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# Development of Solution for Safe Ship Considering Seakeeping Per

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ABSTRACT: In recent years, safety of a ships has become one important issues needed to solved as soon as possible in ship navigation. Optimal weather routing is one of best solution for ensuring safe operation of a ship with a with short passage time or minimum energy to avoid a certain excessive motion. This paper introduced the development of solution for safety and optimal weather routing a ship considering seakeeping performance based on model test result. This study introduced how to apply A* algorithm based on result of the seakeeping model test for determining the optimal ship routes. Seakeeping model test of 8600 TEU container ship was carried out in Changwon National University's seakeeping basin and its RAOs at various frequencies were used to predict the RMS motion values in irregular waves. The specially modelled path-cost function and the safety constraints were proposed for finding the optimal path of the ship. The comparison of ship performances estimated by great circle's path and estimated optimal route during the voyage of the ship was investigated.

## 1 INTRODUCTION

When a ship sails at sea, it will be affected by environmental disturbances such as wind, waves, currents, and ice. These impacts on the speed, fuel consumption, safety and performance of the ship. Optimal ship route is a particular voyage with safest and shortest route for avoiding dangerous sea condition. This is essential for navigating the ship to avoid adverse weather conditions that could cause serious injury or structural damage to ships, machinery and equipment.

In the past, various researchers have investigated an optimal route of a ship based on optimization algorithm, e.g. the modified isochrones method, Dijkstra's algorithm, the dynamic programming (DP), and the three-dimensional modified isochrones (3DMI). Hagiwara and Spaans (1987) proposed the modified isochrones method which used to find the effectively operation ship in ocean cross voyages. The minimum time route and minimum fuel route of 40000 dwt product tanker were predicted using environmental data of the North Pacific Ocean. Otherwise, Calvert et al. (1991) carried out a study of the optimal route to minimize fuel cost for trans-Atlantic passage by using dynamic programming techniques. They used dynamic programming (DP) which was originally developed by Bellman to reduce fuel consumption. After that, Vlachos (2004) studied on the optimal route for small and medium size ships. He carried out the calculation the initial routes in the case of the present of obstacles, definition of the route cost and route optimization. In his theory, route cost is assigned in every possible route between two points. More recently, the minimal time route of a ship has been reported by Padhy et al. (2007), by using wave height information from Geodetic Satellite

(GEOSAT) altimeter record. In their study, the minimum distance between two nodal points was estimated by Dijkstra's algorithm. Next, Sen and Padhy (2010) developed the development of a ship weather routing algorithm based on a form of Dijkstra's algorithm. Wave model and ship's motion is used as the input data for determining optimal ship route in the Arabian sea and Bay of Bengal. As indicated in Panigra et al. (2011), the optimal trajectory was introduced by inverting speed reduction of the ship to weight function for coastal path in Indian. They have used the Dijkstra's algorithm for determining the shortest path considering the WAM wave model. And then, Lin et al. (2013) have proposed the three-dimensional modified isochrones (3DMI) method to calculate the optimization of ship weather routing to enhance speed performance. They have chosen the great circle route as the reference voyage when constructing the floating grid system. Their numerical simulation, covering the speed performance under different sea conditions, fuel consumption and total passage time, were found in comparison with the great circle route. By extending Panigra's work, Sen at al. (2015) have developed an algorithm for optimal ship route considering the weather conditions and realistic practical constraints during the ship's voyage. In the author's former works, Nguyen et al. (2016) the optimization of the ship route by only considering wind, wave conditions and safety values was modeled as a function to avoid slamming and deck wetness.

Overall, the majority of these studies are applied only to single purpose routing problems, and the ship's safety is the only constraint value to avoid adverse weather conditions. This paper focused on the development an optimization algorithm that combines the available technologies in the area of weather forecast with the seakeeping performance of a ship, in conjunction with comprehensive ship operation cost. The present paper introduces the development of the algorithm to find an optimal weather route considering the seakeeping performance obtained from the model test result. The model test of the 8600 TEU container ship is carried out in Changwon National University (CWNU)'s seakeeping basin. The results of the optimal weather route of a ship can inform a captain about potential risk during navigation. In addition, the effects of temperature, wind and wave that change the total ship's resistance are considered.

## 2 MODEL TEST

### 2.1 *Test facility*

Figure 1 shows CWNU's square towing tank, in which the model test was conducted. A wave maker is installed at the end of the towing tank and wave absorber is at the opposite site. The wave maker can make waves with a height up to 20 cm, and a wavelength up to 3 m. Table 1 lists the principal dimensions of the CWNU square wave basin.


Figure 1. The CWNU square wave basin

Figure 2 shows motion measurement device and wave probe. Heave, roll, and pitch are measured using each potentiometer.

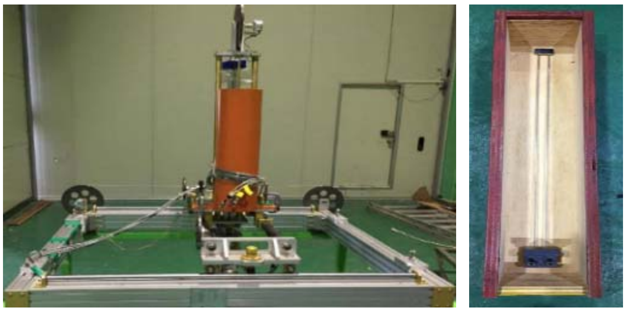


Figure 2. Motion measurement device and wave probe

Since the experiment is performed at various wave directions and wave frequencies, it is necessary to evaluate the quality of the waves. Right photo in Figure 2 shows the wave probe that is used in this experiment.

### 2.2 *Test condition*

In the present study, the 8600 TEU container ship is selected in this experiment. Table 1 shows the principal dimensions of the model ship of 8600 TEU container ship. Most tests in regular waves are concerned with the experimental determination of the motion response amplitude operator (RAO). The experiment is carried out in regular waves in seven wave directions. The test conditions are 105 waves for 15 wave frequency conditions. Table 2 shows the set values for each test condition in regular waves.

Table 1. Principal dimensions of model ship

| Particulars | Unit | Real | Model |
|---|---|---|---|
| Scale ratio | - | 1 | 285.630 |
| $L_{pp}$ | m | 322.6 | 1.129 |
| $B$ | m | 45.6 | 0.160 |
| $D$ | m | 24.6 | 0.086 |
| $T$(design) | m | 13 | 0.046 |
| $C_B$ | - | 0.5908 | 0.5908 |
| $\nabla$ | m3 | 112983 | 0.0048 |
| $\Delta$ | kg | 115909259.7 | 4.974 |
| LCB | m | -6.625 | -0.023 |
| GM | m | 1.5 | 0.0053 |

Table 2. Test conditions in regular waves

| λ / L | λ [m] | Wave frequency [rad/s] | Wave period [s] | Wave height [cm] |
|---|---|---|---|---|
| 0.5 | 0.56 | 10.45 | 0.60 | 1.4 |
| 0.6 | 0.68 | 9.54 | 0.66 | 1.4 |
| 0.7 | 0.79 | 8.83 | 0.71 | 1.4 |
| 0.8 | 0.90 | 8.26 | 0.76 | 1.4 |
| 0.9 | 1.02 | 7.79 | 0.81 | 1.4 |
| 1.0 | 1.13 | 7.39 | 0.85 | 1.4 |
| 1.2 | 1.35 | 6.74 | 0.93 | 1.4 |
| 1.3 | 1.47 | 6.48 | 0.97 | 1.4 |
| 1.4 | 1.58 | 6.24 | 1.01 | 1.4 |
| 1.5 | 1.69 | 6.03 | 1.04 | 1.4 |
| 1.6 | 1.81 | 5.84 | 1.08 | 1.4 |
| 1.7 | 1.92 | 5.67 | 1.11 | 1.4 |
| 1.8 | 2.03 | 5.51 | 1.14 | 1.4 |
| 1.9 | 2.15 | 5.36 | 1.17 | 1.4 |
| 2.0 | 2.26 | 5.22 | 1.20 | 1.4 |

## 2.3 *Wave maker calibration*

Since seakeeping analysis is done for the assessment of the ship motion in waves, the was characteristics should be checked in advance. The wave evaluation values are obtained through the amplifier and wave probe device in the model test. Figure 3 shows the process of wave probe calibration, and the typical relationship between wave height and output signal voltage of the amplifier.

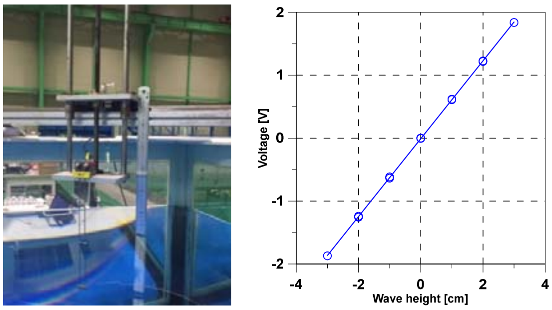



Figure 3. Wave probe calibration

Table 3. Evaluation input stroke for each wave frequency

| Input Stroke [cm] | Wave period [s] | Measured Wave height [cm] | Target value [cm] | Error [%] |
|---|---|---|---|---|
| 1.79 | 0.60 | 1.43 | 1.40 | 2.46 |
| 1.62 | 0.66 | 1.42 | 1.40 | 1.70 |
| 1.55 | 0.71 | 1.35 | 1.40 | 3.56 |
| 1.51 | 0.76 | 1.38 | 1.40 | 1.76 |
| 1.51 | 0.81 | 1.45 | 1.40 | 3.33 |
| 1.50 | 0.85 | 1.37 | 1.40 | 2.11 |
| 1.48 | 0.93 | 1.38 | 1.40 | 1.29 |
| 1.49 | 0.97 | 1.37 | 1.40 | 1.80 |
| 1.51 | 1.01 | 1.38 | 1.40 | 1.41 |
| 1.52 | 1.04 | 1.39 | 1.40 | 0.49 |
| 1.54 | 1.08 | 1.40 | 1.40 | 0.34 |
| 1.58 | 1.11 | 1.42 | 1.40 | 1.26 |
| 1.59 | 1.14 | 1.43 | 1.40 | 1.97 |
| 1.58 | 1.17 | 1.38 | 1.40 | 1.31 |
| 1.64 | 1.20 | 1.36 | 1.40 | 2.60 |

Wave maker calibration is also necessary for evaluation of the wave quality, and finding the input stroke of the wave maker system for each wave frequency. Wave maker calibration at different frequencies are performed at the center of the basin, in order to find the input stroke value in the wave maker system. Table 3 lists the results of the input stroke values of the wave maker system.

## 2.4 *Pre-test*

In the seakeeping test, it is very important to exactly match the mass distribution of the model ship to the design waterline. In order to approximate the vertical and longitudinal mass distributions, the mass moments of inertia about longitudinal and transverse axis and metacentric height (GM) must be the same. The ballasted model ship was performed as shown in Figure 4.

Figure 4. Ballasting of model ship

The GM value is obtained through the inclining test. According to the target GM, Eq. 1 determines the angle of inclination at the time of application of the inclined moment by a small weight. Figure 5 shows moving the weight in order to change the GM during the test. Tables 4~5 show the results of the inclining test.

$$\phi = tan^{-1}\left(\frac{wl_y}{W \cdot GM}\right) \tag{1}$$

Table 4. Target value of metacentric height

| Item | Model |
|---|---|
| Mass [kg] | 4.974 |
| GM [m] | 0.0053 |
| Moved weight [kg] | 0.1 |
| Lever $l_y$ [m] | 0.03 |
| Heel angle $\phi$ (deg.) | 6.49 |

Table 5. Measured heel angle

| Item | Measured angle [deg.] | Real angle [deg.] | Error [%] |
|---|---|---|---|
| Start point | -0.3 | - | - |
| Move weight to Port | -6.86 | -6.56 | 1.04 |
| Move weight to Stbd | 6.04 | 6.34 | 2.35 |

Figure 5. Inclining test

According to ITTC (International Towing Tank Conference) recommendation, the radius of gyration in pitch motion is 0.25 of the ship length. In this study, inertia test was performed by inertia swing. Figure 6 shows the inertia swing, and the process of inertia swing calibration. Inertia swing calibration was performed with 4 kgf weight and different distance from the center of inertia of the inertia swing. Then, target moment of inertia and measured moment of inertia value of the model ship are 0.3963 kgm$^2$ and 0.3925 kgm$^2$, respectively.

Figure 6. Inertia swing calibration and inertia test

## 2.5 *Experimental setup*

The model is attached to the motion measuring device in the middle of the measuring frame of the towing carriage. The center of gravity of the model should match the thrust line as much as possible. The wave probe is installed at 1.703 m in front of the center of the model on the right edge of the yaw table, in order to avoid disturbance caused by the model. Figures 7~8 show the detailed set up of this experiment.

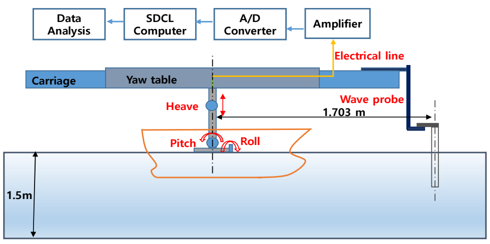



Figure 7. Model test setup

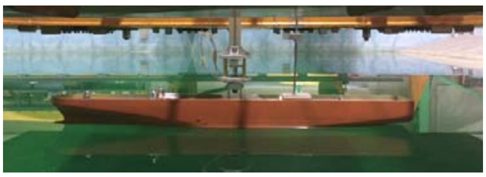


Figure 8. Real model test setup

## 2.6 *Response Amplitude Operator (RAO)*

The results of heave, roll, and pitch RAOs of the model for 7 wave directions in 15 wave frequencies were obtained as shown in Figures 9~11. The relative vertical motion and relative velocity at bow were estimated from result of model test based on ARJM's method. The relative displacement and relative velocity at the bow can be determined by Eqs. 2~3, respectively. In Eq. 2, $\zeta$ is the local wave depression, $\bar{\eta}_3$ and $\bar{\eta}_5$ are the heave and pitch response, respectively. Figures 12~13 show the relative motion and relative velocity at bow depending on wave direction for finding probability of slamming and deck wetness.

$$\xi_R = \bar{\eta}_3 - x_{B1}\bar{\eta}_5 - \zeta \tag{2}$$

$$\dot{\xi}_R = \omega \xi_R \tag{3}$$

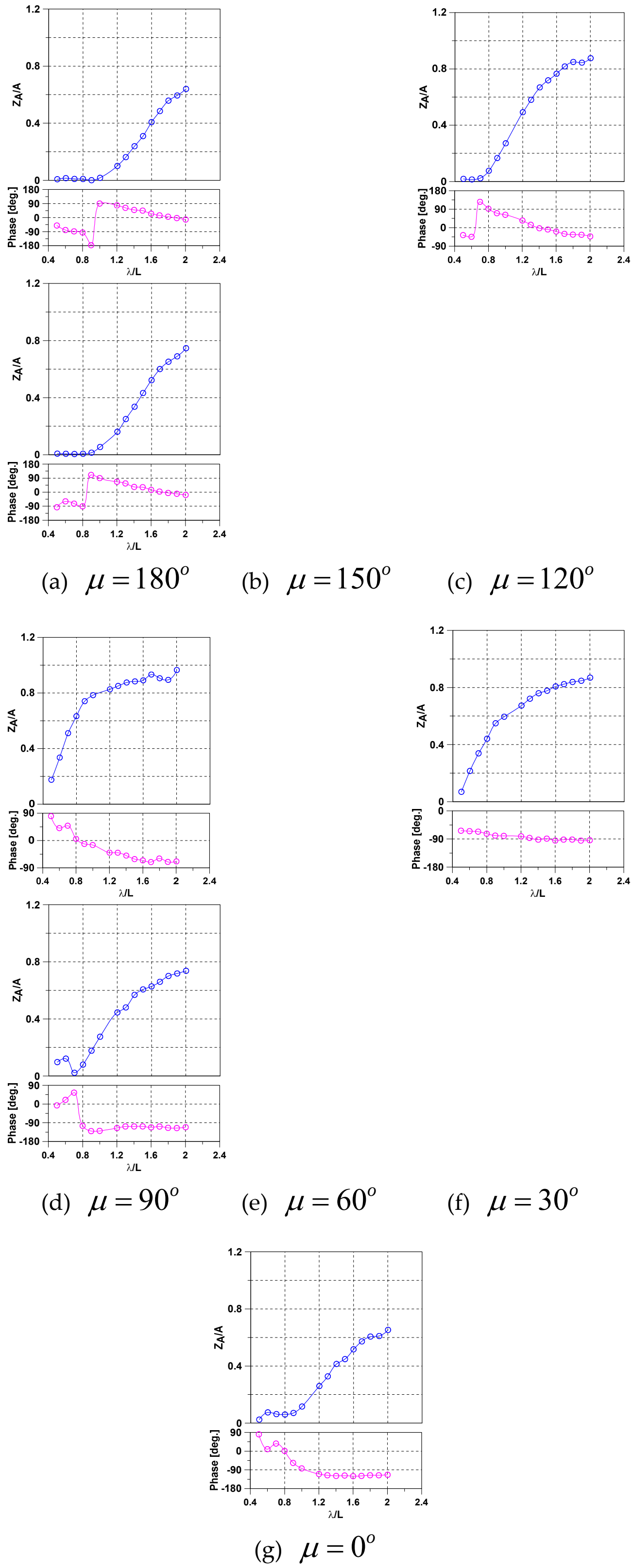
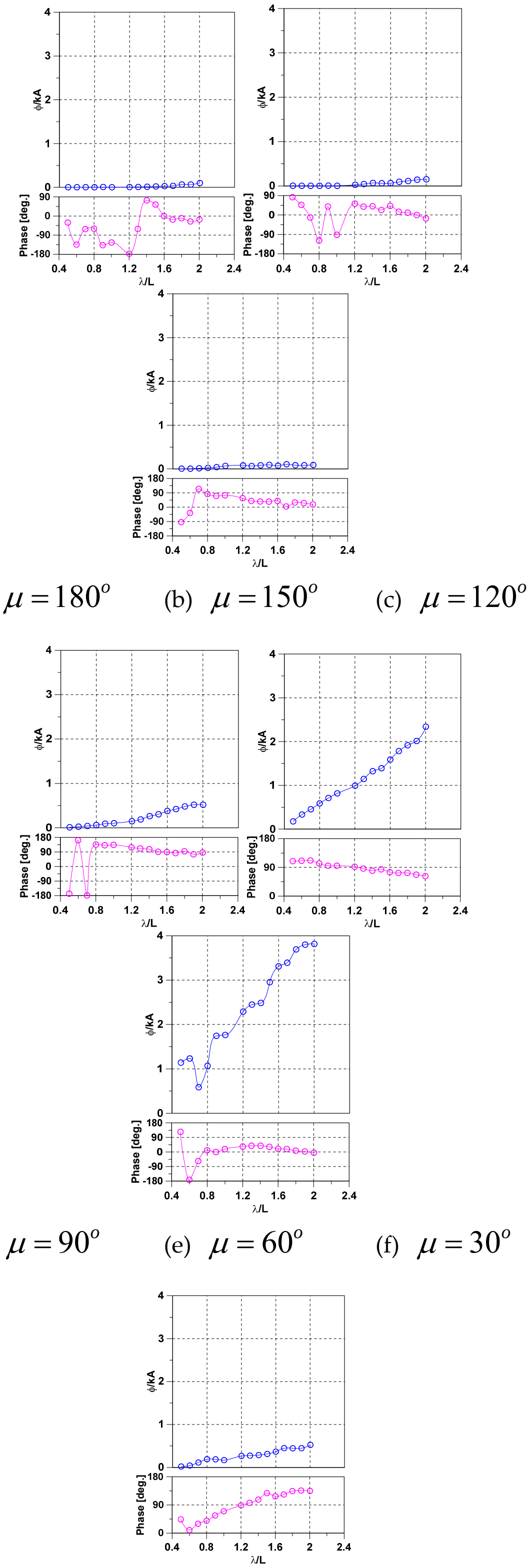



Figure 9. Heave RAO

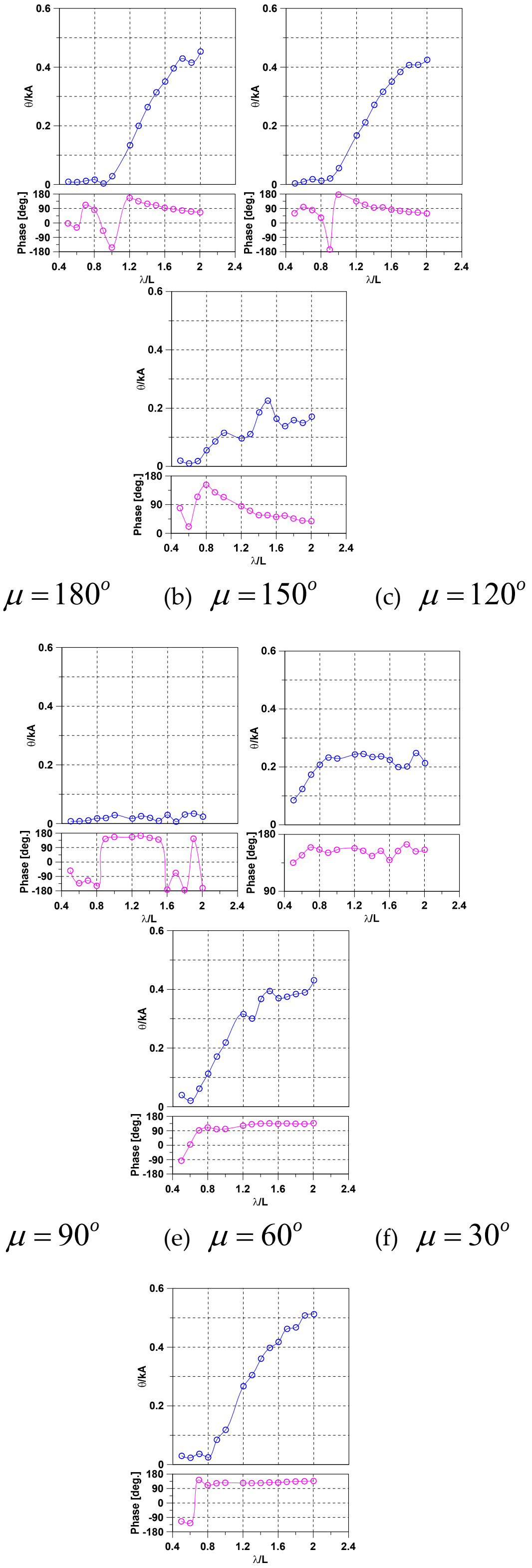



(a) $\mu = 180^o$ (b) $\mu = 150^o$ (c) $\mu = 120^o$

(d) $\mu = 90^o$ (e) $\mu = 60^o$ (f) $\mu = 30^o$

(g) $\mu = 0^o$

Figure 10. Roll RAO




(a) $\mu = 180^o$ (b) $\mu = 150^o$ (c) $\mu = 120^o$

(d) $\mu = 90^o$ (e) $\mu = 60^o$ (f) $\mu = 30^o$

(g) $\mu = 0^o$

Figure 11. Pitch RAO

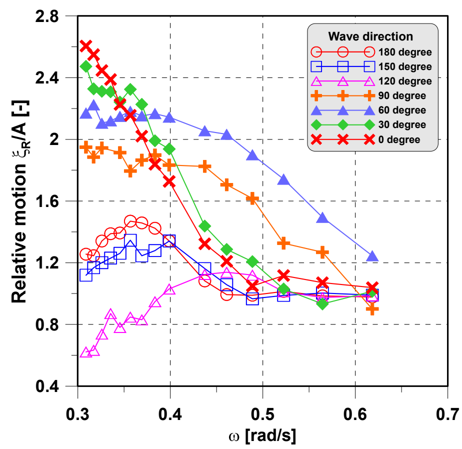



Figure 12. Relative displacement at bow

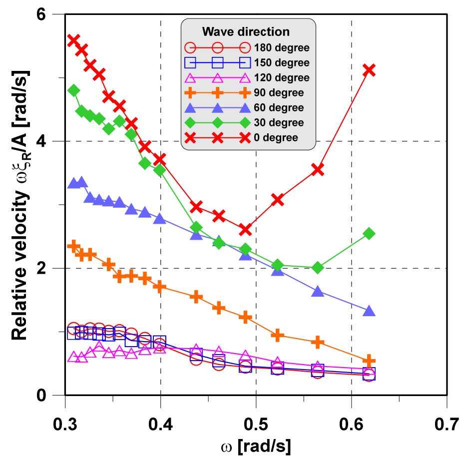



Figure 13. Relative velocity at bow

## 3 WEATHER ROUTING ALGORITHM

### 3.1 *Weather routing class*

Figure 14 illustrates the implementation of Optimal Weather Routing Setting Unit class (OWRSU) in a flowchart. First, ship's data and weather forecast data are initialized by ReadData function which is stored in the Weather class and OwnShip class. These data relate to ship information and weather forecast data. Then, Initialize function is called, and it is used to initialize OwnShip, Weather, and Route classes. Next, FindRoute function is called to estimate cost of a path based on speed reduction to environmental condition and safety constraint value. The last two stages are PrintData and Finalize.

Figure 15 shows the process used in this system to provide a safety solution for ship operation at sea. There are two stages (SHORE and SHIP) in the process of finding safety operation of a ship under a given sea state. Input and output of OWRSU class are shown in Figure 16.

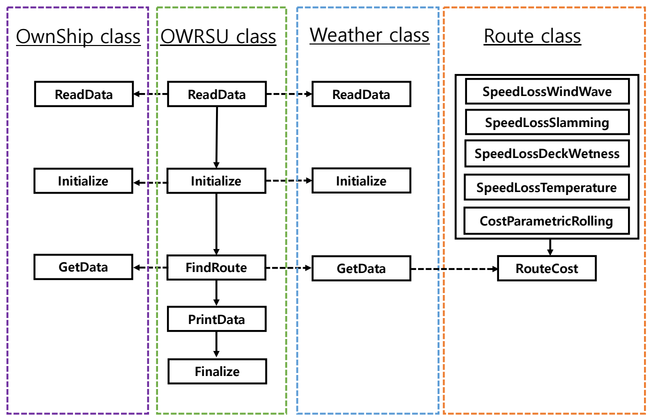



Figure 14. Flow chart for route finding


Figure 15. Flow chart for route finding

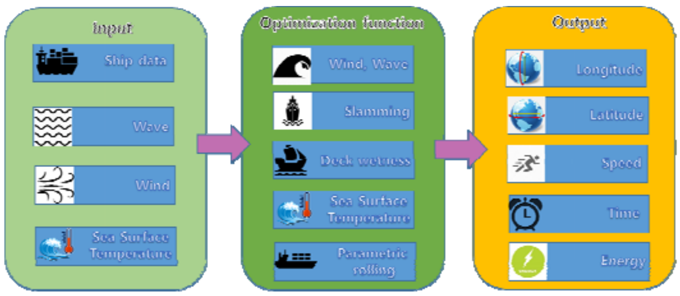



Figure 16. Flow chart for route finding

### 3.2 *Models of cost functions*

In order to apply A* algorithm for optimal ship route, the path cost was proposed as an additive evaluation function $f(n) = g(n) + h(n)$, where $g(n)$ is the path cost and $h(n)$ is the heuristic cost which includes geographic information and weather constraint. Possible areas encompassing of a optimal ship route and weather condition are discretized by candidate nodes. In this study, the candidate nodes that can be traversed are built around the great circle's path. *f(n)* value of a node combines the environmental data with the ship's data and can be estimated by Eq. 4.

$$f_{i+1} = g_{i+1} + h_{i+1} \tag{4}$$

By optimizing the evaluation function $f_{i+1}$ for the complete path, A* algorithm achieves the minimum time route or minimum fuel consumption route of a ship. In addition, parametric rolling is set as the safety constraint value. In order to avoid land and islands, this algorithm treats these hazards by assigning a very large default value of the evaluation function to these grids. To implement the optimal route search algorithm, two models are proposed to minimize the arrival time and minimum energy requirement. In the minimum arrival time model, we assume that the engine of the selected vessel can provide constant power output and ship speed can changed due to weather condition. The ETA (Estimated Time to Arrival) is used to set a shorter route from departure port to destination port node by applying the weather forecast data. In this model, the path cost function can be estimated as as the sailing time. In the minimum energy model, we assume that the ship's energy output can be changed to keep the speed constant. It can be seen that when a vessel operates under the influence of environment such as a wind and wave, more energy should be supplied to the vessel than in case the vessel operates in clam water. Therefore, the path cost function can be estimated as the minimum energy to maintain a constant ship speed.

### 3.3 *Various speed reduction parameters*

The method for avoiding parametric rolling is recommended by IMO circ. 1228, the course and the speed of the ship should be chosen avoiding these condition, encountering period $T_E$ close to the ship roll period $T_R$ $(T_E \approx T_R)$ or one half of the ship roll period $(T_E \approx 0.5T_R)$.

In ship navigation, the speed reduction of a ship can be divided into two types, voluntary and involuntary speed reduction. Involuntary speed reduction can be estimated from empirical formulae suggested by many researchers in the past. We used Kwon's method (1981, 2005) to predict involuntary speed reduction under different weather condition. In addition, the effect of temperature is also considered in terms of involuntary speed reduction.

On the other hand, for avoiding a certain excessive motion, voluntary speed reduction was reduced the ship's captain in dangerous sea condition. However, this method depends not only on the caption's decision but also on his long-standing experience. In this study, the involuntary speed reduction of the vessel was modeled as to avoid slamming and deck wetness phenomena for avoiding excessive motion. The probability of slamming and deck wetness is usually estimated by relative motion and relative velocity at bow. In order to apply the results of model test at various wave heading angle for the optimal ship, the relative vertical motion and relative vertical velocity at bow should be calculated from RAOs motion of the model test in waves based on ARJM's method

## 4 SIMULATION AND RESULTS

### 4.1 *Simulation*

Weather data sets are updated every 12 hours and obtained from SAS. Environmental conditions that are used in the simulation of this study include swell direction, swell height, wind speed and temperature. The sample weather data are given at each node with grid size of 0.1 degree in longitude and 0.1 degree in latitude.

The weather data at any particular time and position of the ship are obtained by linear interpolation of the surrounding environmental data. In order to confirm the ability of the A * algorithm in the OWRSU class, and investigate how the weather conditions influence the optimal weather route, the 8600 TEU container ship was selected for this simulation.

Table 6 shows the route of container ship which was simulated in this study. Two simulations were performed to evaluate the effectiveness of the two models that were suggested in this study for the optimal ship route. In case 1, model of minimum the arrival time of the ship is applied and optimization index is the shortest time under environmental conditions. In case 2, model of minimum energy is used, and the optimization index is the energy of the vessel provided so that the vessel can keep the constant speed under the influence of the environmental conditions.

Table 6. Simulation condition

| Port | Location |
|---|---|
| Departure Tokyo, Japan | 139° East, 35° North. |
| Destination: San Francisco, US | 122° West, 38° North. |

### 4.2 *Results*

Figure 17 shows the ship's speed comparisons estimated by both the Great Circles (GC) and the optimal weather route found by the A * algorithm during a ship's voyage. Speed reduction of a ship in the GC's route has significant difference with that estimated by the A* algorithm. Speed reduction is very small in cases of ship follows the path suggested by the A * algorithm, whereas speed reduction is significant in the case when the ship follows the path suggested by the GC. The reason is that the GC cannot consider the weather condition for finding the optimal ship route, leading to the ship being able to go into dangerous areas to reduce its apparent speed. The ship's arrival time can save 9.10% using the A* algorithm listed in Table 7. A* suggests shorter routes, faster than one is suggested by GC.

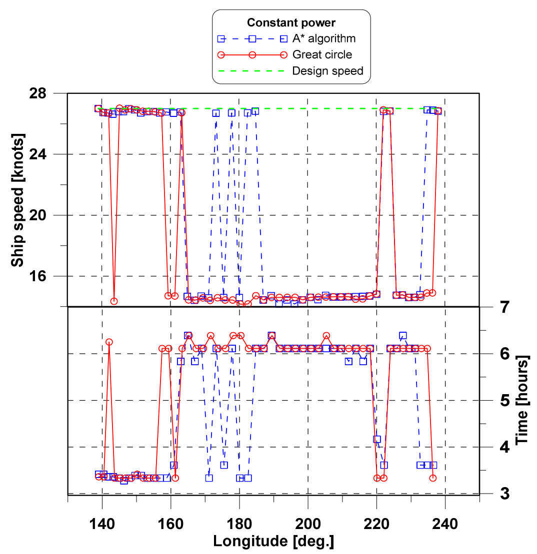


Figure 17. Comparison of speed and time in case of constant power condition

Table 7. Comparison of ETA

| Algorithm | ETA [hours] | Time saving ratio[%] |
|---|---|---|
| GC | 268.61 | - |
| A* | 244.17 | 9.10 |

In case of constant speed conditions, energy consumption will become less if ship goes by the route suggested by the A * algorithm as shown in Figure 18. In particular, when ship follows the path suggested by the A * algorithm, the energy consumption can save about 5.47% as listed in Table 8. However, the arrival time of a ship in case of the ship passes the route suggested by the GC will be faster than the route suggested by A * because the great circle distance is the shortest route. Figure 19 shows the optimal ship route in this simulation.

Table 8. Comparison of estimated energy consumption

| Algorithm | ETA [hours] | Energy [KJ] | Energy saving ratio [%] |
|---|---|---|---|
| GC | 166.39 | 3.4037E+10 | - |
| A* | 168.06 | 3.2175E+10 | 5.47 |

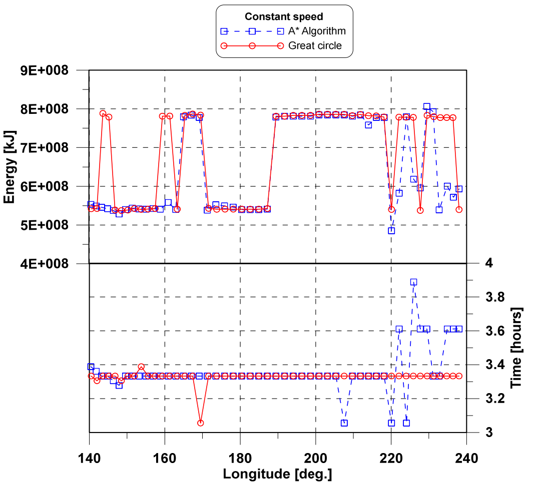



Figure 18. Comparison of energy and time in case of constant speed

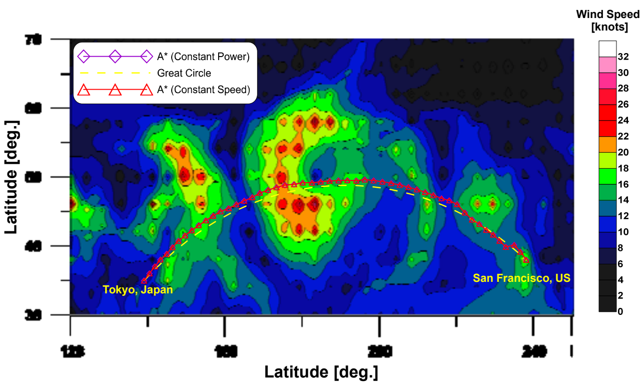



Figure 19. Optimal weather route

## 5 CONCLUSION

In this paper, the seakeeping model test of the 8600 TEU container ship was carried out in Changwon National University's square wave basin, and its RAOs at various frequencies were modeled for finding the optimal weather route minimizing the arrival time or minimum. A* algorithm for avoiding hazard situations has been proposed as an optimization method. The concluding remarks are as follows:

First, the measured ship motions in various waves and heading conditions by performing the model test in the square wave basin. The effect of wavelength and wave direction have a clear effect on the RAO motion of 8600 TEU container ship. The relative vertical motion and relative vertical velocity at bow were estimated from RAO's motion of the model test in waves. In particular, the experimental results of this study have been used to find the optimal route of a ship.

Second, A* algorithm was applied to 8600 TEU container ship. It is clear that the A* algorithm is effective in finding the optimal route based on weather forecast data and experimental result. This study proposes an optimal solution for optimal ship route to ensure vessel safety as well as save time and fuel for the vessel. Users can select ETA or consume ship power. The simulation results show that the path suggested by the algorithm A * is better than the GC with minimum arrival time and minimum energy. Users can choose to save time as well as save energy easily. From the simulation results, the path suggested by the A* algorithm is better and more efficient than the route suggested by the GC.

Finally, the influence of environmental data, such as the influence of temperature, wind and waves, changes the resistance of the entire ship, has been considered. The special feature of this study is that the speed estimation is based on not only the time and location of the vessel, but also the updating of the weather data and on the location of the current vessel. Development of this study can used to contribute to the development of the ship.

## ACKNOWLEDGEMENT

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