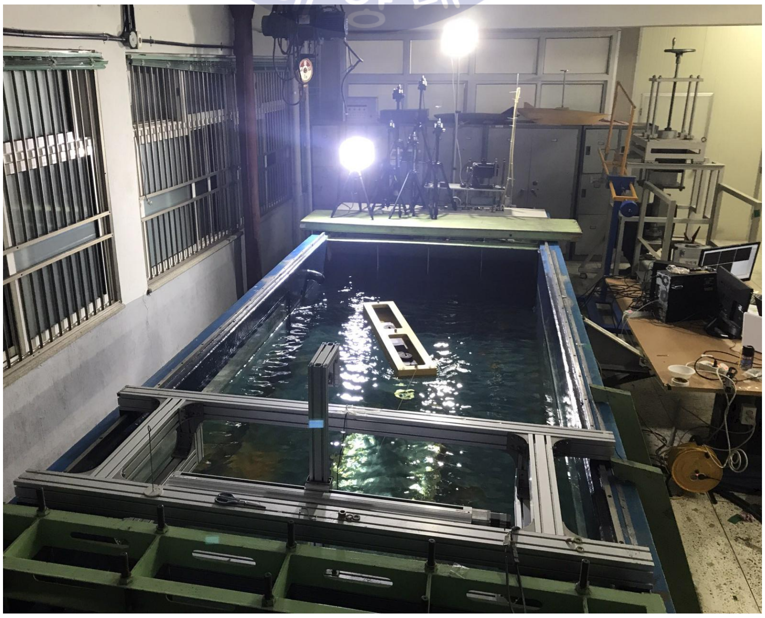


Fig. 3.7 Actual design of the towing system experimental apparatus.

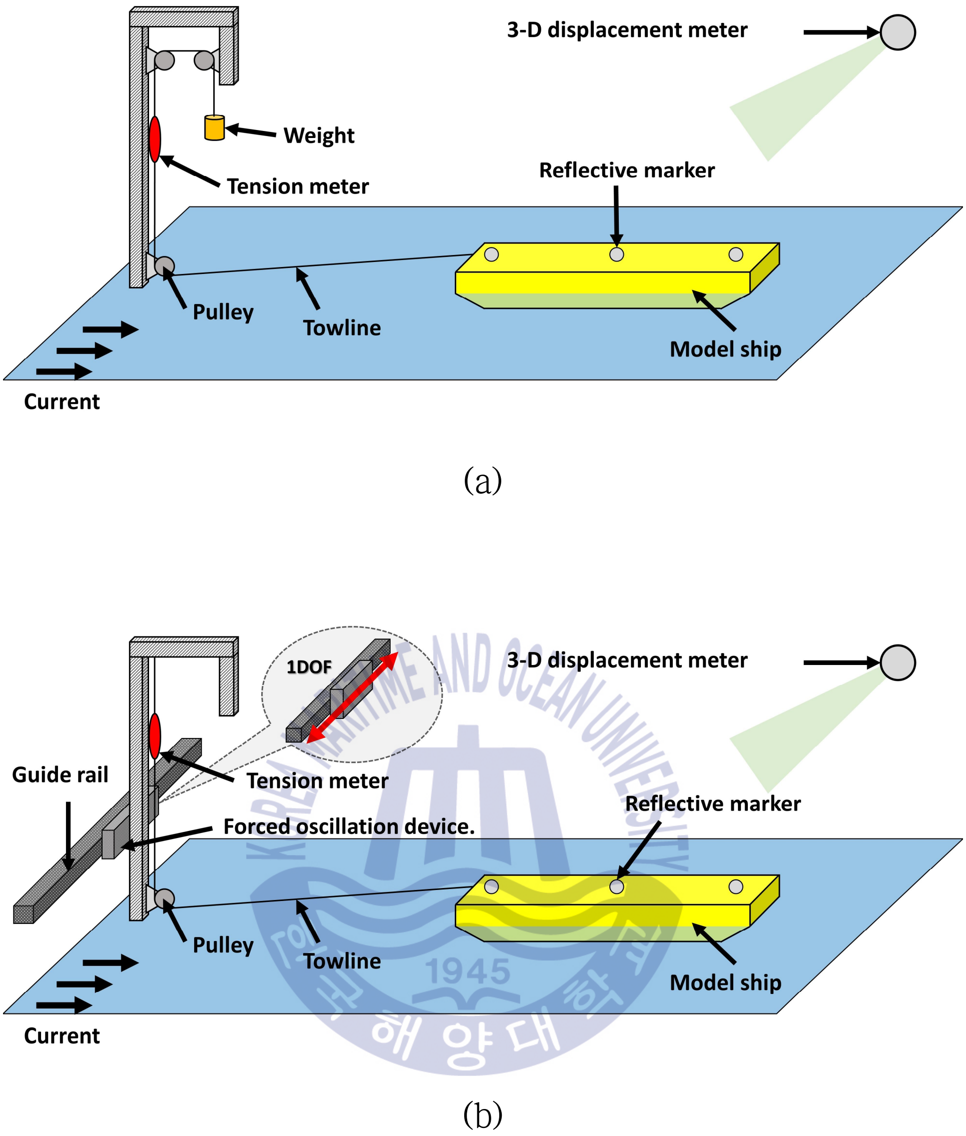


Fig. 3.8 Schematic design of the towing system experimental apparatus.

(a) Conventional experimental method

(b) Developed experimental method

Chapter 4. Test matrix for experiment

4.1 Experimental condition of conventional method

In this study, the inflow velocities of CWC are assumed to be the towing speed(V). and the three towing speeds were considered as 0.257, 0.360, and 0.463m/s, which correspond to 5, 7, and 9 knots, respectively, when converted to a prototype. The values of towing speed and Froude number(Fn) are specified in Table 4.1.

In the trim by bow condition, 0.5kg weight was added to the bow, so that the bow draft and stern draft difference were 1cm, and the trim angle was about 0.5degree. Generally, trim by stern condition is stable. Therefore, the trim by stern is preferred in the actual towing system. However, in this study, we implemented the unstable condition through the trim by bow condition in order to determine stability discrimination.

The length of towline was changed to 1.0L, 1.5L, and 2.0L based on the length of model(L), and the effect of the length of towline change was analyzed. In addition, in order to analyze the effect of the towed point(x_p), the length of the towline was limited to 1.5L, and the distance to the towed point at the center of gravity was changed to 0.6m, 0.75m, and 0.9m. Fig. 4.1 shows the arrangement of the bridle type towline to give a change in towed point. The detailed experimental conditions are shown in Table 4.2.

One method to give the initial disturbance of the towing stability experiment is of rotating the bow angle of the model by 30degree, and another method is of moving the center of the model by 2 times the value of breadth of model. These are practical methods which are used in Maritime Research Institute Netherlands(MARIN). In this study, the latter method was used and the displacement of FPSO was measured for 600s at the steady section.

Table 4.1 Towing speed and Froude number

Scale factor (λ)	Towing speeds		
	Model $[m/s]$	Prototype $[knots]$	Froude number $[Fn]$
100	0.257	5	0.075
	0.360	7	0.105
	0.463	9	0.135

Table 4.2 Experimental conditions and main parameters for trim by bow and even keel

Case	Parameter		
	Length of towline $[m]$	Tow speed $[m/s]$	Towed point (x_p) $[m]$
Case1	1.0L	0.257	0.60
Case2		0.360	
Case3		0.463	
Case4	1.5L	0.257	0.60
Case5			0.75
Case6			0.90
Case7	1.5L	0.360	0.60
Case8			0.75
Case9			0.90
Case10	1.5L	0.463	0.60
Case11			0.75
Case12			0.90
Case13	2.0L	0.257	0.60
Case14		0.360	
Case15		0.463	

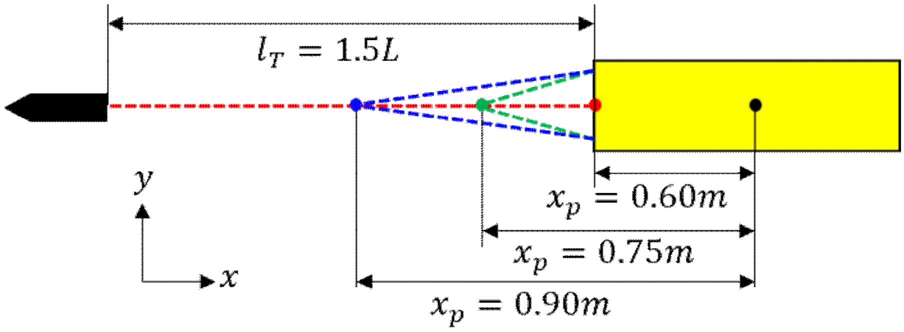


Fig. 4.1 Schematic design of bridle towline for towed point movement.

4.2 Experimental condition of developed method

In order to compare the developed experimental method shown in Fig. 3.8(a) with the conventional experimental method shown in Fig. 3.8(b), experiments were conducted under the even-keel condition and trim-by-bow condition by using two experimental method.

The length of towline was changed to 1.0L, 1.5L, and 2.0L under the conventional experimental method, and it was limited to 1.5L under the developed experimental method. The effect of the towline length change was confirmed in the conventional experiment method, so the developed experiment method focused on the motion of the tug-boat.

The forced motion of the tug-boat was simulated with changes in amplitude(A_{Tug}) and frequency(f_{Tug}). The amplitude of tug-boat motion was changed to 1.0B, 0.5B, and 0.25B based on the breadth of the model(B). Furthermore, frequency of the tug-boat motion was changed to $0.5f_{Fi}$, $1.0f_{Fi}$, and $1.5f_{Fi}$ based on the frequency of fishtailing motion(f_{Fi}). Fishtailing motion is also called slewing motion. The experimental conditions are listed in Table 4.3. it is compared with the conventional experimental method.

Developed experimental method was performed in the same manner as conventional method. However, for developed experimental method, the forced motion of the tug-boat was realized through a forced movement device during the overall measurement time of 600s including initial steady motion of the tug-boat for 100s. Fig4.2 shows the measurement method of the developed experimental method.

Table 4.3 Experimental conditions and main parameters for developed experimental method.

Parameter	Conventional experimental method	Developed experimental method
Length of towline	1.0L / 1.5L / 2.0L	1.5L
Towed speed $[m/s]$	0.257 / 0.360 / 0.463	
Amplitude of tug-boat	-	0.25B / 0.5B / 1.0B
Frequency of tug-boat	-	$0.5f_{Fi}$ / $1.0f_{Fi}$ / $1.5f_{Fi}$
Towing condition	Trim by bow / Even keel	

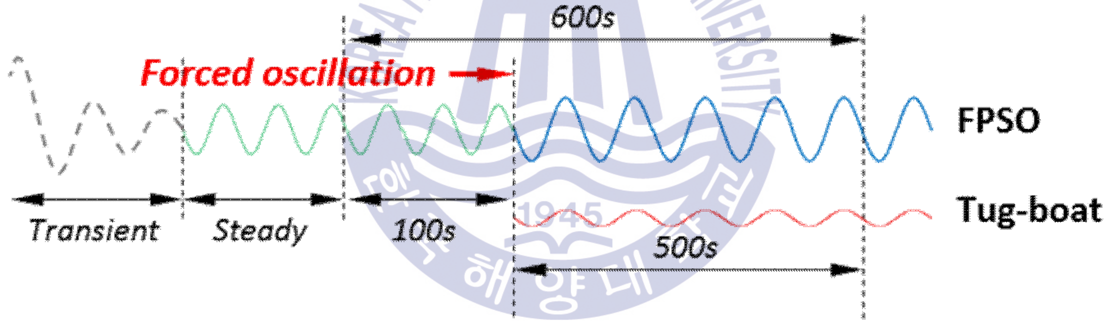


Fig. 4.2 The measurement time of the developed experimental method.

Chapter 5. Experimental results

5.1 Experimental results of conventional method

5.1.1 Effect of trim condition

Fig 5.1 shows the results of FPSO motions and tension of towline obtained with conventional experimental method. where length of towline is 1.5L and towing speed is 0.257m/s. The sway motion of the FPSO was divided by breadth of model, and the results were compared between even-keel and trim-by-bow conditions. Under the even-keel condition, the maximum amplitude of sway motion was approximately 0.5 times breadth of model, and the maximum yaw angle was approximately 8 degree. Under the trim-by-bow condition, the maximum amplitude of sway motion and maximum yaw angle were, respectively, approximately 2times breadth of model and 24 degree. Furthermore, tension of towline was larger under trim-by-bow condition than under even-keel condition. This implies that unnecessary thrust consumption may occur from the perspective of the tug-boat because the velocity vector of the tug-boat is different from that of the unstable FPSO.

The results of Fig. 5.1 can also be inferred from Fig 2.2, which shows the relationship between the towing speed and cousre stability according to the resistance of the towed vessel. The results under trim-by-bow condition in Fig.5.1 are located in the marginal stable region in Fig 2.2 because FPSO's motion of trim-by-bow condition is larger than even-keel condition and the periodic motion is prominent. (Latorre, 1988) It was considered that towing stability decreased under trim-by-bow condition at the same towing speed because the resistance is reduced and the longitudinal cross section of the forward part is larger than the aft part compared with even-keel condition. Fig.

5.2 shows all the results of the trim-by-bow and even-keel condition using the conventional experimental method in this study.

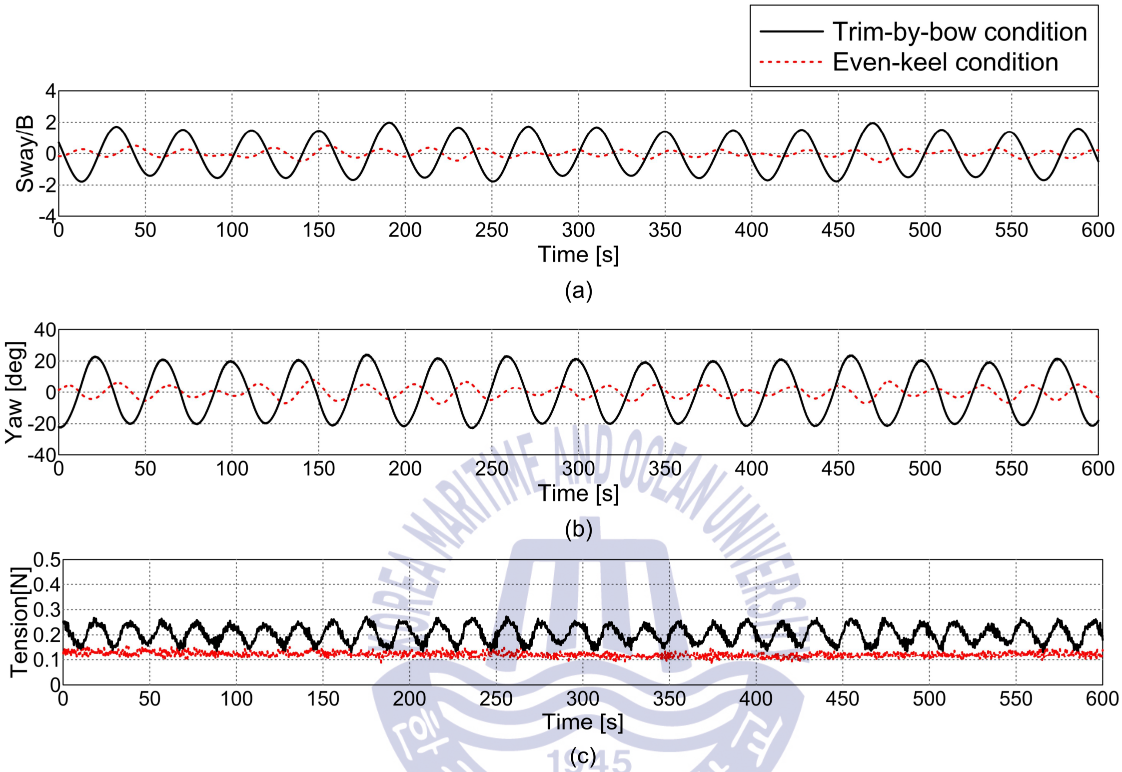


Fig. 5.1 Comparison of motion response and tension of the towline on trim-by-bow and even-keel condition $(l_T = 1.5L,\ V = 0.257m/s)$

(a) Sway motion of towed FPSO

(b) Yaw motion of towed FPSO

(c) Tension of towline

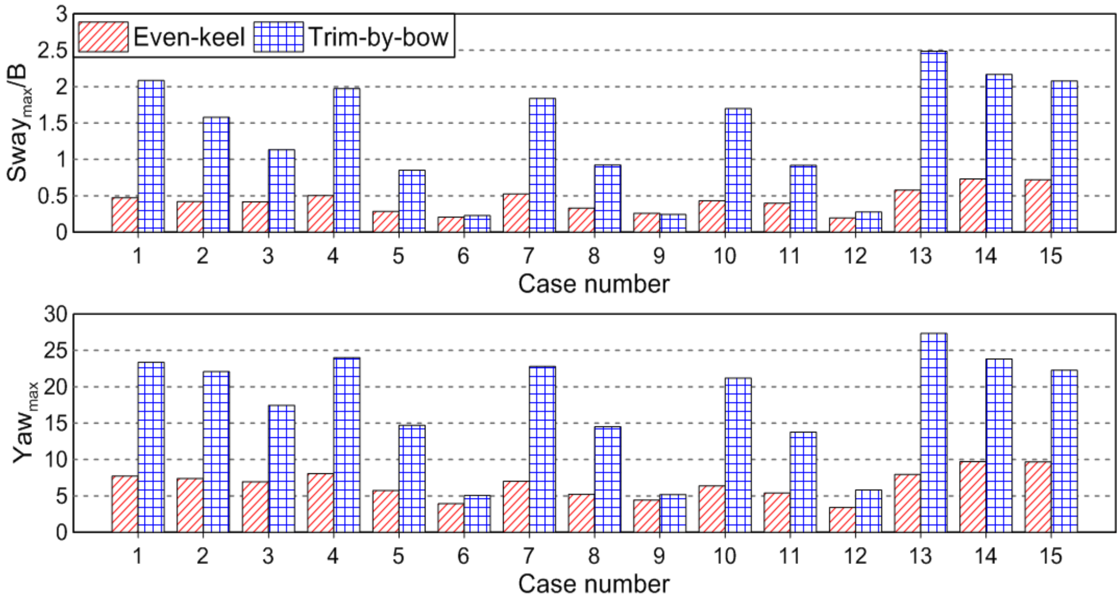


Fig. 5.2 Results of maximum sway and yaw motion in all the case.

5.1.2 Effect of length of towline and towing speed

Fig 5.3 shows the time series of the sway and yaw motions according to the change of length of towline under the trim-by-bow condition. During a total measurement time of 600s, the result of 200s from the time when the center of gravity of the model was located on the straight line with the tug-boat was illustrated. As shown in Fig 5.3, it was confirmed that the period of FPSO's slewing motion become longer with the length of towline increased. In addition, when the length of towline was 1.0L, the maximum amplitude of the sway motion was 1.6times of model's breadth, 1.8times at 1.5L, and 2.1times at 2.0L. Therefore, it can be seen that the amplitude of slewing motion increases as the length of towline increases. On the other hand, the maximum angle of yaw motion is about 22~24 degree, which increases with the length of towline, but the effect is insignificant.

Generally, the length of towline uses more than 3 times length of towed vessel in the actual towing system. In this study, because of the size limitation of the CWC, we tried to determine the effect of the towline length variation by making maximum application of the towline length within the limited range. Fig. 5.4 shows the maximum tension of towline according to the change of towing speed and length of towline. As the length of towline became longer, the maximum tension value tended to decrease at both towing speeds of 0.360m/s and 0.463m/s. However, when the towing speed was 0.257m/s, the variation of the maximum tension due to the towing length change was not large. In addition, it can be seen that the tension of towline increase according to increase the towing speed in Fig. 5.4. This means that the thrust of the tug-boat may need more. Therefore, when the towline length is long, it can be seen from the results of this experiment that the towing system with high towing speed is advantageous from the perspective of the tug-boat's thrust consumption.

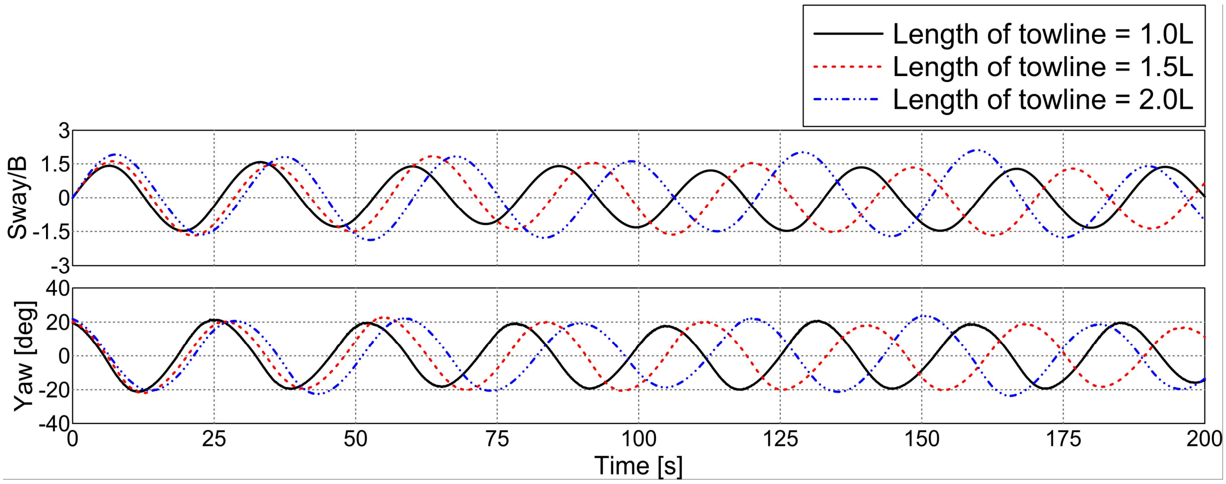


Fig. 5.3 Comparison of motion response with different length of towline. ($V = 0.360 m/s$, Trim-by-bow condition)

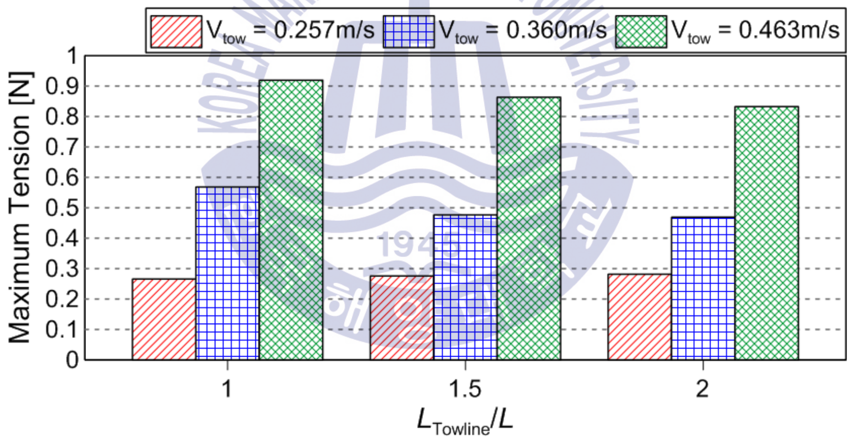


Fig. 5.4 Comparison of the maximum tension of the towline with different length of towline and towing speed. (Trim-by-bow condition)

Fig. 5.5 shows the time series of the slewing motion and tension of towline according to the change of towing speed under the trim-by bow condition. During a total measurement time of 600s, the result of 200s from the time was illustrated. it is the same as the expression in Fig. 5.3. As shown in Fig. 5.5, it was confirmed that the period of FPSO's slewing motion become shorter and amplitude of FPSO's motion with towing speed increased. From the perspective of towing stability, it is improved by reducing the amplitude of the slewing motion when the towing speed is high. However, since the tug-boat requires a larger thrust, a proper towing speed should be selected.

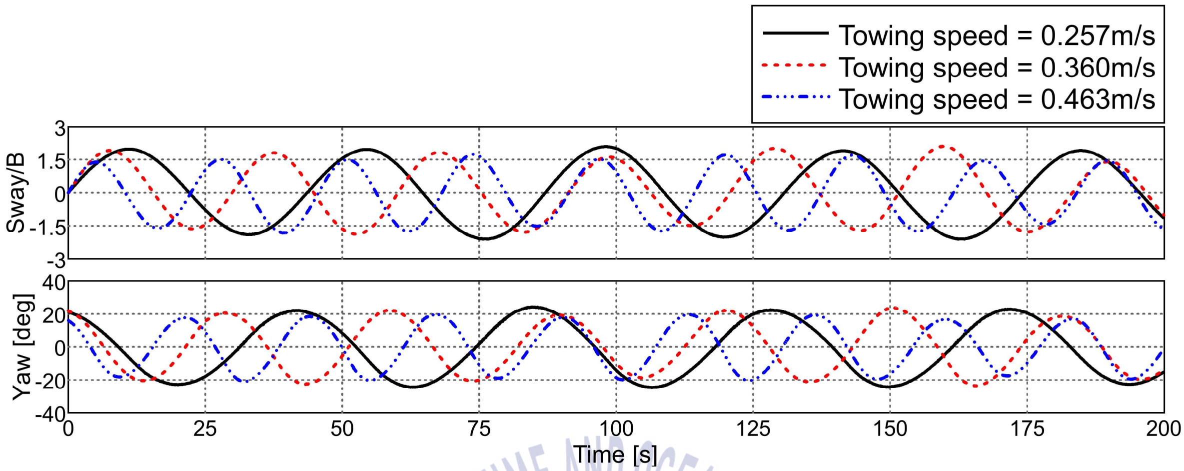


Fig. 5.5 Comparison of motion response with different towing speed ($l_T = 2.0L$, Trim-by-bow condition)

5.1.3 Effect of towed point

Fig. 5.6 shows the measured values of the towline tension, sway and yaw motion according to the distance from the center of gravity of the model to the towed point(x_p), using the bridle towline in the trim-by-bow condition. During a total measurement time of 600s, the result of 300s from the time when the center of gravity of the model was located on the straight line with the tug-boat was illustrated.

As shown in Fig. 5.6, The longer the distance from the towed point to center of gravity of the FPSO, the shorter the period of the slewing motion of FPSO. In addition, when the towed point divided by length of model is increase, the maximum amplitude of the sway motion is decreased. it can be seen that the maximum sway motion was approximately 2times of model's breadth at $x_p/L = 0.50$, 0.9times at $x_p/L = 0.625$, and 0.2times at $x_p/L = 0.75$ in Fig. 5.6. At this time, the yaw motion of FPSO respectively decreased to 24, 15, and 5 degrees. In addition, the tension of towline was decreased as the towing point was moved away from the FPSO's center of gravity in Fig. 5.6.

Therefore, it can be seen that the towing stability is improved as the towed point is moved away from the FPSO's center of gravity using the bridle towline. In addition, it can be seen that the use of the bridle towline is advantageous in perspective of tug-boat's thrust consumption.

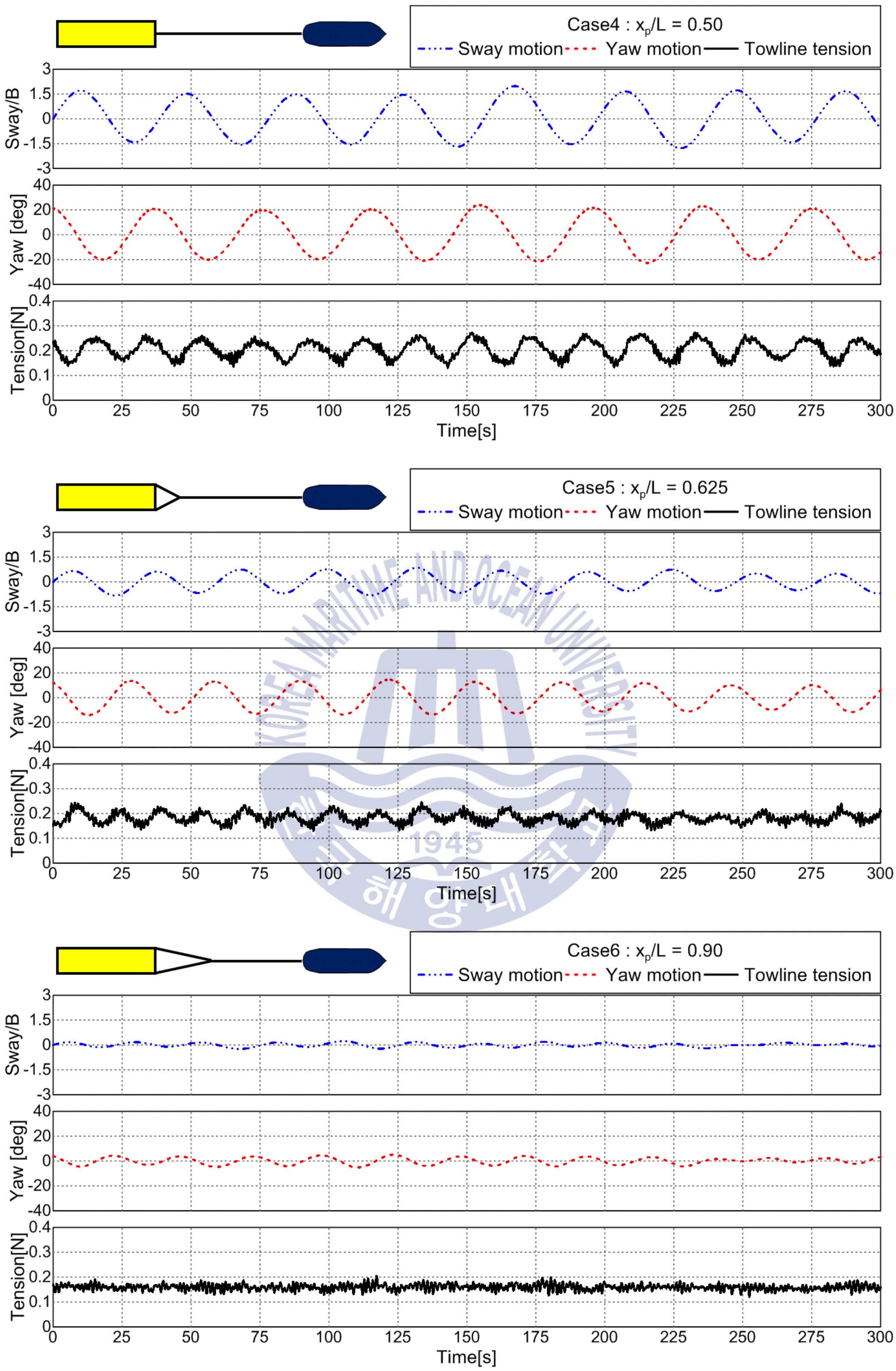


Fig. 5.6 Comparison of motion response and tension with different towed points ($l_T = 1.5L$, $V = 0.257m/s$ Trim-by-bow condition)

5.2 Validation of the conventional experiment results

5.2.1 Compare to results of other research

Fig. 5.7 shows the slewing motion period of the FPSO with respect to length of towline and towing speed under the trim-by-bow and even-keel conditions. Under both conditions, period of slewing motion increased as length of towline increased, and period of slewing motion decreased as towing speed increased. In addition, period of slewing motion is lower under the even-keel condition than under the trim-by-bow condition.

In order to verify the experimental results, Fig. 5.7 compares the results of Nam et al. (2014) with the results of the present study. The results of period of slewing motion respect to the increase of towing speed are quantitatively different owing to the difference in parameters such as the experimental environment, shape of the model, and number of tug-boats. However, the towing characteristics of a decreasing period of slewing motion with an increasing towing speed or a decreasing length of towline are qualitatively similar to the experimental results of the present study.

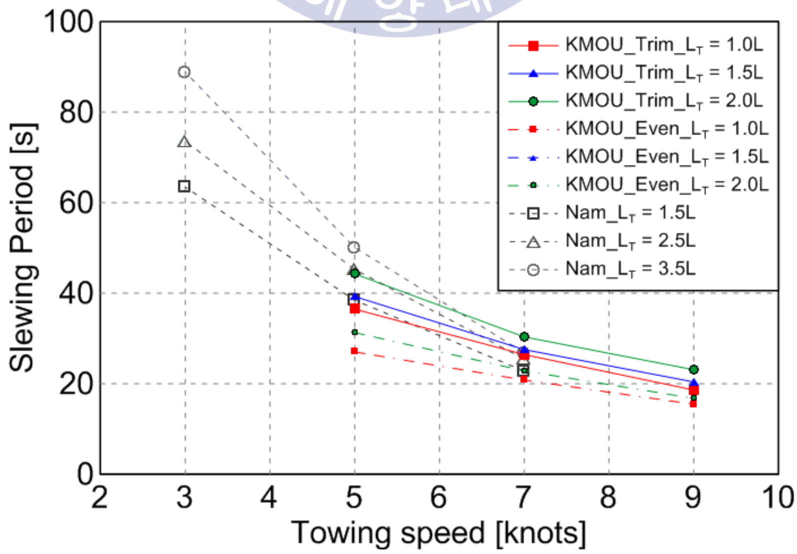


Fig. 5.7 Comparison of slewing motion period with different towline length and towing speed with Nam et al.(2014)

5.2.2 Compare to results of stability criteria

In order to use the stability discriminant, we need to know hydrodynamic derivatives. These are mainly obtained through the planar motion mechanism(PMM) and virtual captive model test. However, in this study, the PMM test not performed, and hydrodynamic derivatives were obtained using empirical formulas. (Inoue & Kijima 1981) It was calculated by Equation (2). These values were listed in Table 5.1. The added mass and added moments of inertia were obtained using the Clarke's estimation equation in Equation (11). However, in order to reduce the uncertainty, the added mass was additionally calculated through ANSYS-AQWA. These values were listed in Table 5.2. As shown in Table 5.2, the value of ANSYS-AQWA were used because the comparison results of ANSYS-AQWA did not show any significant difference with Clarke's estimation equation..

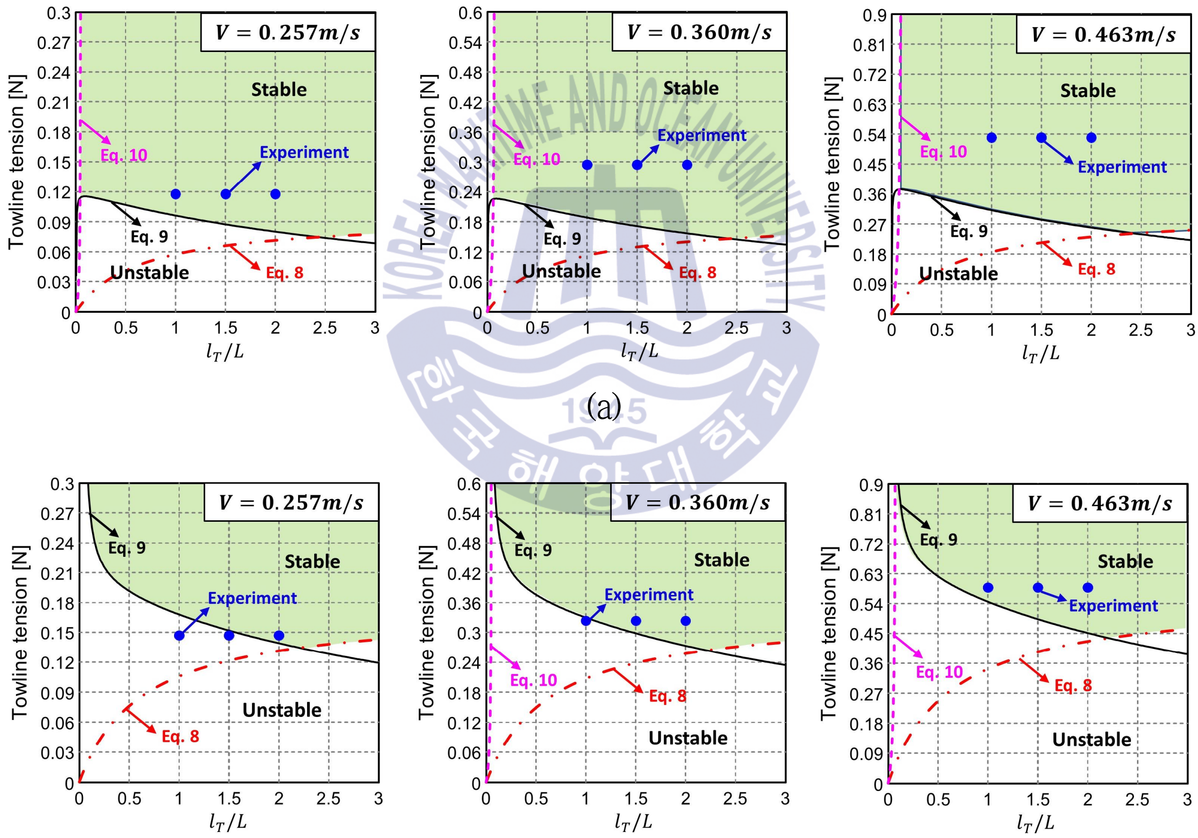
Fig. 5.8 shows the results of the stability discriminant domain. The results of experiment are initial tension of towline each towing condition. The results of stability domain using the Routh-Hurwitz method is not consistent with the results of the experiment, because quantitative discrimination is difficult. However, compared to the even-keel condition result of Fig. 5.8(a), we confirmed that the trim-by-bow condition result of Fig. 5.8(b) is closer to the unstable area and qualitatively similar to experimental results.

Table 5.1 Hydrodynamic derivatives of model ship.

	Even-keel	Trim-by-bow
Y_v'	-0.399	-0.350
Y_r'	0.046	0.034
N_v'	-0.090	-0.109
N_r'	-0.041	-0.038

Table 5.2 Clarke and ANSYS-AQWA comparison of model's added mass

Condition	Even-keel		Trim-by-bow
	Clarke(1983)	ANSYS-AQWA	ANSYS-AQWA
m_x	0.717	0.948	1.014
m_y	8.070	8.412	8.986
J_{zz}	0.710	0.788	0.841



(a)

(b)

Fig. 5.8 Stability discriminant domain of towing stability

(a) Even-keel condition, (b) Trim-by-bow condition

5.3 Experimental results of developed method

5.3.1 Effect of pulley system

In the case of developed experimental method using the pulley system in this study, the pulley system used in conventional experimental method could not be used, because the length of towline changes with the movement of the forced oscillation device that causes the motion of the tug-boat. Therefore, in order to compare the results of developed method with those of conventional method, we investigated the effect of the pulley system under the relatively unstable trim-by-bow condition. Fig. 5.9 compares the root mean square(RMS) errors of the length of towline, sway and yaw motion of FPSO under trim-by-bow condition between cases with and without the pulley system. The higher towing speed, the RMS error of towline tension was increased at the non-pulley system. However, the results of sway and yaw motion RMS was not different significantly. Thus, we confirmed that the pulley system does not significantly affect the motion of the FPSO. Therefore, the pulley system was removed because the motion of FPSO is more important in stability discriminant.

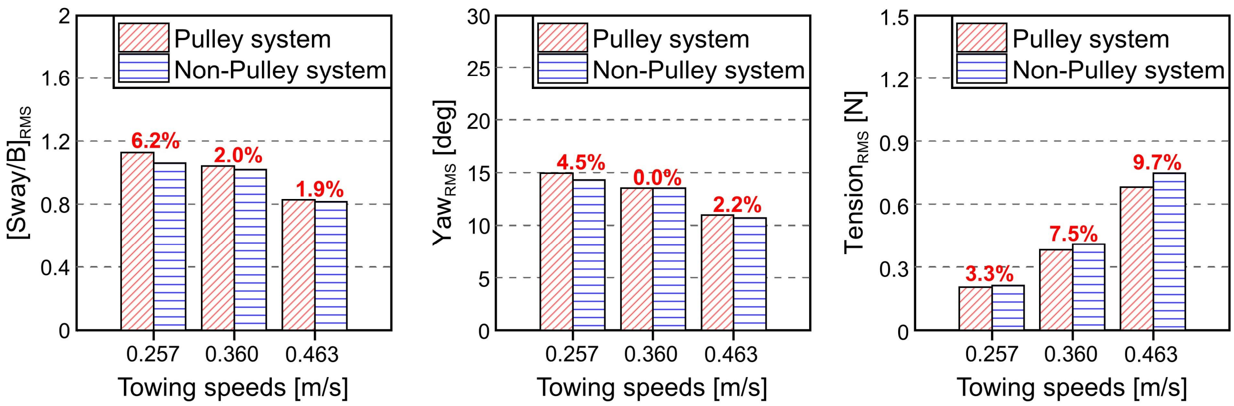


Fig. 5.9 The RMS error of slewing motion of FPSO and the tension of towline due to application of non-pulley system.

5.3.2 Perspective of towing stability

Fig. 5.10 shows the results of RMS for sway and yaw motion of the FPSO according to the amplitude of tug-boat's motion(A_{tug}) and frequency of tug-boat's motion(f_{tug}) at different values of towing speed under the trim-by-bow condition. Fig. 5.10(a), (b), and (c) show the results of developed experiment method under the trim-by-bow condition. when f_{tug} is 0.5times or 1.0times of slewing motion frequency of FPSO(f_s) and A_{tug} was increased from $0.25B$ to $1.0B$, the RMS values of sway and yaw of the FPSO tend to increase. This implies that the towing stability of the FPSO is deteriorated when f_{tug} is less than or equal to f_s. On the other hand, when f_{tug} was $1.5f_s$, the RMS of motion of the FPSO tended to decrease as A_{tug} increased. It was confirmed that the towing stability of the FPSO was improved when the tug-boat had an A_{tug} greater than breadth of FPSO. However, the effect of improving the towing stability is insignificant even if A_{tug} is less than breadth of FPSO or towing speed is high. Furthermore, it is unrealistic to achieve an A_{tug} greater than breadth of FPSO and a f_{tug} greater than f_s in an actual towing operation. Therefore, changing the motion of the tug-boat to improve the towing stability was considered inefficient.

Fig. 5.11 shows the results of RMS for sway and yaw motion of the FPSO according to the A_{tug} and f_{tug} at different values of towing speed under the even-keel condition. when f_{tug} is $1.0f_s$, the RMS values of yaw motion of FPSO was the largest, as in Fig. 5.11(a), (b), and (c). This implies that a resonance phenomenon occurs when the forced motion period of the tug-boat coincides with slewing motion period of FPSO. However, when f_{tug} is $0.5f_s$ and A_{tug} is $1.0B$ in Fig.5.11(a) and (b), the RMS values of sway and yaw motion of the FPSO are greater than those when f_{tug} is f_s. This implies that the sway motion of the FPSO can be amplified even when f_{tug} is less than f_s from the perspective of towing stability.

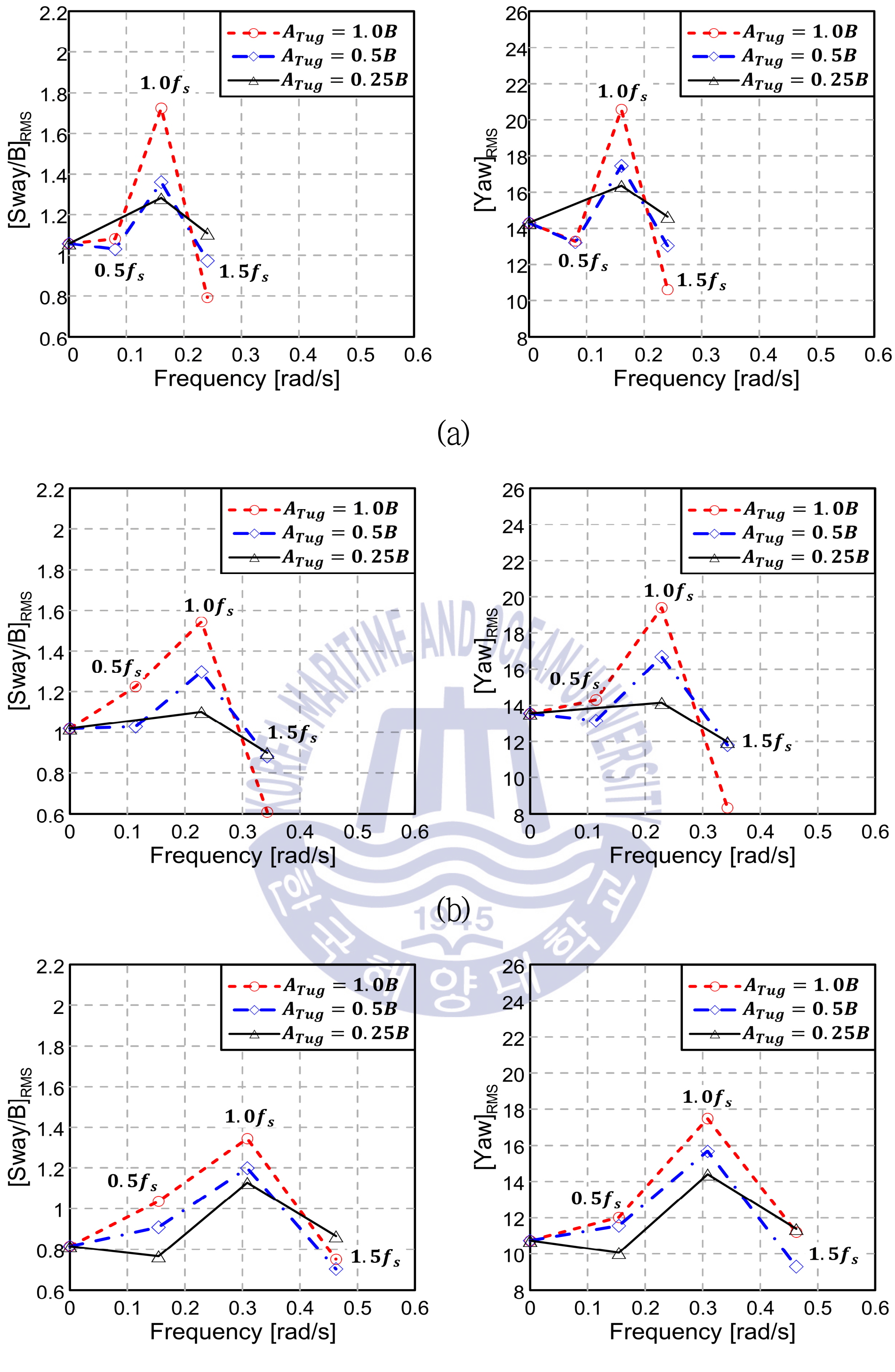
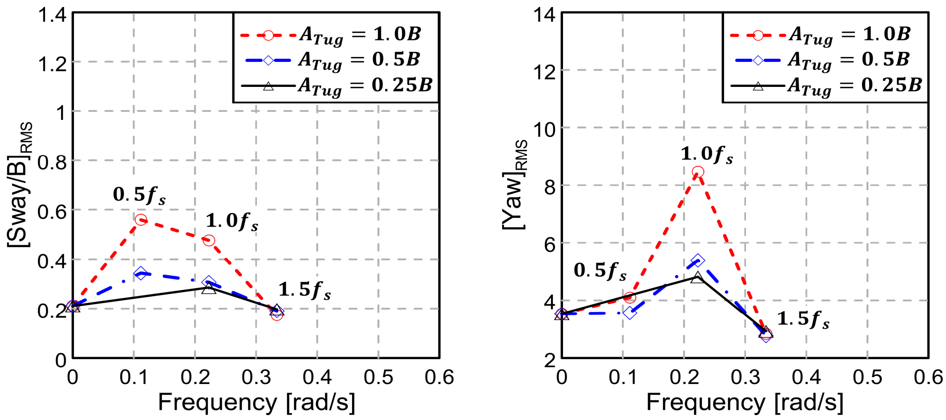
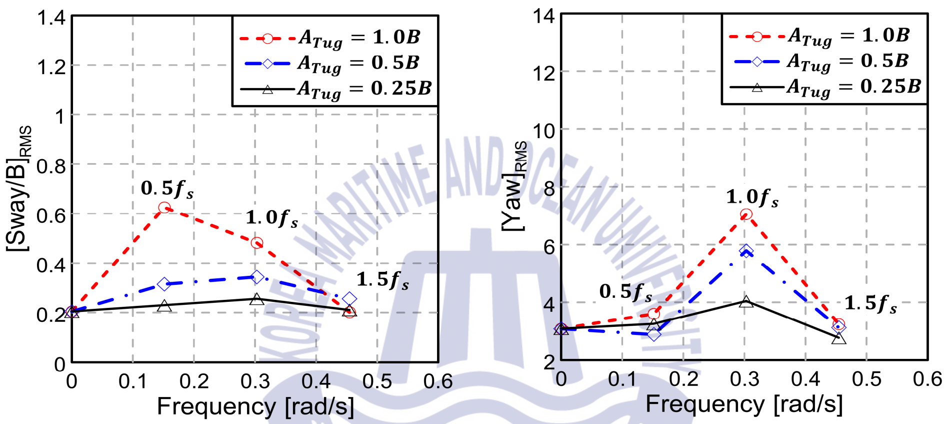


Fig. 5.10 The results of influence of the amplitude and frequency of tug-boat under the trim-by-bow condition

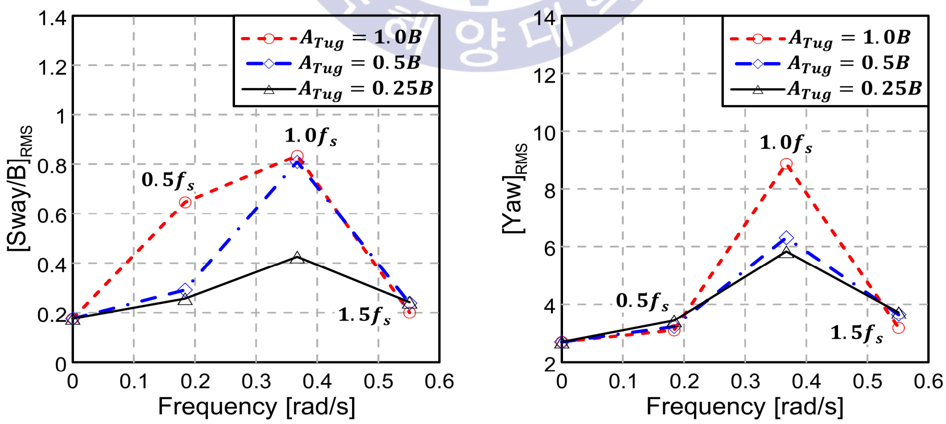
(a) $V = 0.257m/s$, (b) $V = 0.360m/s$, (c) $V = 0.463m/s$



(a)



(b)



(c)

Fig. 5.11 The results of influence of the amplitude and frequency of tug-boat under the even-keel condition

(a) $V = 0.257 m/s$, (b) $V = 0.360 m/s$, (c) $V = 0.463 m/s$

5.3.3 Perspective of course stability

Fig. 5.12 shows the sway motion of the FPSO and the time history of towline tension with respect to f_{tug} when A_{tug} is $1.0B$ and towing speed is 0.257m/s in Fig. 5.10(a) and Fig. 5.11(a). Fig. 5.12(a) shows the case in which f_{tug} is $0.5f_s$ under the trim-by-bow condition. Because the FPSO is more unstable under trim-by-bow condition than under even-keel condition, as shown Fig. 5.1, the harmonic motion due to period of tug-boat motion and period of slewing motion appears. This implies that, under trim-by-bow condition, the FPSO has a relatively unstable slewing motion and follows the course of the tug-boat from the perspective of course stability of the FPSO. In addition, the towline tension in Fig. 5.12(a) is relatively higher than that in Fig. 5.12(b) owing to the slewing motion of the FPSO. However, it can be seen that towline tension is small before and afte the start of forced motion.

Fig 5.12(b) shows tht the FPSO motion has a phase difference with respect to the tug-boat motion and follows the course of the tug-boat from the perspective of course stability when f_{tug} is $0.5f_s$ under the even-keel condition. In addition, the towline tension maintains the initial tension, and the fluctuation of the towline tension is small. This implies that, to ensure the two vessels avoid unexpected obstacles, changing the course of the tug-boat such that it is slower than the slewing motion of FPSO may be advantageous from the perspective of course stability and thrust consumption of the tug-boat.

Fig. 5.12(c) and (d) show the case in which f_{tug} is $1.0f_s$. Both trim-by-bow and even-keel conditions increased the sway motion of the FPSO and tension of the towline after the start of forced motion of the tug-boat. It is considered that the phases between the two vessels are opposite to each other throughout their time history, which is caused by the resonance phenomenon due to the coincidence of f_{tug} and f_s. Therefore, when the tug-boat changes its course to the same period of the FPSO motion, it can be considered that unnecessary thrust consumption of the tug-boat may occur.

Fig. 5.12(e) and (f) show the case in which f_{tug} is $1.5f_s$. In Fig. 5.12(e), the sway motion of the FPSO was reduced in comparison with the result of Fig. 5.1, in which the tug-boat does not have forced motion. This contributes to the towing stability of the FPSO discussed in the results from Fig. 5.10(a), (b), and (c), when f_{tug} is higher than f_s and has an A_{tug} greater than B. However, the tension of towline under the trim-by-bow condition of Fig. 5.12(e) increased intermittently compared with that before the start of forced motion of the tug-boat. Likewise, under the even-keel condition in Fig. 5.12(f), the tension of towline was greater that before the start of forced motion of tug-boat. From the perspective of course stability of the FPSO, this is attributed to the fact that the two vessels were distant from each other because the FPSO could not follow the course of the tug-boat. In addition, the intermittent in the tension of towline can have a strong impact on both vessels due to the unexpected expansion of the towline.

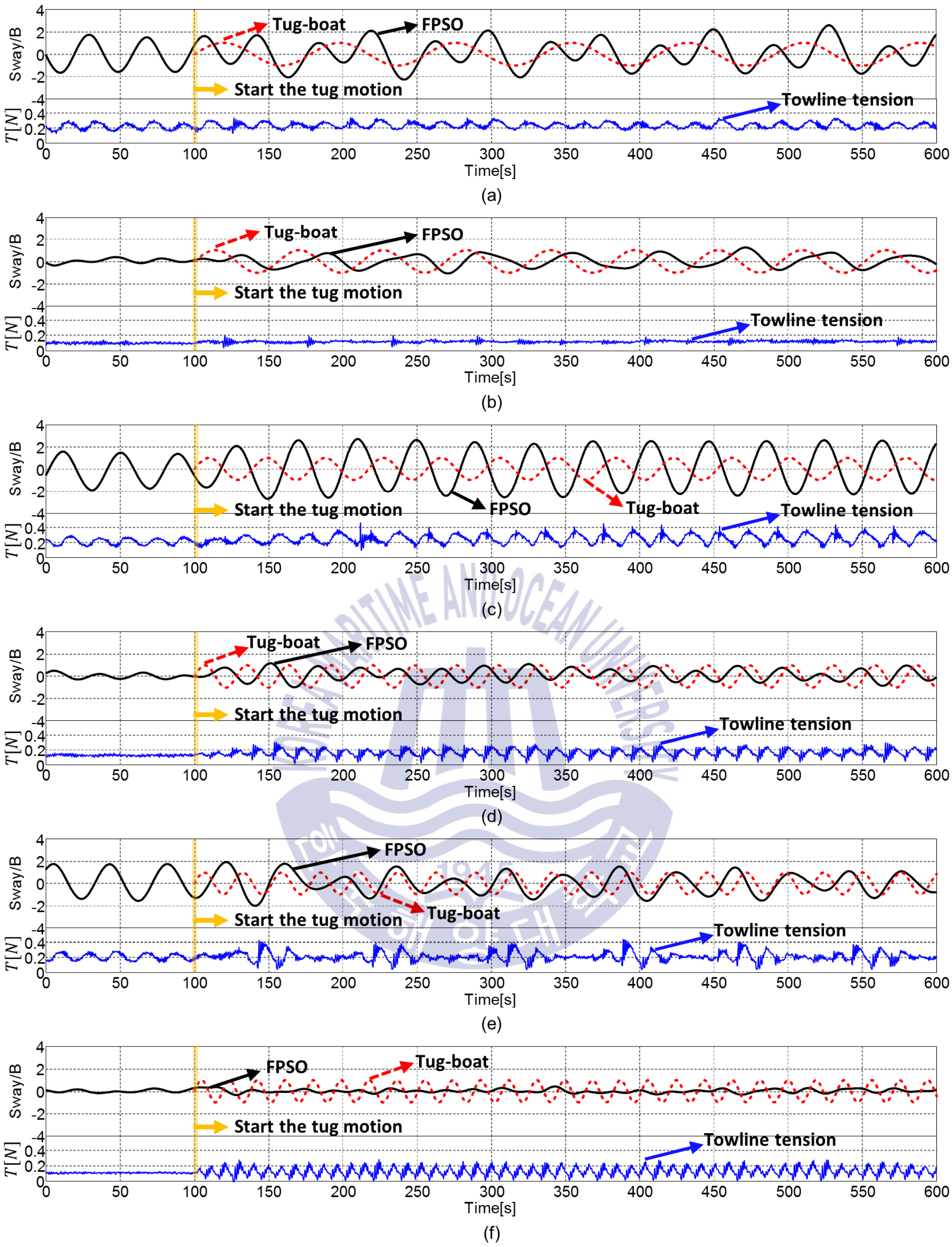


Fig. 5.12 Sway motion and towline tension with respect to excitation frequency of tug-boat. ($V = 0.257m/s$, $A_{tug} = 1.0B$)

(a) trim-by-bow ($f_{tug} = 0.5f_s$), (b) even-keel ($f_{tug} = 0.5f_s$)

(c) trim-by-bow ($f_{tug} = 1.0f_s$), (d) even-keel ($f_{tug} = 1.0f_s$)

(e) trim-by-bow ($f_{tug} = 1.5f_s$), (f) even-keel ($f_{tug} = 1.5f_s$)

5.4 Proposal of developed experimental method procedure

We propose a developed experimental method proceudre for determining the towing stability and course stability of an FPSO on the basis of the results of A_{tug} and f_{tug} change of the tug-boat in section 5.3. Fig. 5.13 shows the overall procedure of the proposed the experimental method. When designing the initial towing system, the towing stability is determined through conventional experimental method from the motion characteristics of the FPSO is evaluated through the developed experimental method from the result of FPSO motion and towline tension. This result is expected not only to consider the towing stability of the FPSO but also to be an effective indicator of the towing operation to avoid stranding or collision in an unexpected situation for the tug-boat operator.

Fig. 5.14 shows the time history for conventional experimental method and the developed experimental method under equivalent conditions except for the forced motion of the tug-boat. In order to distinguish the course stability according to the forced motion of the tug-boat, f_{tug} was kept lower than f_s in the observation. Fig. 5.14(a) shows the results with conventional experimental method, and Fig. 5.14(b) shows the result with developed experimental method. Fig. 5.14(a) showed relatively stable results, However, Fig. 5.14(b) shows that the FPSO could not follow the course of the tug-boat. This implies that, even when the FPSO is found to be relatively stable through conventional experimental method, it can be unstable when turning or changing course. Therefore, in addition to conventional experimental method, it is necessary to evaluate the course stability of the FPSO according to the course change of the tug-boat.

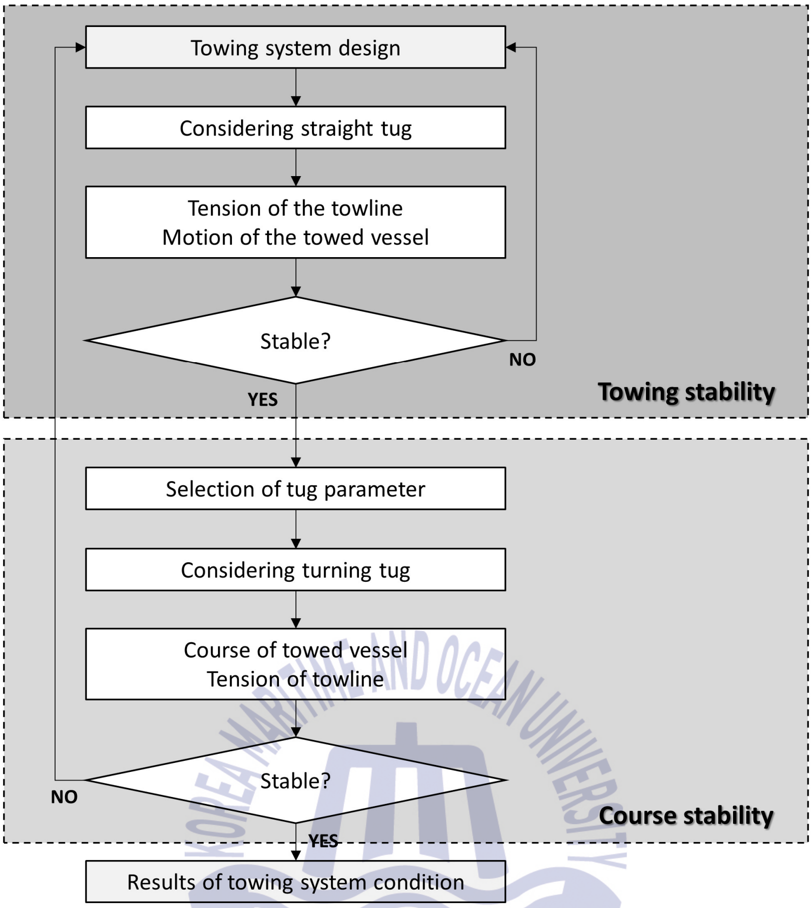


Fig. 5.13 Experiment procedure for towing stability and course stability

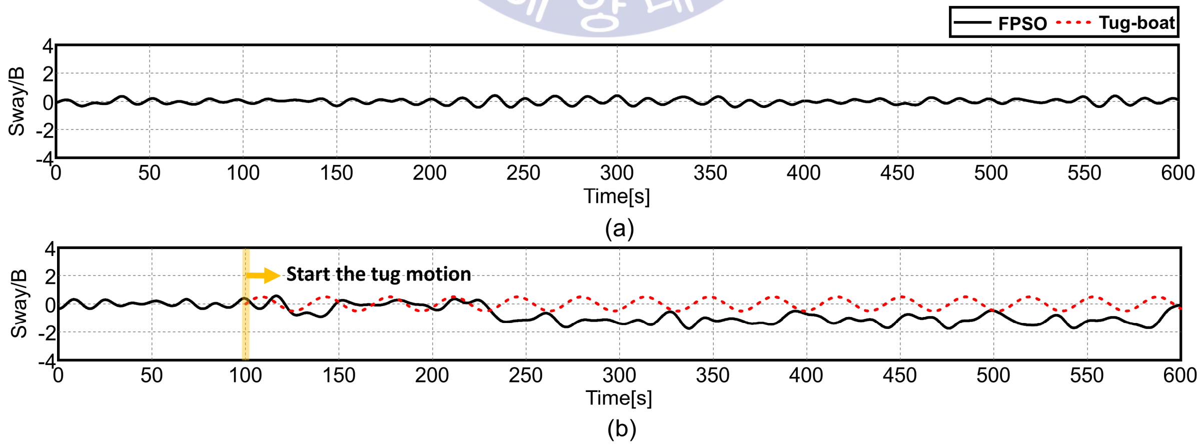


Fig. 5.14 Comparison of experimental time history results ($l_T = 1.5L$, $V = 0.463m/s$)

(a) Conventional experimental method

(b) Developed experimental method ($f_{tug} = 0.5f_s$, $A_{tug} = 0.5B$)

Chapter 6. Conclusion

In this study, we developed a model test method to determine the cousre stability of an FPSO for a course change of the tug-boat. The towing stability of FPSO implemented with stable or unstable through trim condition. Experiments were conducted by both conventional experimental method and the devloped experimental method.

First, the conventional experimental method was conducted to investigate the towing characteristic of the towed FPSO. It carried out by selecting parameters affecting towing stability such as length of towline, towing speed, trim condition and towed point. In the trim-by-bow condition, the sway and yaw motion are increased, and tne towline tension is increased. In addition, it was confirmed that it is located in the marginal stable region because the periodic motion is prominent.

As shown the results of towed point change, it was confirmed that the towed point can be located at a long distance from the center of gravity of FPSO using the bridle towline to improve the towing stability.

Second, the developed experimental method was conducted to consider the tug-boat motion. The results of experiment were analyzed from two perspectives.

From the perspective of towing stability, the stability was improved when the amplitude of tug-boat motion was larger than the breadth of model and the frequency of tug-boat motion was higher than the frequency of slewing motion. However, these conditions are unrealistic and inefficient to be implemented in actual towing operations.

From the perspective of course stability, the FPSO follows the cousre of the tug-boat when the frequency of the tug-boat is lower than the frequency of the slewing motion. In addition, it was confirmed that unnecessary thrust consumption of the tug-boat could be reduced because the change of towline tension was samll.

Based on the experimental results of this study, we proposed an experimental method to determine the course staiblity. In addition, we demonstrated the necessity of the developed method by showing that the FPSO, even when found to be stable through the conventional experimental method, fails to follow the course of the tug-boat as per the proposed experimental method.

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