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RESPONSE CHARACTERISTICS OF A TRAILER TYPE MULTI-CONNECTED BARGE SYSTEM IN WAVES

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ABSTRACT

A trailer type multi-connected barge system is a new type of ocean transportation system composed of several barges connected to each other with a mechanical connecting device and a tug ship. To design the trailer type multi-connected barge system, it is necessary to grasp the exact response characteristics of the trailer type multi-connected barge system in waves.

A model basin test was conducted for the trailer type multi-connected barge system in waves. In the model basin test, the tug ship and three barges were connected to each other by the mechanical connecting device, and the tug ship towed three barges in waves.

As a result, the response characteristics of the trailer type multi-connected barge system in waves were obtained. A non-linear phenomenon of a longitudinal connecting force caused by relative pitch motions of barges was observed. A way to avoid the non-linear phenomenon and reduce the longitudinal connecting force could be found, and the realization of the trailer type multi-connected barge system was experimentally confirmed.

1. INTRODUCTION

The devastation of climate change and global warming has been a serious problem in recent years. A variety of measures has been taken against that problem in various fields. In the field of transport, the modal shift of transportation, namely from the ground transportation to the ocean transportation, is considered to be one of the most available measures, and it is planed to promote a use of the domestic shipping. In the present circumstances, however, the transportation share of the domestic shipping tends to decrease. This is due to the fact that the domestic shipping takes a long time and heavy cost for transportation. Therefore, shortening of the time to wait for discharge that accounts for 40 percent of all transportation time is effective as the measures. [1]

A trailer type multi-connected barge system is considered to be the most effective means answering the request. The trailer type multi-connected barge system is a new type of ocean transportation system composed of many barges connected to each other with a mechanical connecting device and a tug ship. This system circulates through ports accumulating cargo, and delivers barges to each port and collects barges from these ports. This system has a potential to give an epoch-making change to the ocean transportation system because it has a number of advantages comparing with a usual this kind of barge system such as the pusher barge system. This system can shorten a time to wait for discharge because it can uncouple only the required barges and leave port immediately. This system can fractionate and transport many kinds of cargos all at once. This system can get an unobstructed view in front, and has a good directional stability comparing the pusher barge system.

The key to realizing this system is the technology to connect each barge or a tug ship and a barge. In order to make use of the

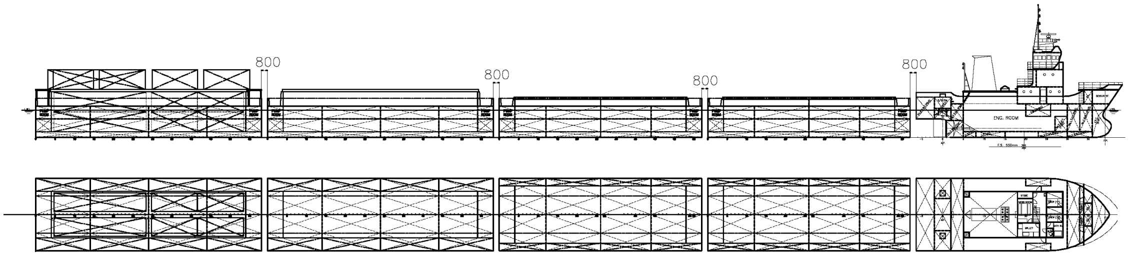

Fig.1 Concept of the trailer type multi-connected barge system

advantages of the system, a mechanical connecting device is necessary to connect and disconnect each barge or a tug ship and a barge and to endure heavy loads due to waves. Moreover, a technique to lubricate sliding parts and by means of seawater instead of oil is required to prevent pollution of the sea.[2] We have already developed a new type of mechanical connecting device to satisfy the above conditions.[3,4,5]

In order to design the trailer type multi-connected barge system, it is necessary to grasp the exact response characteristics of the trailer type multi-connected barge system in waves. In this study, a model basin test and a theoretical calculation were conducted for the trailer type multi-connected barge system in waves to investigate the response characteristics of the multi-connected floating body system.

2. BASIC CONSTITUTION OF THE TRAILER TYPE MULTI-CONNECTED BARGE SYSTEM

2.1 Tug Ship and Barge

The concept of the trailer type multi-connected barge system is shown in Fig.1, and the principal particulars of the tug ship and the barge are shown in Table 1. The tug ship is a twin-screw vessel, and propeller shafts are inclined outward so that a flow induced by propeller does not hit the stem of barge. The breadth of the tug ship coincides with the breadth of the barge, so that the breadth of the tug ship is wider than the usual normal ship. Therefore the tug ship has relatively good stability because of very large metacentric height. Ballast tanks are equipped to cope with changes of drought and trim.

The bottom of the barge is cut up at stem and stern to reduce hull resistance. The barge has ballast tanks to cope with changes of drought and trim, too.

2.2 Mechanical Connecting Device

The basic idea of a mechanical connecting device is shown in Fig.2. The concept for this mechanical connecting device features a multi-degrees of freedom coupling mechanism and restricting mechanism. The multi-degrees of freedom coupling mechanism is positioned at the center of floating body unit and permits relative rotations in all directions between floating body units, thus reducing the connecting forces acting on the mechanical connecting device.

Table 1 Principal particulars of the tug ship and barge

Tug ship

			Ship	Model
Length	L_{PP}	[m]	21.50	0.717
Breadth	B	[m]	9.50	0.317
Draft	d	[m]	3.60	0.120
Displacement	Δ	[ton]	560.0	0.0202

Barge

			Ship	Model
Length	L_{OA}	[m]	29.87	0.996
Breadth	B	[m]	9.50	0.317
Draft	d	[m]	3.60	0.120
Displacement	Δ	[ton]	1047.1	0.0378

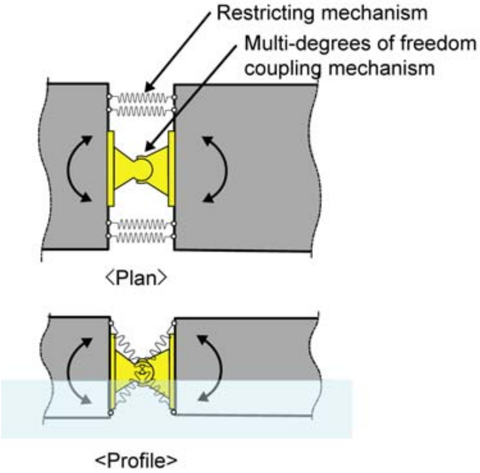

Fig. 2 Basic idea of the mechanical connecting mechanism

The restricting mechanism is positioned at both sides of floating body unit and adjusts the restricting condition between floating body units.

According to the basic idea of the mechanical connecting device, the multi-degrees of freedom coupling mechanism adopts the method of the universal joint, with freedom of rotation in the axial direction added to the mechanism. Thus a mechanical joint that permits rotation in all directions like a ball joint was realized easily at a low cost.

3. OUTLINE OF CALCULATION METHOD

The theoretical calculations were carried out using the computer program for motion analysis of multiple floating bodies connected to each other in waves. This computer program can be used widely for multifarious problems by modeling connecting conditions to the linear dynamic system of mass-spring-damper.[6,7]

The basis of the present study is the analytical procedure for prediction of motions of a single body freely floating in waves, and for the calculation of hydrodynamic forces we adopted the strip method with two-dimensional singularity distribution method. The equation of motions for a single body freely floating in waves is given as follows in matrix notations,

$$\left(\mathbf{M}+\mathbf{A}\right)\ \ddot{\boldsymbol{\eta}} + \mathbf{B}\dot{\boldsymbol{\eta}} + \mathbf{C}\boldsymbol{\eta} = \mathbf{F} \qquad (1)$$

where

$\mathbf{M}$: generalized mass for body; 6 x 6 matrix
$\mathbf{A}$: added mass ; 6 x 6 matrix
$\mathbf{B}$: damping coefficients ; 6 x 6 matrix
$\mathbf{C}$: hydrostatic restoring coefficients ; 6 x 6 matrix
$\boldsymbol{\eta}$: motions $(\eta_j = \eta_{A\,j} e^{i\omega_e t},\ j = 1, 2, \cdots, 6)$; 6 x 1 vector
$\mathbf{F}$: wave exciting force and moment $(F_j = F_{A\,j} e^{i\omega_e\, t},\ j = 1, 2, \cdots, 6)$; 6 x 1 vector
ω_e : encounter circular frequency of regular waves
A : subscript indicating complex amplitude

Defining the linear operator $\mathbf{D}$ as follows:

$$\mathbf{D} = -\omega_e^{\,2}\ \left(\mathbf{M}+\mathbf{A}\right) + i\omega_e\ \mathbf{B} + \mathbf{C} \qquad (2)$$

Equation (1) may be simplified in the form:

$$\mathbf{D}\cdot\boldsymbol{\eta}_A = \mathbf{F}_A \qquad (3)$$

The equation of motions for multiple floating bodies moored and connected to each other is given in a general form as follows:

$$\begin{bmatrix} & \vdots & & \vdots & \\ \cdots & \mathbf{D}_l+\mathbf{E}_{ll} & \cdots & \mathbf{E}_{lm} & \cdots \\ & \vdots & & \vdots & \\ \cdots & \mathbf{E}_{ml} & \cdots & \mathbf{D}_m+\mathbf{E}_{mm} & \cdots \\ & \vdots & & \vdots & \end{bmatrix} \begin{bmatrix}\vdots\\ \boldsymbol{\eta}_{lA}\\ \vdots\\ \boldsymbol{\eta}_{mA}\\ \vdots\end{bmatrix} = \begin{bmatrix}\vdots\\ \mathbf{F}_{lA}\\ \vdots\\ \mathbf{F}_{mA}\\ \vdots\end{bmatrix} \qquad (4)$$

where

$\mathbf{D}_l$: coefficients for a single body freely floating ; 6 x 6 matrix
$\mathbf{E}_{lm}$: added coefficients due to connecting members ; 6 x 6 matrix
$\mathbf{F}_{lA}$: wave exciting forces for a single body freely floating ; 6 x 6 matrix

The subscripts l, m indicate quantities related to number of bodies, and added coefficients matrices $\mathbf{E}_{lm}$ can be obtained from the forces acting on the l -th body when the m -th body is forced to oscillate and the other bodies are obtained. The hydrodynamic interaction is ignored.

The matrix $\mathbf{K}$ representing the characteristics of the connecting member is defined in reference to the local coordinate system as follows,

$$\mathbf{K} = \left[\ K_{ij}\ \right] \quad ;\ i,\ j = 1, 2, \cdots, 6 \qquad (5)$$

It is assumed that the transformation matrices $\mathbf{T}_l$ and $\mathbf{T}_m$ are defined for the transformation from the fixed coordinate systems located bodies to the local coordinate system of connecting member, respectively, where in the local coordinate systems of connecting members, the one is a parallel translation of the other. The added coefficients $\mathbf{E}_{ll}$, $\mathbf{E}_{lm}$ due to connecting members are expressed as follows,

$$\begin{aligned} \mathbf{E}_{ll} &= \mathbf{T}_l^{\,t}\mathbf{K}\mathbf{T}_l \\ \mathbf{E}_{lm} &= \mathbf{T}_l^{\,t}\mathbf{K}\mathbf{T}_m \qquad (l \neq m) \end{aligned} \qquad (6)$$

By taking into account the damping and the inertia forces as well as the restoring forces, the matrix $\mathbf{K}$ can be written in the same form as the matrix $\mathbf{D}$ shown in equation (2). Its form can be written as follows,

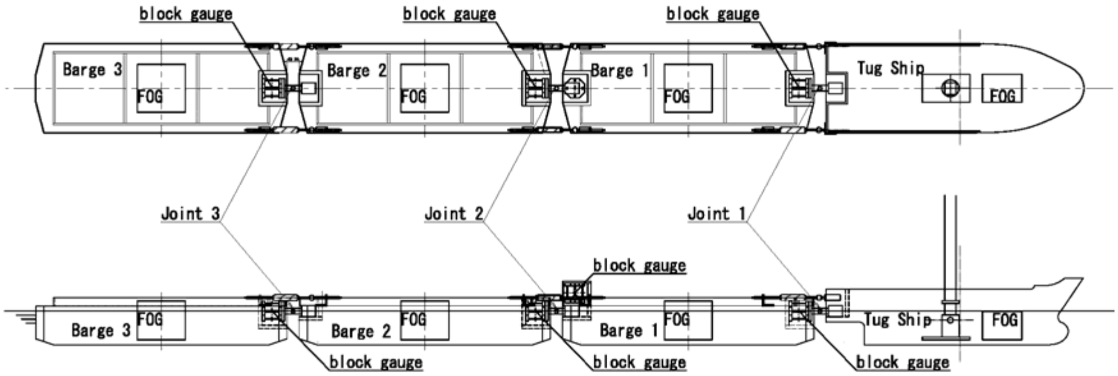

Fig. 3 Test arrangement

$$\mathbf{K} = -\omega_e^2 \mathbf{A}^k + i\omega_e \mathbf{B}^k + \mathbf{C}^k \qquad (7)$$

where

$\mathbf{A}^k$: mass coefficients due to connecting member; 6 x 6 matrix

$\mathbf{B}^k$: damping coefficients due to connecting member; 6 x 6 matrix

$\mathbf{C}^k$: restoring coefficients due to connecting member; 6 x 6 matrix

Since it treats the connecting member as a linear dynamic system in a unified manner, the present method can be applied to a wide variety of motion problems related to multi-connected floating bodies.

4. FUNDAMENTAL MODEL BASIN TEST

In order to investigate the fundamental response characteristics of the trailer type multi-connected barge system in waves and the applicability of the theoretical calculation method, the model basin test was conducted for the trailer type multi-connected barge system in waves.

4.1Test Procedure

The test arrangement is shown in Fig.3. The 1/30 scale models of the tug ship and three barges were connected to each other by the mechanical connecting device on the surface of the water. The spring constant of connecting line of restricting mechanism was set to 100 kN/m. The tug ship was towed by towing carriage in waves. Six components of motions of the tug ship were measured at the center of gravity by carriage type motion sensor, and three components of motions of each barge, that is, roll, pitch and yaw, were measured by fiber optic gyro. The connecting forces acting on the mechanical connecting device were measured by block gauge. A photograph of the model basin test is shown in Fig.4.

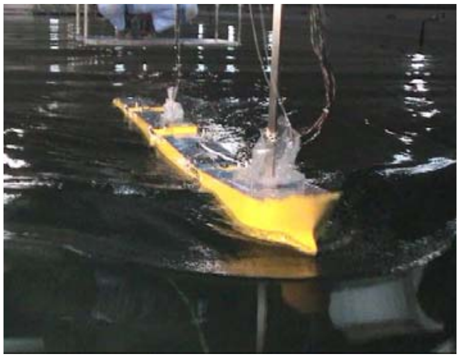

Fig. 4 Model basin test

The model basin test was conducted in irregular waves while varying the wave condition, namely significant wave height, wave period and wave direction

4.2Test Results

Some typical example of the test results indicating the response characteristics of the trailer type multi-connected barge system are shown in this chapter. The results of measurements of motions of the tug ship and the barge are shown in Figs.5 and 6 in comparison with the calculated results. In these figures, the significant amplitudes of motions for unit significant wave height in each wave direction are shown as a function of significant wave period. We found a tendency that the motions of the tug ship are larger than those of the barge. This is mainly due to the fact that the tug ship is smaller than the barge. Especially, such tendency is remarkable in pitch motion. This is due to the effect of connection between the tug ship and the barge. Namely, the tug ship is connected to the barge at stern and the vertical motion of stern of the tug ship is restricted, so that the vertical motion of bow of the tug ship becomes larger.

The results of measurements of roll and pitch motions of each barge indicate almost the same tendency and values. Comparing the measured and calculated results, even though some discrepancies are present for roll and pitch motions in longer wave period range, it can be said that fairly good agreement is obtained on the whole.

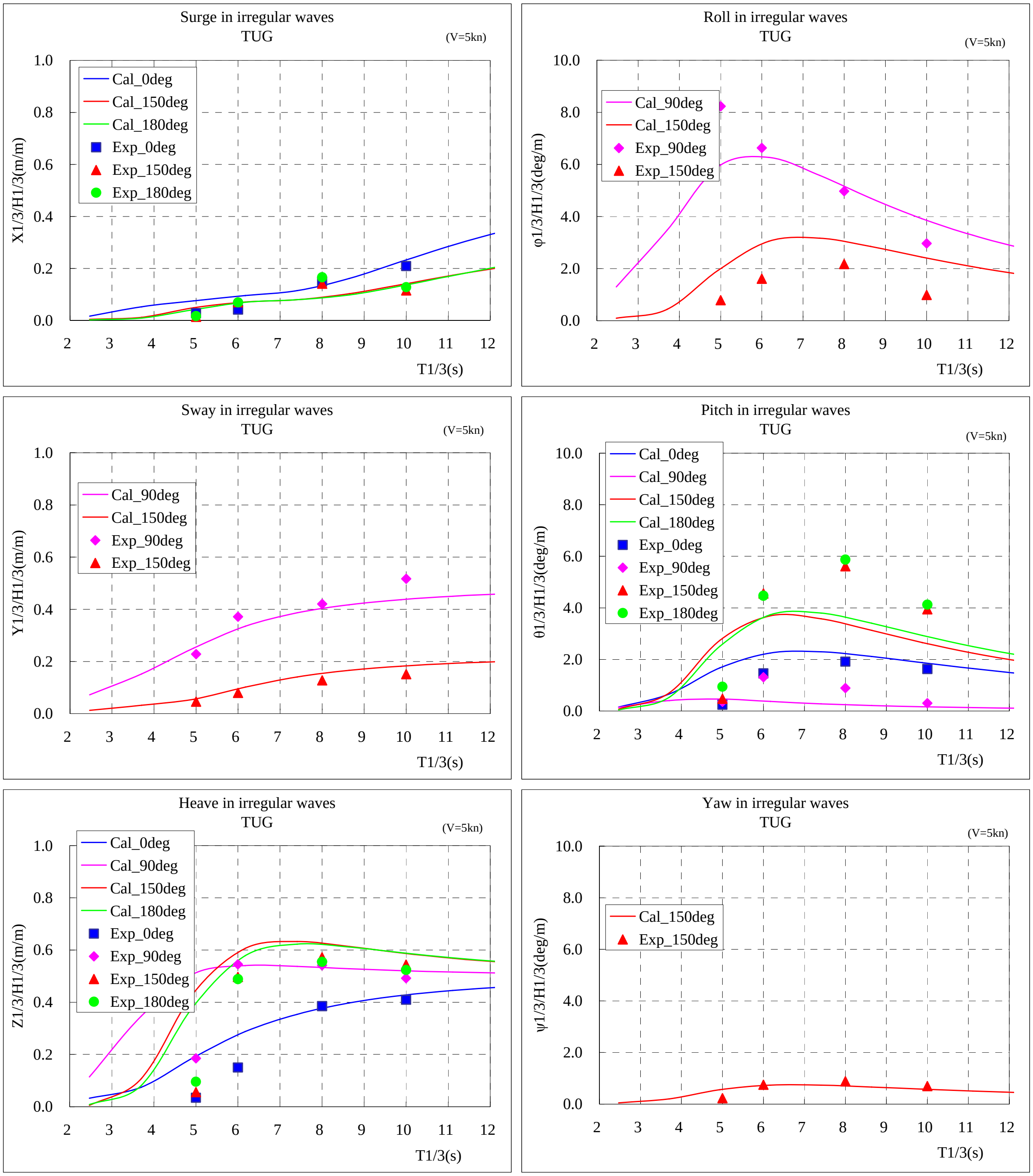

Fig. 5 Measured results of ship motion of the tug ship in irregular waves

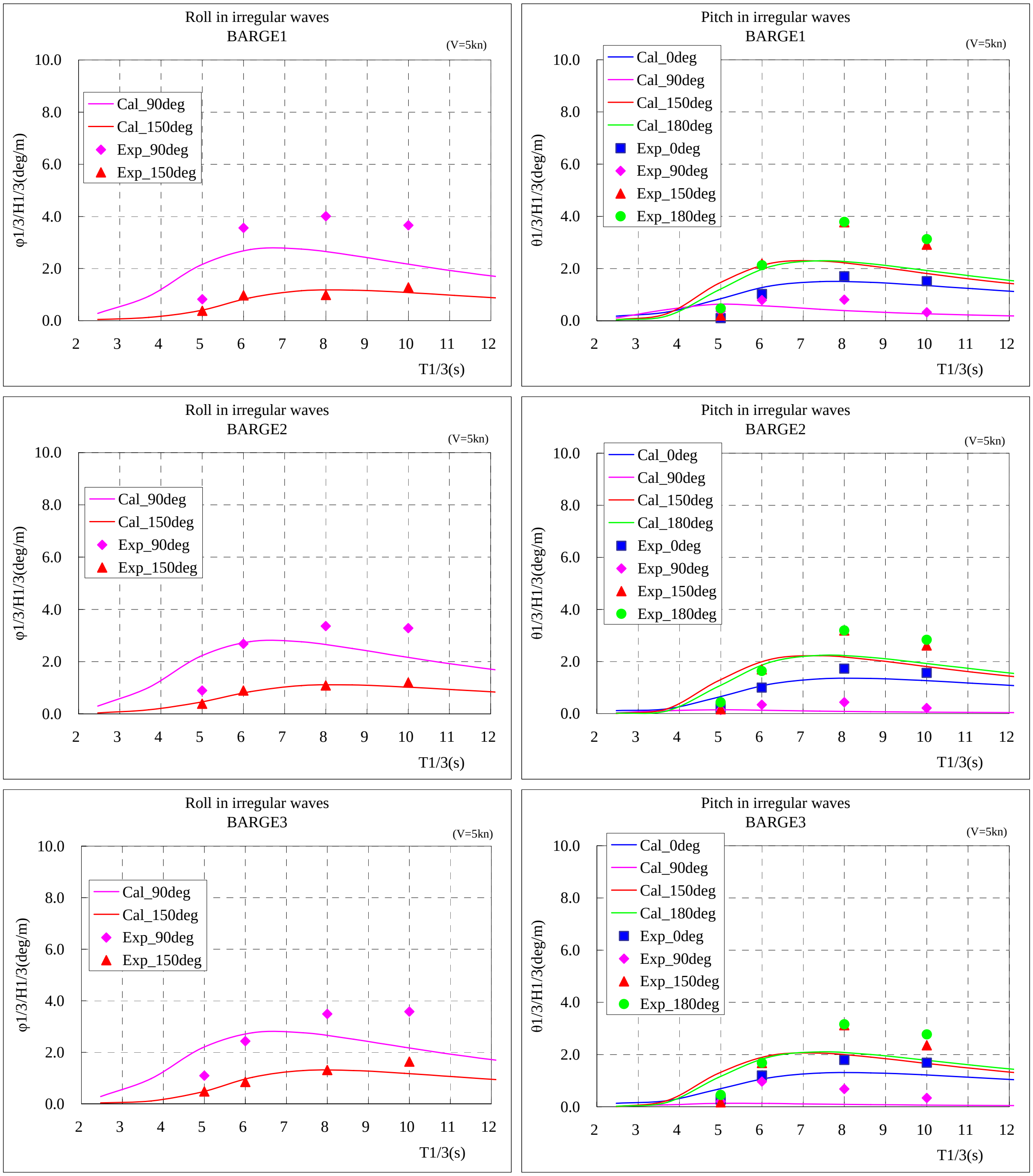

Fig. 6 Measured results of ship motion of the barges in irregular waves

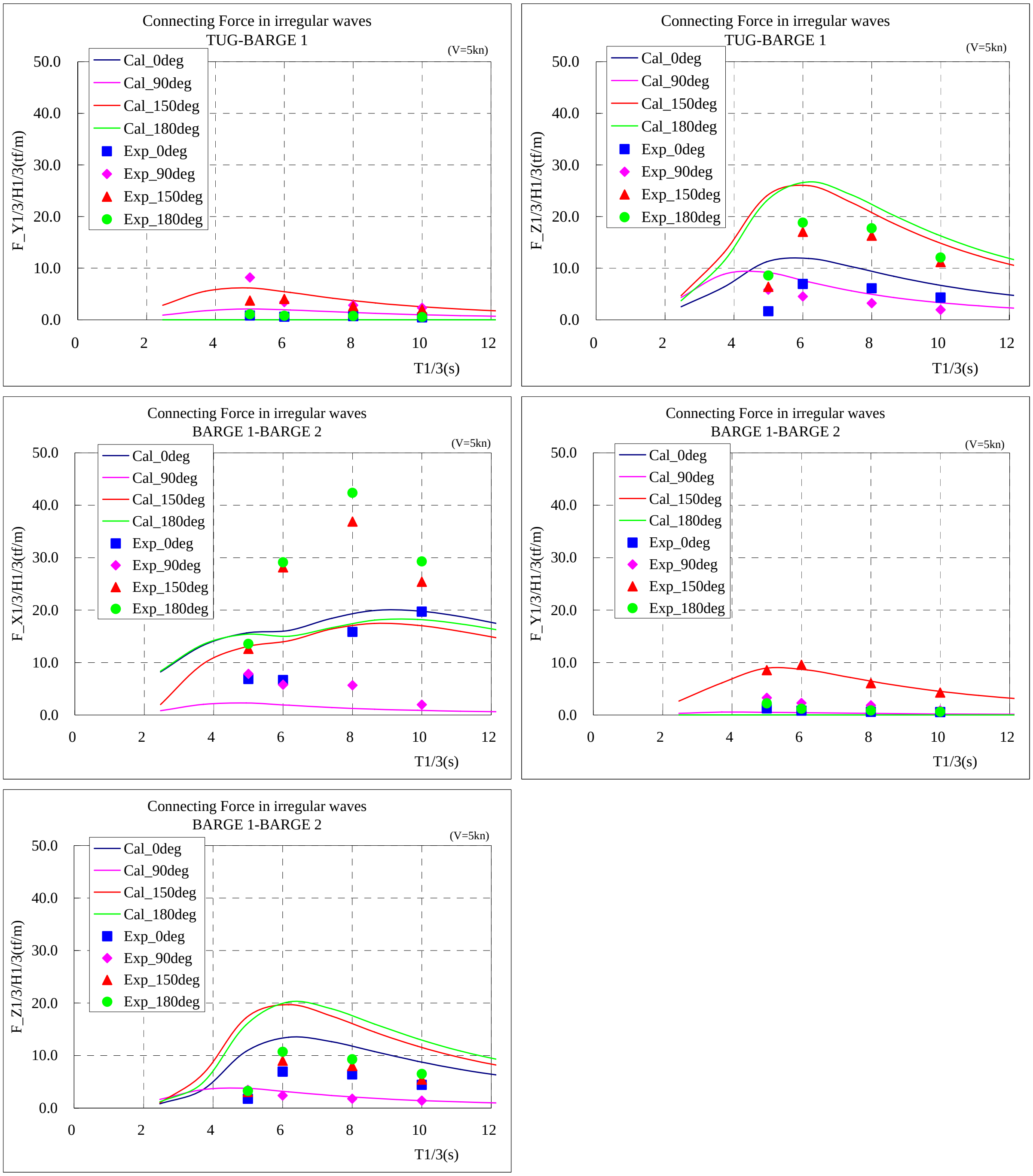

Fig. 7 Measured results of connecting forces in irregular waves

The results of measurements of connecting forces are shown in Fig.7 in comparison with the calculated results. In these figures, the significant amplitudes of connecting forces for unit significant wave height in each wave direction are shown as a function of significant wave period. Comparing the measured and calculated results, we found that the measured results of the longitudinal connecting forces are remarkably larger than the calculated ones. On the other hand, the measured results of the vertical connecting forces are smaller than the calculated ones. Especially, careful investigation should be given to the remarkable discrepancy between the measured and calculated results for the longitudinal connecting force. The lateral connecting forces are not so large, and fairly food agreement is obtained between measured and calculated results.

4.3 Discussion

We investigate the characteristics of the longitudinal connecting force. Fig.8 gives the spectra of pitch motion of the barge and longitudinal connecting force. In the spectrum of pitch motion, there appears one peak at period of about 6 seconds. On the other hand, there appear two peaks at periods of about 6 and 3 seconds in the spectrum of the longitudinal connecting force. The peak at 6 seconds comes from a component of response to waves, and the peak at 3 seconds represents a response of double frequency because of the effect of a non-linear phenomenon.

In order to investigate the cause for the non-linear phenomenon, an additional model basin test was conducted in regular waves. The measured time histories of longitudinal connecting force between barges are shown in Fig.9. These figures also contain the time histories of incident regular waves. In the wave period of 6 seconds, the non-linear response of double frequency can be found for longitudinal connecting force. In the wave period of 8 seconds, such non-linear response dose not observed. The wave length with wave period of 6 seconds is about two times as long as the barge, therefore, the phase lag of pitch motions of adjacent barges becomes to be 180 degrees as shown in Fig10. Moreover, the natural period of pitch motion of the barge is about 6 seconds. Therefore, it seems to be probable that relative surge motion between connecting points of adjacent barges caused by pitch motions becomes larger and the response of double frequency appears in the longitudinal connecting force.

In order to verify the above inference, theoretical calculations were conducted using the non-linear time history simulation method [8] which can consider the relative surge motion between connecting points of adjacent barges caused by pitch motions. The relative surge motions given as the following formula.

$$\delta CL = L(1-\cos\theta) \qquad (8)$$

Where,

δCL : relative surge motion between connecting point
L : length of barge
θ : pitch angle

In the linear theory, this term is neglected based on the following assumption.

$$\cos\theta \approx 1 \qquad (9)$$

Fig.11 gives the calculated results of time histories of the ship motions and the longitudinal connecting force in regular waves with wave period of 6 seconds. The response of double frequency appears in relative surge motion between connecting points of adjacent barges and longitudinal connecting force. Therefore, it was proved that the non-linear phenomenon was caused by relative surge motion between connecting points of adjacent barges due to pitch motions of barges. To realize the trailer type multi-connected barge system, it is desirable to avoid such non-linear phenomenon and reduce the longitudinal connecting force.

Based on the above investigation, it was guessed to be valid that each barge has a different own length as one of ways to avoid the non-linear phenomenon in the longitudinal connecting force. In order to examine that validity, the non-linear time history simulations were carried out for ship motion and connecting force while varying the length of each barge in regular waves with wave period of 6 seconds. The calculation conditions are shown in Fig.12. The length of the middle barge among three barges was varied for three cases such as shorter, original and longer lengths. Fig.13 gives the calculated results of time histories of ship motion and longitudinal connecting force. We can find that the longitudinal connecting force in the case that each barge has different length becomes smaller than in the case that each barge has the same length.

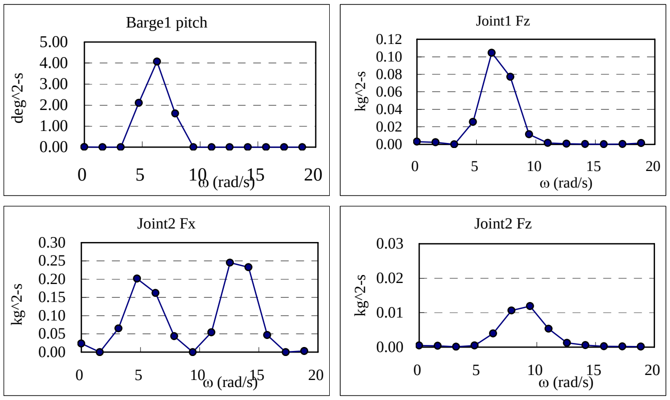

Fig. 8 Spectrum of pitch motion of the barge and connecting force in irregular waves

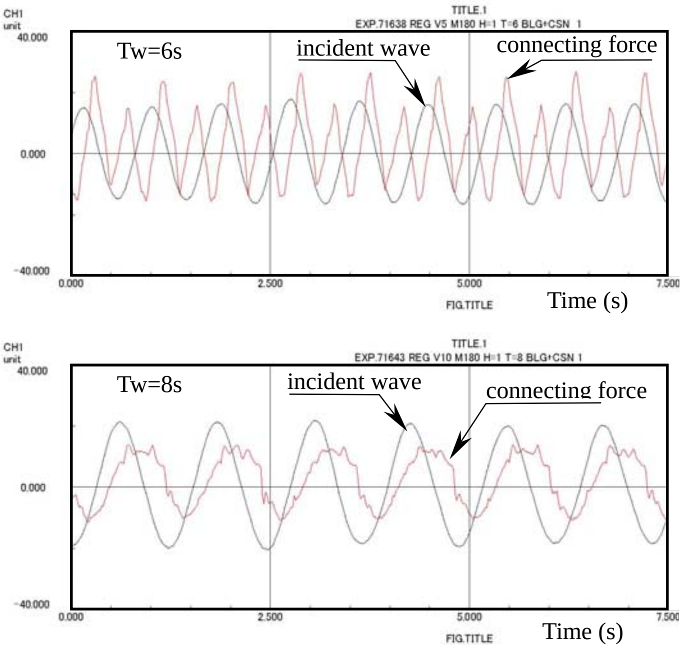

Fig. 9 Measured results of time history of connecting force in regular waves

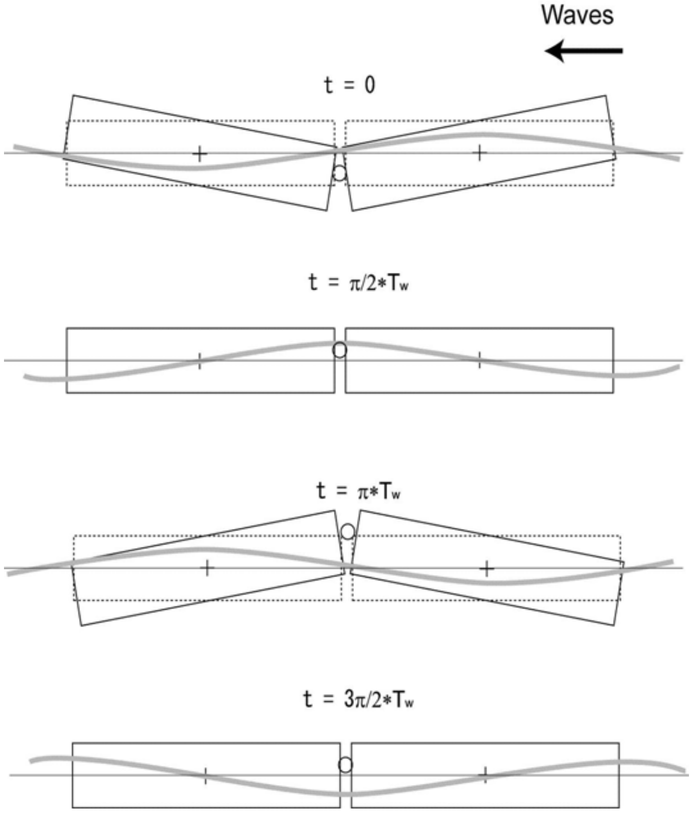

Fig. 10 Relation between wave and barge motion in irregular waves with wave period of 6 seconds

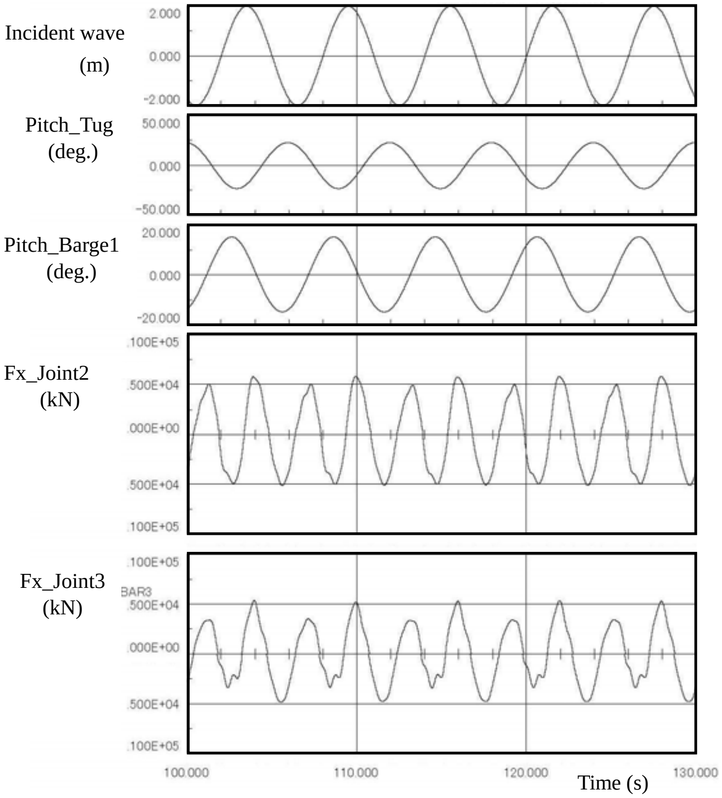

Fig. 11 Calculated results of time history of ship motion and connecting force in regular waves

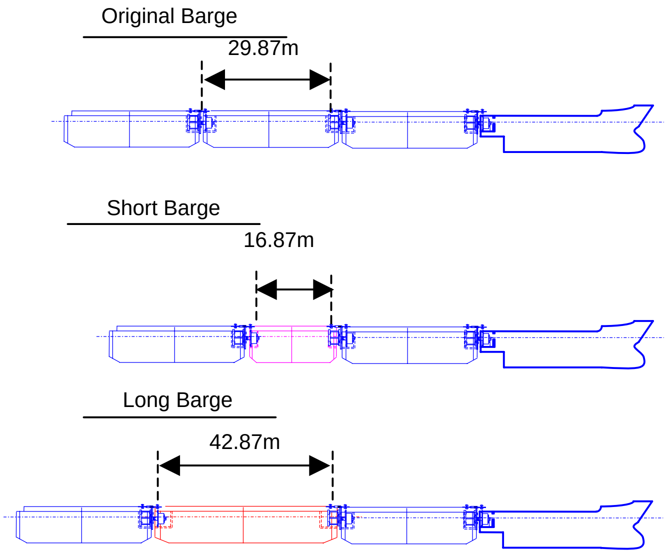

Fig. 12 Calculation condition varying the length of middle barge

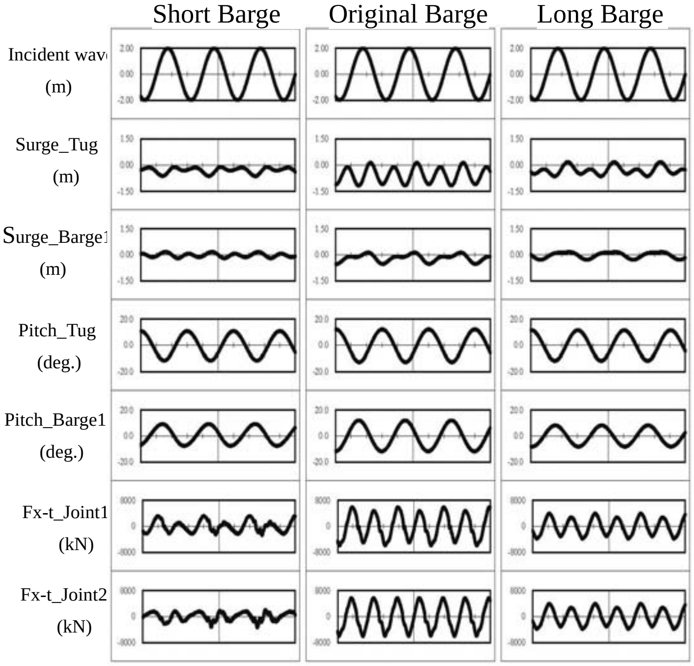

Fig. 13 Calculated results of time history of ship motion and connecting force while varying the length of middle barge in regular waves

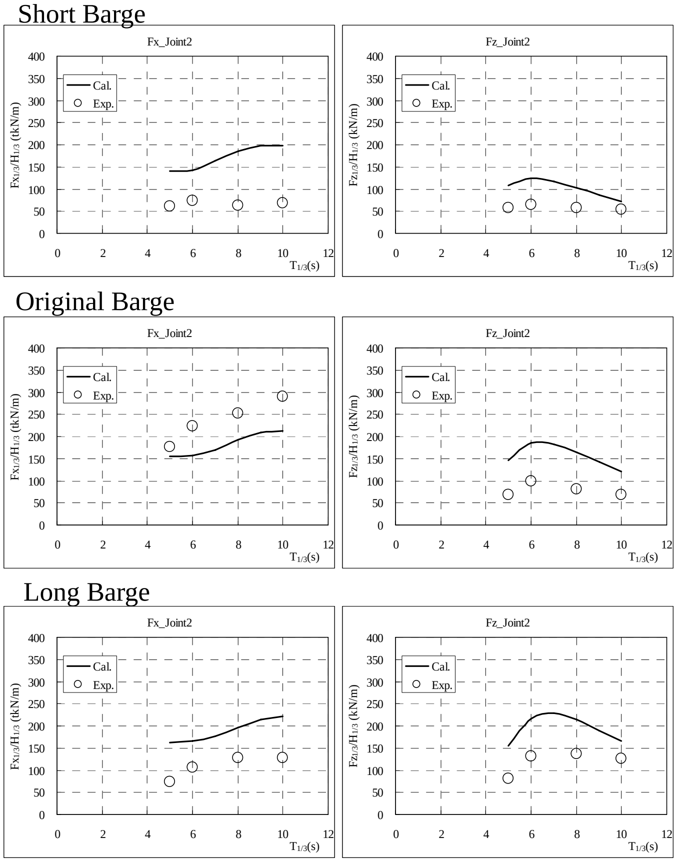

Fig. 14 Measured results of connecting forces while varying the length of middle barge in irregular waves

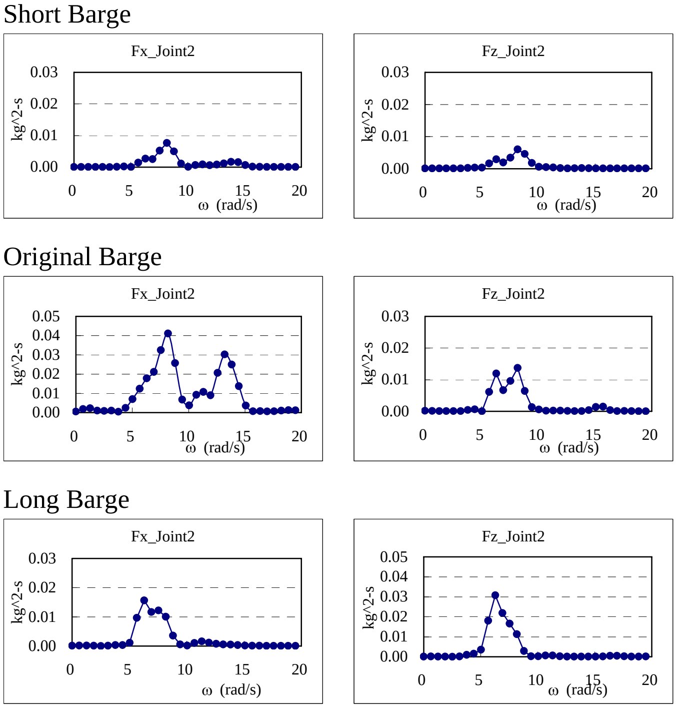

Fig. 15 Spectrum of connecting forces while varying the length of middle barge in irregular waves

5. APPLIED MODEL BASIN TESIN

In the above fundamental model basin test, the non-linear phenomenon of the longitudinal connecting force was observed. The cause of this non-linear phenomenon was elucidated and the way to avoid the non-linear phenomenon and reduce the longitudinal connecting force was proposed. A validity of that way was examined by an applied model basin test.

5.1 Test Procedure

The model ship conditions coincide with those of the calculation shown in Fig.12. The test arrangement was the same as the arrangement of the abovementioned fundamental model basin test. Motions of the tug ship and barges were measured at the center of deck by optical motion sensor. The connecting forces acting on the mechanical connecting device were measured by block gauge.

The model basin test was conducted in irregular head waves while varying significant wave height and wave period.

5.2 Test Result

Some typical example of the test results indicating the validity of the way to reduce the longitudinal connecting force are shown in this chapter. The results of measurements of connecting forces obtained while varying the length of middle barge among three barges are shown in Fig.14 in comparison with the calculated results obtained using the linear calculation method. In these figures, the significant amplitudes of longitudinal and vertical connecting forces for unit significant wave height are shown as a function of significant wave period. The calculated results of longitudinal connecting force indicate almost the same tendency and value for all cases of barge length. On the other hand, the measured results in the shorter or longer middle barge lengths are remarkably smaller than in the same barge length. With regard to the vertical connecting force, the measured results are smaller than the calculated ones, and the values become larger as the middle barge length increases.

Fig.15 gives the spectrum of connecting forces obtained while varying the length of middle barge among three barges. When the length of middle barge is shorter or longer, the peak at double frequency of response to waves cannot almost be found in spectrum of longitudinal connecting force. It seems to be valid that each barge has a different own length to avoid the non-linear phenomenon and reduce the longitudinal connecting force. Thus the validity of the way to avoid the non-linear phenomenon and reduce the longitudinal connecting force was confirmed experimentally.

6. CONCLUDING REMARKS

The model basin test and theoretical calculation were conducted for the trailer type multi-connected barge system in waves to grasp the response characteristics of the trailer type multi-connected barge system in waves. The results of the present study can be summarized as follows.

(1) The feasibility of the trailer type multi-connected barge system was confirmed experimentally.

(2) The characteristics of the motions of the trailer type multi-connected barge system and connecting forces acting on the mechanical connecting device can be grasped experimentally and theoretically.

(3) The non-linear phenomenon of the longitudinal connecting force was especially observed, and it was proved that the non-linear phenomenon was caused by relative surge motion between connecting points of adjacent barges due to pitch motions of barges. The way to avoid the non-linear phenomenon and reduce the longitudinal connecting force could be proposed.

The trailer type multi-connected barge system is a new type of ocean transportation system, and has potential to give an epoch-making change to the ocean transportation system. The authors hope to realize this system and promote the modal shift of transportation, and to contribute the protection against the devastation of climate change and global warming.

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