Coupled Dynamic Simulation of a Tug-Towline-Towed Barge based on the Multiple Element Model of Towline

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Abstract : *Recently, tug boats are widely used for towing a barge which transports building materials, a large block of a ship, offshore crane, and so on. In order to simulate the dynamics of the coupled towing system correctly, the dynamics of the towline should be well modeled. In this paper, the towline was modeled as the multiple finite elements, and each element was assumed as a rigid cylinder which moves in five degrees of freedom except roll. The external tension and its moment acting on each element of the towline were modeled depending on the position vector's direction. Tugboat's motion was simulated in six degrees of freedom where wave and current effects were included, and towed barge was assumed to move in the horizontal plane only. In order to confirm the mathematical models of the coupled towing systems, standard maneuvering trials such as course changing maneuver, turning circle test and zig-zag test were simulated. In addition, the same trials were simulated when the external disturbances like wave and current exist. As the result, it is supposed that the results might be qualitatively reasonable.*

Key words : *Tug-towline-towed barge, Multiple element model, Coupled dynamics, Maneuvering simulation*

1. Introduction

Recently, according to the development of the global economics and the international division of labor, the quantity of goods transported at sea increases dramatically. While a large special-purpose ship is used for transporting the cargos for long range, a tugboat and a towed barge is widely used for short range and coastal transportation. In our country, shipbuilding industries have been much developed, and they have tried to enlarge their production capability. For this reason, many blocks of a newly constructing ship are made in other area such as western area of Korea or China. In case of transporting such blocks, towing system composed of a tugboat and a towed barge is frequently used. In addition, towing system is also used for delivering dredged sand, offshore crane, construction materials, and so on. More than 1,200 tugboats are used in Korea and the number increases rapidly.

Towing system is less course-keeping stable than the conventional single ship. Also, it is dangerous when it runs in harsh environmental condition. The collision accident of Samsung offshore crane barge and Hebei Spirit tanker which occurred in the west sea of Korea in 2007 was due to the drifting barge towing offshore crane after towline was broken. Towline could not endure very large inertial

and hydrodynamic force acting on a barge due to rough weather condition(You, 2011).

In order to simulate the motion of a tugboat and a towed barge and predict tension acting on a towline correctly, towline dynamics should be well established. Several kinds of models describing towline dynamics, which are catenary model, fixed length model, and finite element model have been suggested(Berteaux, 1976; Yoon et al, 2011; Yoon et al, 2012). Catenary and fixed length models assume that towline shape is predetermined. For this reason, those cannot describe various situations such as floating on the free surface, high frequent fluctuating, and so on. In this paper, finite element model was used of which final mathematical form has been already described with respect to the element-fixed coordinate as the vector-matrix forms(Yoon et al, 2012).

The mathematical models of a towing system consist of independent models of a tugboat, a towed barge, and a towline and the coupled adjacent conditions in various environmental conditions. The motion of tugboat was simulated in six degrees of freedom where wave and current effects can be included using Froude-Krylov force and the impulse response function for input wave, aerial drag and relative velocity to water. On the contrary, a towed barge was assumed to move horizontal plane only,

and it was assumed that the wave effect could be neglected. In order to confirm the mathematical models of the coupled towing system, standard maneuvering trials such as course changing maneuver, turning circle test and zig-zag test were simulated. In addition, the course changing maneuvers were simulated when the external disturbances like wave and current exist.
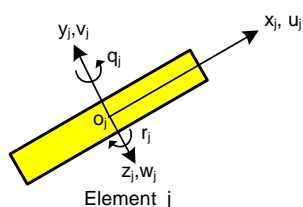
2. Equations of motion

2.1 Coordinate systems

In order to describe the motion of the towing system, earth-fixed coordinate system and body-fixed coordinate systems are defined as shown in Fig. 1.
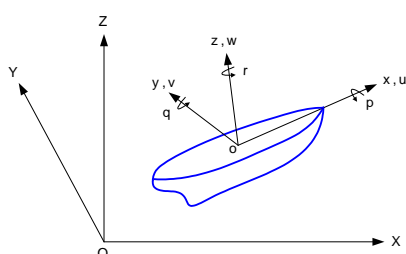
(a) Earth-fixed and tug and towed barge-fixed coordinates

(b) Towline element-fixed coordinate

Fig. 1 Coordinate systems

Body-fixed coordinate systems are redefined as the tugboat-fixed, the towed barge-fixed, and the element of towline-fixed coordinate systems. As stated above, towline is divided as many elements and those are dealt with independent bodies and connected at the joint point. Therefore, every element of the towline has its body-fixed coordinate system. The linear displacement is represented in the earth-fixed frame denoted by O-XYZ, while the equations of motion of the components of the towing system are described in the body-fixed frames denoted by o-xyz. External force and moment acting on a body component can be more easily described in the body-fixed frame than the earth-fixed frame. The origin of the body-fixed frame of the tugboat and the towed barge is the cross point of the longitudinal center line, the water line, and the midship section, and the direction of the

positive z axis is upward. Also, the center of the element of the towline is the centroid of the element volume, and its x-axis is positive forward and its z-axis is positive upward. The subscript in Fig.1(b) is the index of the element of the towline.

2.2 Towline

As shown in Fig. 2, towline is divided into N elements. The forward end position of the zero element is attached at the towing point in the tugboat, and the afterward end position of the N element is attached at the towed point on the barge. Adjacent elements are connected by the spring and the damper, and those are freely moved depending on the force balance.
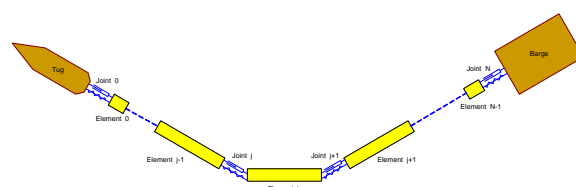

Fig. 2 Configuration of the towing system (Yoon, 2012)

In order to describe the five degrees of freedom equations of motion of the element of the towline except roll, we assumed that the shape of each element is a cylinder of which sectional mass is uniformly distributed.

Fig. 3 depicts the force components acting on the j-th element, and the equations of motion presented by vector-matrix form is as follows;

$$\left(M + M_A\right)\underline{V}' = \underline{C} + \underline{C}_A + \underline{D} + \underline{D}_M + \underline{H} + \underline{B} + \underline{W} + \underline{T}^f + \underline{T}^a, \quad (1)$$

where, M : mass of the element

M_A : added mass of the element

$\underline{V}'$: rate of the velocity components

$\underline{C}$: Coriolis force of the element

$\underline{C}_A$: Coriolis force of the added mass

$\underline{D}$: drag due to enclosing fluid

$\underline{D}_M$: material damping of the element

$\underline{H}$: hydrodynamic force

$\underline{B}$: buoyancy

$\underline{W}$: weight

$\underline{T}$: tension

and, the underbar in Eq.(1) represents vector.

The detailed models of the force components acting on an element of towline are referred to Yoon(2012) and only the typical models are summarized again in this paper.

The x-directional added mass is assumed as zero and the y and z-directional added masses and the added mass moments of inertia are the same as the full cylinder of

which density is the same as the enclosed fluid. Coriolis force of the added mass can be modeled by using the added mass model mentioned before and the relation between inertial coordinate and non-inertial coordinate like element-fixed coordinate.

Drag force is simply modeled using axial and side drag coefficients and the square velocity component for each direction. Lift force and the moment due to hydrodynamic damping force were neglected following the assumption that the drag is much larger than the lift.

Impact force due to water entry of the element was simply modeled using the time changing rate of the added mass during entry. And, buoyancy was modeled as same as the weight of the element depending on the vertical position of the center of the element.

Material damping force is included in order for the deformation of the towline which will be represented by the element's attitude to be calculated stably and reasonably even though the stiffness of the element is large. For this reason, it might be difficult to determine the correct values, and it should be determined empirically after comparing with the sample test result of the towline. In this paper, we assumed that the y and z directional material damping coefficients are one tenth of the x-directional one, and the standard damping ratios of y-direction is 0.5. The real damping coefficients are calculated considering the maximum tension of the element provided by the maker of the towline.

Finally, tension, which acts on the forward and afterward joint points of the each element, is modeled by multiplying the stiffness into the distance($\Delta \underline{R}_j$) at the joint points of adjacent elements. $\Delta \underline{R}_j$ is updated as time marching and tension of the j-th afterward joint point which is the same magnitude but the opposite direction at the j+1-th forward joint point of the j+1-th element can be calculated. When the distance between the center of the j-th element and the forward joint point of the j+1-th element is less than the half of the length, tension will not be acted, and modeled that its value should be zero logically.

2.3 Tugboat

Tugboat dynamics was modeled based on Newton's second law with respect to the tug‐fixed coordinate as shown in Fig.1(a). In general, since the tugboat is smaller than the towed barge in size, it might be easily influenced by the environment such as wave, and current. For this reason, the six degrees of freedom motion of a tugboat were considered.

If the notations of the motion and the force are defined as the same as the ones in Eq.(1), the equations of motion of tugboat are as follows;

$$\left(M + M_A\right)\underline{\dot{V}} = \underline{C} + \underline{C}_A + \underline{D} + \underline{D}_M + \underline{H} + \underline{B} + \underline{W} + \underline{P} + \underline{R} \qquad (2)$$
$$= \underline{F}_{wave} + \underline{F}_{current} + \underline{T}$$

where, $\underline{P}$ and $\underline{R}$ are thrust and rudder force respectively, and subscripts wave, and current are environmental forces due to those names.

In Eq.(2), velocity vector consists of surge, sway, heave, roll, pitch and yaw velocity. Buoyancy is calculated considering the submerged volume which will be changed at every time step. Hydrodynamic force is updated by mathematical polynomial model depending on the motions and the hydrodynamic coefficients determined by the empirical formulas. Wave force is calculated as the radiation force determined by convolution integral of the motion velocity and its impulse response function and Froude-Krylov force(Newman, 1977). Current effect is considered as the relative velocity to current velocity when the hydrodynamic force is calculated(Fossen, 1994). Finally, the magnitude of tension is the same as the one of the magnitude of tension at the forward position of the 0-th element of the towline, and the direction is opposite each other.

2.4 Towed barge

As assumed earlier, the towed barge is not easily influenced by the environmental condition because of its box-type shape. For this reason, it is proper that its dynamics was considered only for three degrees of freedom motion in the horizontal plane. Since the first-order wave force exerts relatively high oscillation on the floating body, it can be neglected in case of the towed barge. Current which influence on the slow-varying drifting of the barge was considered using the same methods in case of tugboat.

The towed barge's three degrees of freedom equations of motion are as follows;

$$\left(M + M_A\right)\underline{\dot{V}} = \underline{C} + \underline{F}_{current} + \underline{T} \qquad (3)$$

where, velocity vector components are only surge, sway and yaw velocities, and weight and buoyancy is always balanced because attitude is not changed for all time under the above assumption.

3. Simulation

3.1 Towing system

The typical specifications of the towing system consisting of a tugboat, a towed barge, and a towline used in this paper are listed in Tables 1~2. Towline was 115 m

in length which should be over 90 m to satisfy the regulation for a towing system running in the sea along the coast(KR, 1999). It was divided into 11 elements and the indices of the elements of the towline, the tugboat and the towed barge are defined in Fig. 3.

Table 1 Principal dimensions of the tugboat and the towed barge

Item	Value	
	Tug	Barge
Length overall (m)	20.0	48.0
Breadth (m)	4.30	15.0
Depth (m)	1.99	3.0
Draft (m)	1.02	1.0
Displacement (ton)	41.7	626.4
x of towing point (m)	2.0	24.0
z of towing point (m)	1.0	3.0

Table 2 Principal dimensions of the towline

Item	Value
Total length (m)	115.0
Diameter (m)	0.05
Weight per unit length (kgf/m)	1.725
Max. tensile intensity (ton)	16.0
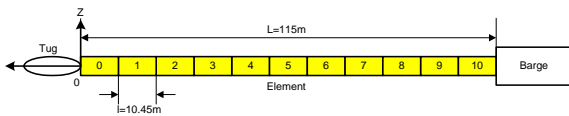
Fig. 3 Configuration of the elements of the towline

Hydrodynamic coefficients were obtained using Kijima's empirical formulae(Kijima et al, 1990) which are valid for a conventional ship. For this reason, the barge might be more stable than the conventional one without skeg. In order to confirm the simulation program and identify the characteristics of the towing system's maneuverability, various simulations were carried out following the scenarios listed in Table 3. The initial condition for all scenarios, which a tugboat and a towed barge are at the same position and the tugboat accelerates after simulation starts, are common.

Table 3 Simulation scenarios

Class	Scenario	Remarks
Calm sea	Straight running	Acc. included
	Course changing	45° for port
	10-10 Zig-zag	Tugboat
	35 Stbd turn	Tugboat
Disturbed sea	Beam sea	Sea state 2
	Side current	0.5 knots

3.2 Straight running

As the simplest condition, straightly running was simulated in order that the coupled dynamics of the towing system established in this paper works correctly. Fig. 4
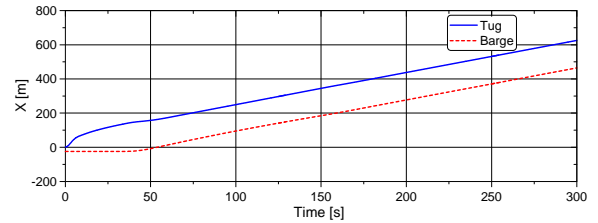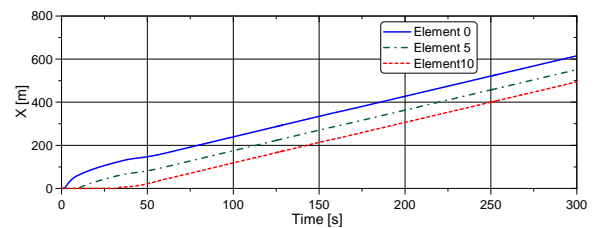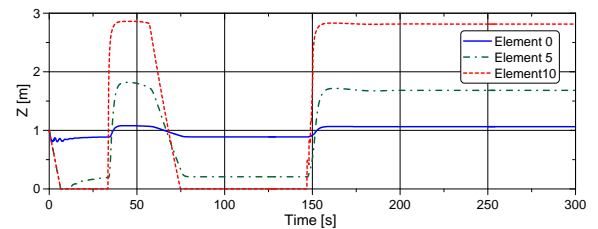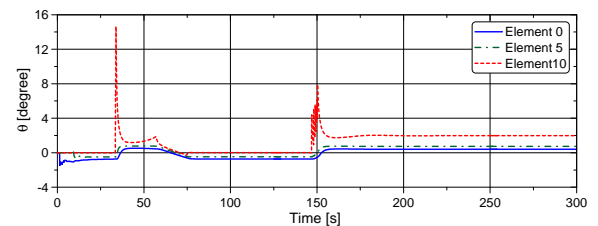

(a) X trajectory
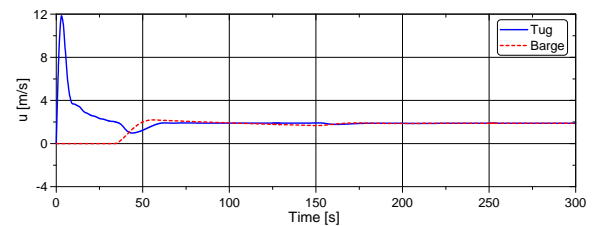
(b) Forward velocity

Fig. 4 Simulation results of the tugboat and the barge when straight running

(a) X trajectory

(b) Z trajectory

(c) Pitch angle

Fig. 5 Simulation results of the elements of the towline when straight running

shows the X trajectories and forward velocities of the tugboat and the towed barge, and Fig. 5 shows the X and Z trajectories and the pitch angles of the 0, 5 and 10-th elements of the towline.

As shown in Fig. 4.(a), the distance between the tugboat and the towed barge keeps well about 115 m which is the original towline length. Tug is accelerated freely before it runs the distance of an element length of towline, and then it is decelerated because towline pulls the tugboat as depicted in Fig. 4(b). In Fig. 5, after about 40 seconds, the tension starts to act on the barge, and the 10-th element becomes tight, then the barge's inertia and towline element's restoring force increase. Such a similar situation occurs again since around 145 seconds and the barge goes to steady state because there is not any restoring force acting on the barge.

3.3 Course changing in calm sea

As the more complex case than the previous straight running, the changing course to 45° port side was simulated. The detailed scenario was that the tugboat runs straightly for 300 seconds and then changes course following the command of PD controlled autopilot. Fig. 6 shows XY trajectories of the tugboat and the towed barge, and rudder angle and roll angle of the tugboat. Positive rudder angle makes the heading of a tugboat turn starboard and positive roll means to incline starboard side. Fig. 7 shows XY trajectories, yaw angles and pitch angles of several elements of the towline.

As shown in Figs. 6~7.(a), the towing system changes the preselected course well. Roll of the tugboat occurs largely inward when it starts to change its course and its time series are very similar to the ones of rudder angle. It means that roll angle of the tugboat is related to the rudder force as well as the tension from the barge because the towing point of the towed barge is higher than the tugboat as listed in Table 1.

3.4 10-10 Zig-zag

Figs. 8 and 10 show the simulation results of the 10-10 zig-zag test of the tugboat. Before the zig-zag test starts, the towing system keeps straight running for 300 seconds in order to be steady state.

As shown in Fig. 8, the overshoot yaw angle is very small because the tension due to barge prevents changing course, and after opposite execution of the rudder angle, it helps the tugboat change opposite direction. The changing pattern of the heading angles of tugboat and towed barge are similar to the sea trial case of the conventional different tugboat and the towed barge as shown in Fig.
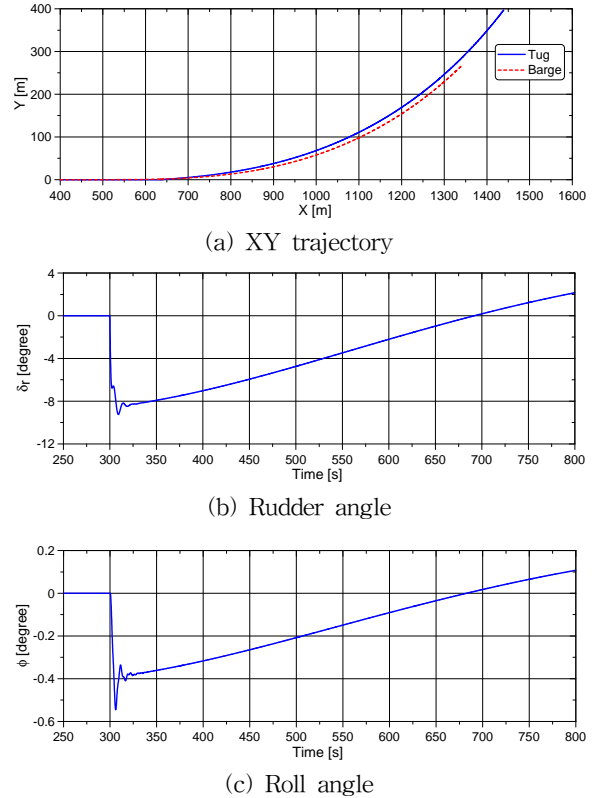

(a) XY trajectory

(b) Rudder angle

(c) Roll angle

Fig. 6 Simulation results of the tugboat and the barge when course changing
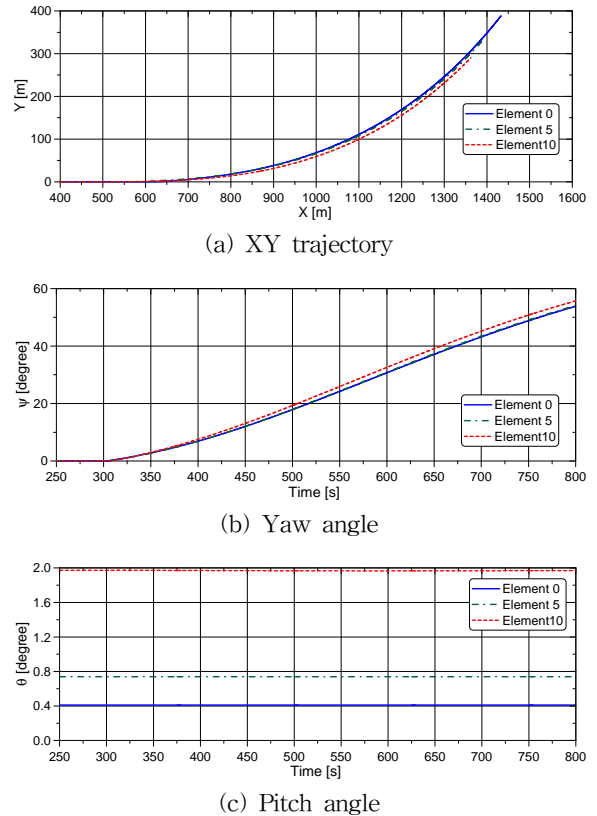

(a) XY trajectory

(b) Yaw angle

(c) Pitch angle

Fig. 7 Simulation results of the elements of the towline when course changing

9(Yun et al, 2012). Fig. 10 shows that the element near the tugboat responds faster than the one near the towed barge. However, higher oscillated motion occurs in the element near the tugboat because of the restoring force of the elements of the towline.

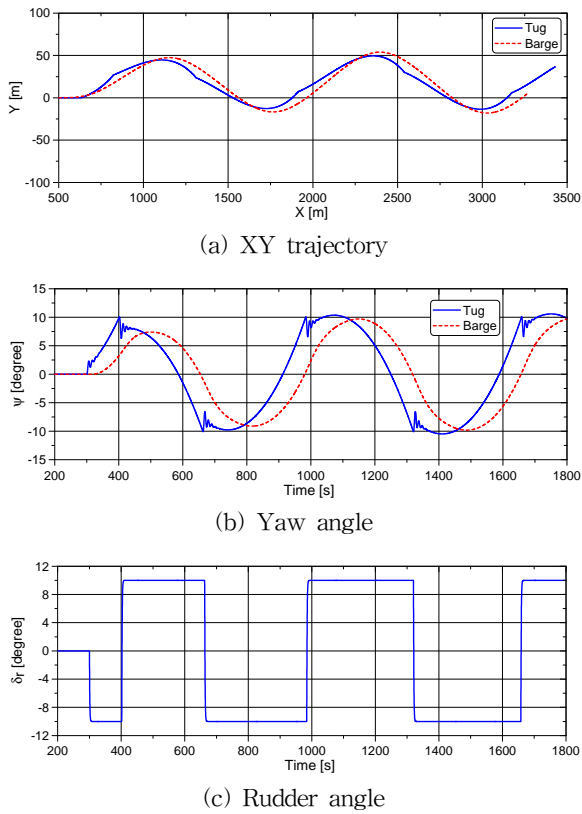(a) XY trajectory

(b) Yaw angle

(c) Rudder angle

Fig. 8 Simulation results of the tugboat and the barge in case of 10-10 zig-zag test
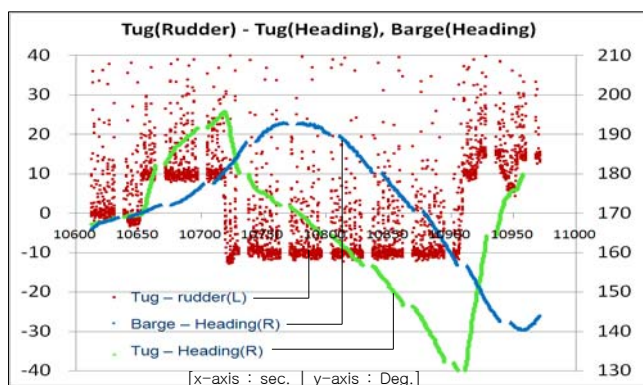
Fig. 9 Sea trial result of the tugboat and the towed barge in case of 10-10 zig-zag test(Yun et al, 2012)

3.5 35 starboard turn

Figs. 11~12 show the simulation results of the towing system when it carries out the 35º starboard turning circle

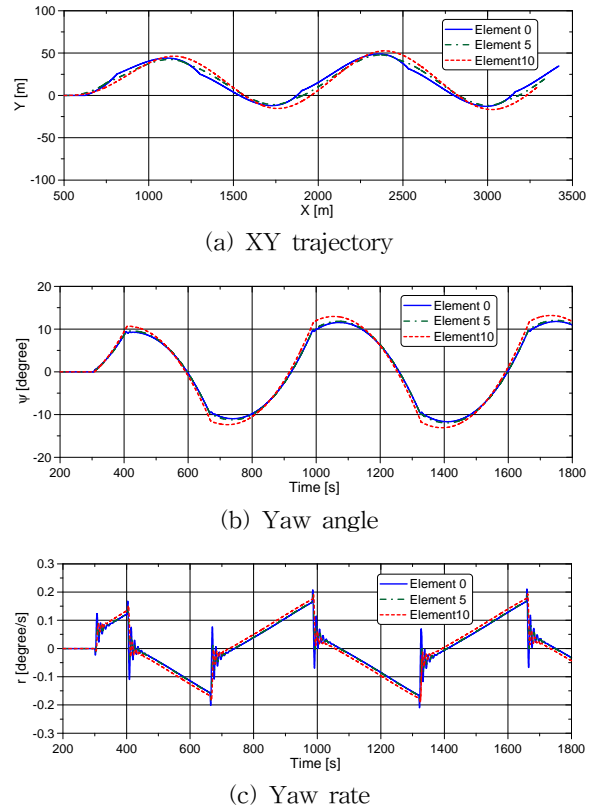
(a) XY trajectory

(b) Yaw angle

(c) Yaw rate

Fig. 10 Simulation results of the elements of the towline in case of 10-10 zig-zag test

test. The test starts after straightly running for 300 seconds which is the same as the case of the zig-zag test.

As shown in XY trajectories in Figs. 11~12, the element near the tugboat has large turning diameter. The surge velocities are oscillated within 0.1 knots. Also, low frequency motion of the elements far from the tugboat lasts for long time until the towing system becomes steady.

3.6 Course changing at beam sea

Figs. 13~14 show the simulation results of the towing system which changes the course in beam waves of which direction is from port to starboard. The scenarios after this section are all the same as the course changing in calm sea which changes the course of 45˚ port direction. Wave was assumed as the long-crested irregular wave composed of 10 regular wave components divided using the ITTC wave spectrum(Lewis, 1989).

XY trajectories and yaw angle are similar to the case of changing course in calm sea except that the highly oscillation motion occurs due to the first-order wave force.
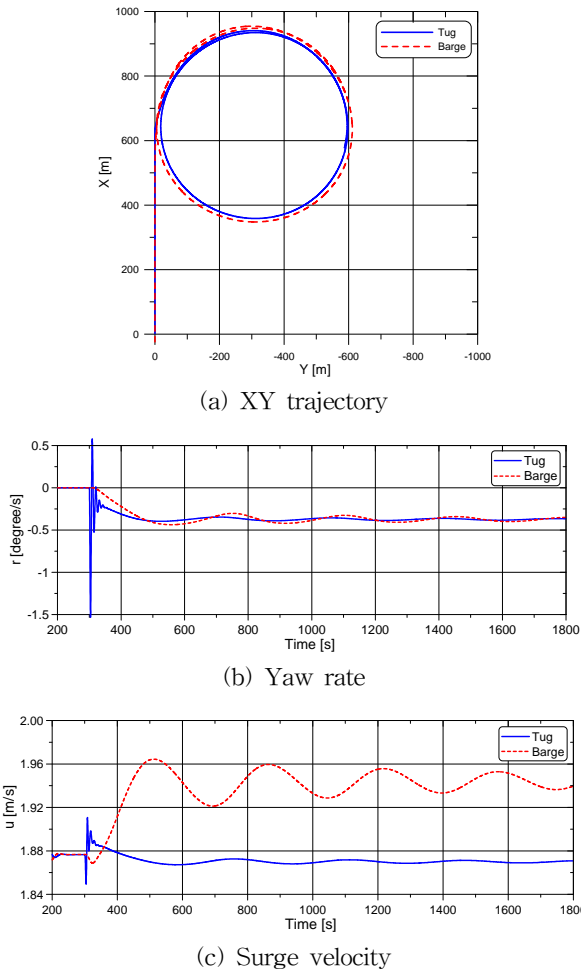
(a) XY trajectory

(b) Yaw rate

(c) Surge velocity

Fig. 11 Simulation results of the tugboat and the barge in case of 35 stbd turn

(a) XY trajectory

(b) Yaw rate
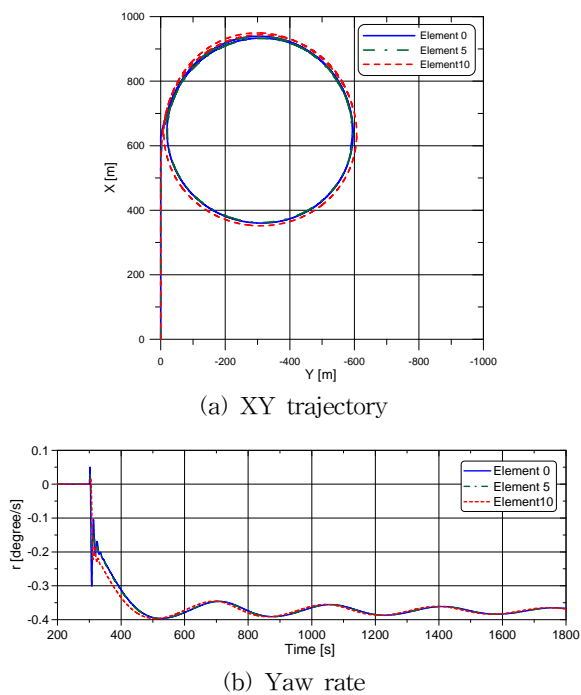
Fig. 12 Simulation results of the elements of the towline in case of 35 stbd turn
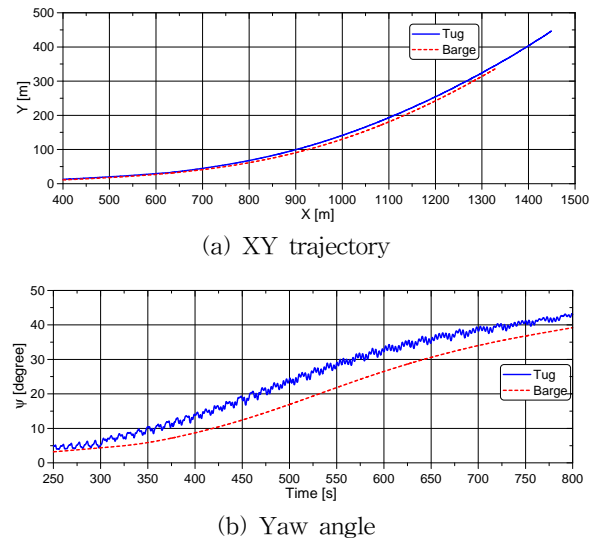

(a) XY trajectory

(b) Yaw angle

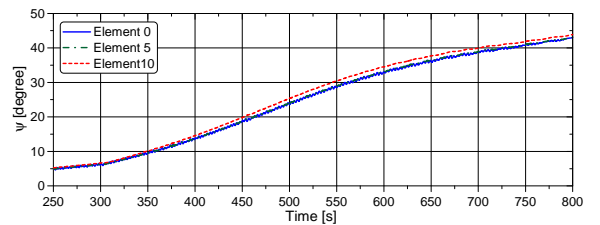Fig. 13 Simulation results of the tugboat and the barge when course changing at beam sea

Fig. 14 Yaw angles of the elements of the towline when course changing at beam sea

3.7 Course changing in side current

Figs. 15~16 show the simulation results of the towing system which changes the course in side current. Current flows from port to starboard.

Since the stable yaw angle is −90˚, the towing system changes the course negatively before the positive yawing moment has been developed. Fig. 15(c) shows that the rudder deflection calculated by the autopilot is larger than the case of course change in calm sea depicted in Fig. 6(b). When the tension acts on the barge, highly oscillating motion occurs and after a little time passed, the towing system changes the course positively.

7. Conclusion

The coupled dynamics of the towing system which consists of a tugboat, a towed barge, and a towline was established based on the finite element model of the towline and Newton's second law. In order to confirm the established dynamic model, various maneuvering scenarios in calm sea and at real sea where wave and current exist, were simulated.

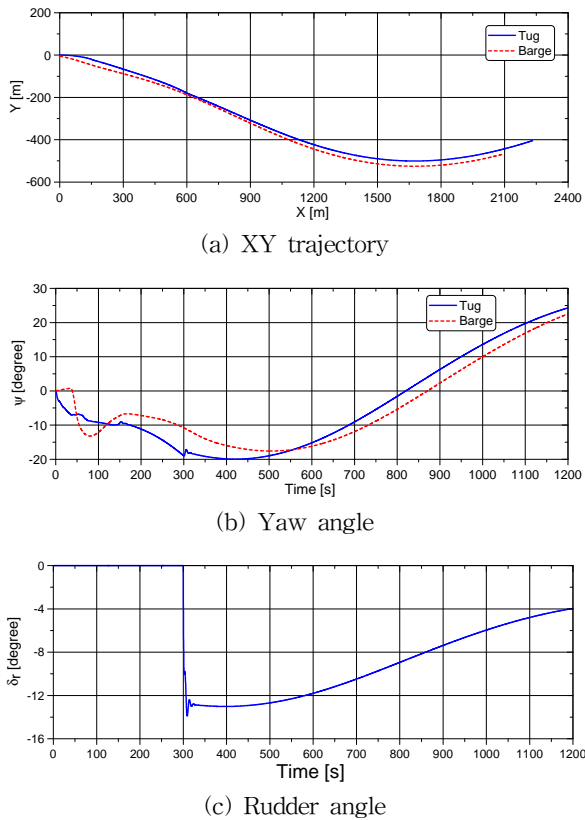(a) XY trajectory

(b) Yaw angle

(c) Rudder angle

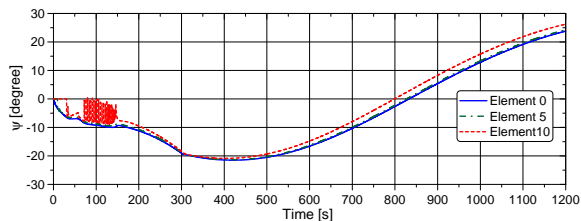Fig. 15 Simulation results of the tugboat and the barge when course changing in side current

Fig. 16 Yaw angles of the elements of the towline when course changing in side current

As the result, the dynamic model can estimate the maneuverability of the towing system properly in common sense. In the future, if those simulation results compare with the ones of the real sea trial or free running model test, and then the dynamic model is improved, it can be widely used for predicting the towing performance by towing simulation and for educating tug-handling mate by using simulators.

Acknowledgements

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