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Case study of detection and maneuvering performance of naval ships using engagement simulation of engineering level

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Abstract. Many different engagement situations require naval ships to achieve some level of effectiveness. The performance of the naval ships is very important for such effectiveness. There have been many studies that analyze the effectiveness and the performance. The former are largely related to engagement level simulations, while the latter are largely related to engineering level simulations. However, there have been few studies that consider both the engagement level and the engineering level at the same time. Therefore, this study presents three case studies using engagement simulation of the engineering level to check the performance of the related parameters. First, detection performance simulations are carried out by changing the specifications of the passive sonars of a submarine in different scenarios. Maneuvering performance simulations are carried out by changing the specification of the hydroplanes of a submarine in different scenarios. Lastly, in order to check whether or not our forces would succeed in attacking enemy forces, we perform an engagement simulation with various naval ship models that consist of several engineering level models, such as command systems, weapon systems, detection systems, and maneuver systems. As a result, the performance according to the specifications of the naval ships and weapons is evaluated.

Keywords: modeling and simulation; engagement level; engineering level; DEVS & DTSS model; naval ships

1. Introduction

Broadly defined, modeling is a method for organizing knowledge that is accumulated through observation or deduced from underlying principles, while simulation refers to a method for implementing a model over time (Etter 2013). In naval applications, Modeling and Simulation (M&S) is used for analyzing and developing the strategies and tactics of naval ships, and the performance of naval ships (Kim *et al.* 2014, Kim *et al.* 2017). M&S in naval applications could be categorized according its fidelity. There are four general classifications: theater, mission, engagement, and engineering levels (Etter 2013). The theater level is generally applied to evaluate force structures or strategies. The mission level is normally applied to evaluate force employment concepts. The engagement level is used to evaluate the effectiveness (accomplishment of mission

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objectives and achievement of desired results in engagement situation) of an individual system against another system in one-on-one, few-on-few, and many-on-many scenarios. Lastly, the engineering level provides measures of performance, concerning such issues as design, cost, manufacturing, and supportability. In other words, the engagement level models and simulations are for analyzing and developing the tactics of naval ships in engagement scenarios, while the engineering level models and simulations are for analyzing and developing the performance of naval ships. In particular, this study focuses on the engagement level and the engineering level.

Traditionally, during the engagement level simulation, many engineering level performances, such as maneuvering or the detection range of sonar, have been assumed, or simplified models have been used. Therefore, the accuracy would be lowered. In contrast, the engineering level simulations have used mathematical models for more accurate analysis results of the target submarine or the surface vessel than the results from engagement level simulation. However, the engineering level simulations have not been able to consider the performance during the engagement scenarios. Therefore, both engagement and engineering level simulations had limits between performance and effectiveness.

To overcome these limits, this study proposed the engagement simulation of engineering level for the detection and maneuvering performances which are the most important feature of naval vessels. The most important merit of simultaneously considering engagement and engineering simulation is accuracy. The most engagement simulation uses simplified models. For example, in the most of the engagement simulation, it is assumed that the submarine detects the enemies which enter in the detection range. However, the detection in the real world is done by SONAR which detects the enemies by sounds propagated through the sea. Moreover, this study takes into account both flexibility and reusability of the models. Therefore, simulation models of engineering level can participate in the engagement simulation easily.

2. Related works

Many studies have been carried out of engagement and engineering levels in naval applications. However, few studies have simultaneously taken into account the two levels. Also, few studies have considered the flexibility and reusability of models. The examples of studies about such M&S of the engagement level and the engineering level are as follows.

Hwang *et al.* (2011) focused on the maneuvering and detection performance of Unmanned Underwater Vehicles (UUVs) in engagement scenarios. The engineering level models and simulations for the maneuvering performance were considered by applying maneuvering equations, and the control of hydroplanes. However, in the case of detection performance, it is hard to say that the engineering level models and simulations for the detection performance were considered. The detection performance was just considered by the default values of detection probability.

Cho and Kim (2012) analyzed the detection performance of UUVs. The engineering level models and simulations for the detection performance were considered by applying a passive sonar equation and beam patterns. However, the engineering level models and simulations for the maneuvering performance of naval ships were not considered. The paths of naval ships with constant speed were just considered.

Son (2012) focused on the maneuvering performance of submarines. The engineering level models and simulations for the maneuvering performance were considered, applying maneuvering equations. Also, Discrete EVent System specification (DEVS) and Discrete Time System

Specification (DTSS) were applied for the flexibility and reusability of models. However, the engineering level models and simulations for the detection performance of the submarines were not considered.

Kaymal (2013) analyzed which ship design factors were key drivers in the effectiveness of surface ships in Anti-SUrface Warfare (ASUW), based on realistic engagement scenarios. Although the key factors were compared for various ASUW scenarios, the engineering level models and simulations were not considered.

Lind (2014) focused on the maneuvering performance of submarines. The engineering level models and simulations for the maneuvering performance were considered, applying maneuvering equations and the control of hydroplanes. However, neither the detection performance of submarines nor engagement scenarios were considered.

Khaledi *et al.* (2014) analyzed the detection performance of UUVs. The engineering level models and simulations for the detection performance were considered by applying an active sonar equation. However, neither the maneuvering performance of the UUVs nor engagement scenarios were considered.

These studies show that there are few studies that take into account both the engineering level and the engagement level, and that there are few studies that consider the flexibility and reusability of models. This study takes into account both levels, and the flexibility and reusability of models, as shown in Table 1. This study can consider the maneuvering and detection performance with high fidelity, applying maneuvering equations, the control of hydroplanes, a passive sonar equation, and beam patterns.

3. Engagement simulation of engineering level

Several modules are developed in this study for the engagement simulation of engineering level. Jeong *et al.* (2017) presents the details of these theoretical backgrounds. In this study, these theoretical backgrounds are introduced briefly as follows.

3.1 Simulation core for the engagement simulation of engineering level

For the engagement simulation, the command and the relation between the models are important. However, in the engineering level, the proper mathematical models are important.

Table 1 Summary of the studies and this study

Studies	Maneuvering performance	Detection performance	Engagement scenarios
Hwang *et al*. (2011)	O	X	O
Cho and Kim (2012)	X	O	O
Son *et al*. (2012)	O	X	O
Kaymal (2013)	X	X	O
Lind (2014)	O	X	X
Khaledi *et al*. (2014)	X	O	X
This study	O	O	O

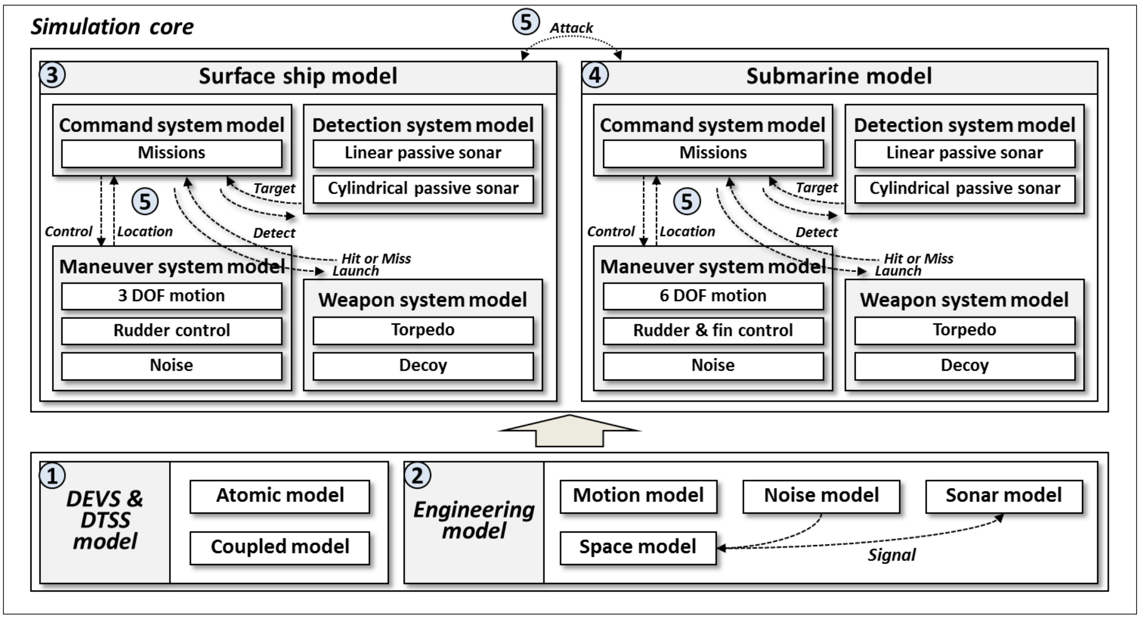

Fig. 1 Configuration of the simulation core and GUI

The command and the relations between the models are input values at each time step during the simulation. Technical difficulties are the method how to build simulation models which contain in both engagement and engineering level properties simultaneously. Therefore, we developed simulation core based on DEVS & DTSS model to overcome this limit.

The simulation core is based on maneuvering equations, the control of hydroplanes, a passive sonar equation, beam patterns, and DEVS and DTSS (Cha *et al.* 2010a, b). Fig. 1 shows the configuration of the simulation core.

The DEVS & DTSS model (Fig. 1①) represents the state changes of naval ships over discrete events and discrete times. The Engineering model (Fig. 1②) represents the performance of naval ships and the environment that could affect the performance of the naval ships. First, the motion model represents the maneuvering performance of the naval ships, by applying maneuvering equations and the control of hydroplanes. The noise model represents the noise level of the naval ships. Then, the Sonar model represents the detection performance of the naval ships, by applying a passive sonar equation and beam patterns. Lastly, the Space model represents the environment that could affect the performance of the naval ships. For example, the Space model calculates the distance and time for the radiated noise from the naval ships to propagate to the other naval ships.

Based on such DEVS & DTSS model and Engineering model, surface ships and submarines can be represented by the naval ship models: Surface ship model and submarine model (Figs. 1-③ and ④). The naval ship models correspond to the coupled model in the DEVS & DTSS model, and are composed of the command system model, maneuver system model, detection system model, and weapon system model. The command system model, maneuver system model, detection system model, and weapon system model correspond to the atomic model in the DEVS & DTSS model.

The command system model represents commanders, and issues orders following defined scenarios. Each order works as a discrete event to the Maneuver system model and the detection system model. Then, the maneuver system model and the detection system model calculate maneuvering equations, the control of hydroplanes, a passive sonar equation, and beam patterns every discrete time through the motion model and sonar model, respectively. The weapon system model represents the decoys and torpedoes of naval ships. The decoys are devices intended to deceive enemy forces into attacking them, and by so doing, protect real naval ships. The torpedoes are self-propelled weapons with explosive warheads.

3.2 Maneuvering equations

In general, surface ships are assumed to have 3 Degrees-Of-Freedom (DOF) motion of surge, sway, and yaw. Submarines are assumed to have 6 DOF motion of surge, sway, heave, roll, pitch, and yaw. The maneuvering equations for these motions can be obtained by changing Newton-Euler equations from an inertial frame to a body-fixed frame. The maneuvering equations are given by Eqs. (1)-(6) (Fossen 2002, Gertler and Hagen 1967, Babaoglu 1998, Ha *et al*. 2012).

$$m[\dot{u} - vr + wq - x_G(q^2 + r^2) + y_G(pq - \dot{r}) + z_G(pr + \dot{q})] = X \tag{1}$$

$$m[\dot{v} - wp + ur - y_G(r^2 + p^2) + z_G(qr - \dot{p}) + x_G(qp + \dot{r})] = Y \tag{2}$$

$$m[\dot{w} - uq + vp - z_G(p^2 + q^2) + x_G(rp - \dot{q}) + y_G(rq + \dot{p})] = Z \tag{3}$$

$$\begin{aligned} I_x\dot{p} + (I_z - I_y)qr - (\dot{r} + pq)I_{xz} + (r^2 - q^2)I_{yz} + (pr - \dot{q})I_{xy} \\ + m[y_G(\dot{w} - uq + vp) - z_G(\dot{v} - wp + ur)] = K \end{aligned} \tag{4}$$

$$\begin{aligned} I_y\dot{q} + (I_x - I_z)rp - (\dot{p} + qr)I_{xy} + (p^2 - r^2)I_{zx} + (qp - \dot{r})I_{yz} \\ + m[z_G(\dot{u} - vr + wq) - x_G(\dot{w} - uq + vp)] = M \end{aligned} \tag{5}$$

$$\begin{aligned} I_z\dot{r} + (I_y - I_x)pq - (\dot{q} + rp)I_{yz} + (q^2 - p^2)I_{xy} + (rq - \dot{p})I_{zx} \\ + m[x_G(\dot{v} - wp + ur) - y_G(\dot{u} - vr + wq)] = N \end{aligned} \tag{6}$$

where, m is the mass, (I_x, I_y, I_z, I_{xy}, I_{yz}, I_{zx}) is the mass moment of inertia, and (x_G, y_G, z_G) is the center of gravity. (u, v, w) is the body-fixed linear velocity, (p, q, r) is the body-fixed angular velocity, (X, Y, Z) is the force, and (K, M, N) is the moment.

The forces in the above maneuvering equations consist of hydrostatic forces and hydrodynamic forces. The hydrostatic forces depend on gravity and buoyancy, while the hydrodynamic forces depend on the velocity, acceleration, angle of traverse, and so on. Such hydrodynamic forces can be represented by hydrodynamic coefficients. These hydrodynamic coefficients vary in the specifications for the hull, rudder, fin, and so on. Thus applying the maneuvering equations makes it possible to analyze the maneuvering performance of naval ships according to their specifications.

3.3 Passive sonar equation

Targets generate noise, and the noise radiates in all directions. The radiated noise propagates far away, undergoing the loss of acoustic energy, and the addition to background noise. Once the radiated noise arrives at sonars, the sonars analyze the radiated noise. Finally, sonar operators determine whether or not the noise represents targets. Such target detection can be expressed as a passive sonar equation (Michael 2010, Urick 1983)

$$SE = SL - PL - NL - BW + AG - DT \tag{7}$$

The first term, the Source Level (*SL*), is the magnitude of the radiated noise, whose major sources are engines and propellers. The second term, Propagation Loss (*PL*), refers to the loss of acoustic energy that the radiated noise undergoes when propagating. This loss of acoustic energy results mainly from the spreading of acoustic energy and chemical relaxation. The third term, Noise Level (*NL*), is the magnitude of the background noise. The fourth and fifth terms, BandWidth (*BW*) and Array Gain (*AG*), are related to signal processing. The sixth term, Detection Threshold (*DT*) is the standard for determining whether there are targets or not. Finally, Signal Excess (*SE*) expresses the amount of excess of *DT*. If the sign of the value of *SE* is positive, the sonar operators decide that there is a target.

Such terms in the passive sonar equation vary in the specifications for the sonars of naval ships and the underwater environment. Thus, applying the passive sonar equation and signal propagation makes it possible to analyze the detection performance of naval ships according to the specifications of their sonars and the underwater environment.

3.4 Beam patterns

The principle of beam patterns was well described in (Michael 2010, Li 2011). The passive sonars of naval ships carry out spatial filtering, which involves sampling noise in space to remove any noise of undesired direction. In other words, spatial filtering clarifies the noise of desired directions. This spatial filtering helps sonar operators not only to detect the radiated noise from targets, but also to know the directions of the radiated noise.

Such spatial filtering is largely determined by the beam patterns of the hydrophone arrays at the passive sonars. A hydrophone is a device that is designed to receive underwater noise. Hydrophone arrays are collections of hydrophones, and there are various types of hydrophone arrays, according to their configuration. The beam patterns of the hydrophone arrays represent how the measured magnitude of noise varies depending on the direction of the noise. The beam patterns are related to the term, Array Gain (*AG*), in the passive sonar equation (Eq. (7)).

The noise would propagate to the hydrophone arrays in the form of an acoustic wave, and then differences in the phases of the acoustic wave at each hydrophone would occur. These differences result in the beam patterns. Fig. 2 shows how the differences in the phases of an acoustic wave at each hydrophone occur in a linear hydrophone array. If the acoustic wave comes perpendicularly to the linear hydrophone array, the phases of the acoustic wave at each hydrophone are the same. Meanwhile, if the acoustic wave comes obliquely to the linear hydrophone array, the phases of the acoustic wave at each hydrophone are different, and then the acoustic wave energy would be lost.

In other words, the measured magnitude of the noise coming obliquely is smaller than that of the noise coming perpendicularly. In contrast, it is possible to lose the energy of acoustic wave coming perpendicularly, by the hydrophones intentionally making differences in the phases of acoustic wave at each hydrophone, as shown in Fig. 3 In this case, the measured magnitude of the noise coming obliquely is greater than that of the noise coming perpendicularly. In this way, the measured magnitude of the noise could vary depending on the direction of the noise, and this is represented by the beam patterns.

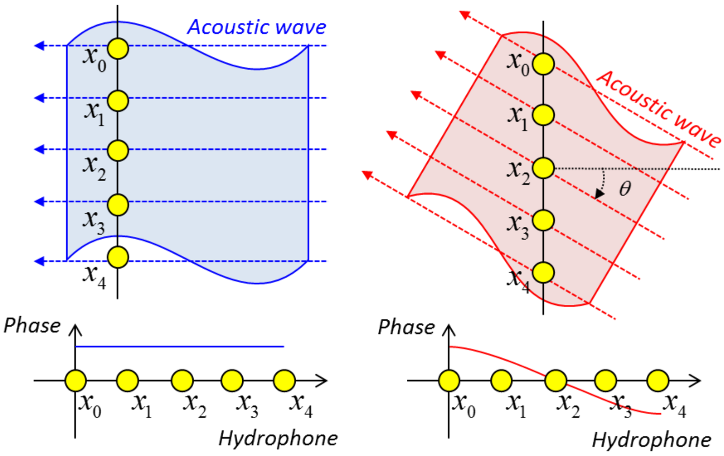

Fig. 2 Differences in the phases of the noise at each hydrophone

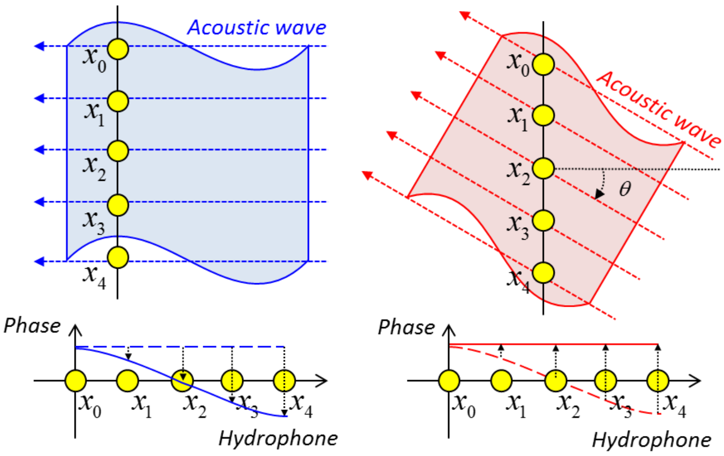

Fig. 3 Intentional differences in the phases of the noise at each hydrophone

4. Case studies

To verify the applicability of the simulation core, this simulation core was applied to detection performance simulations, maneuvering performance simulations, and engagement simulations. The results of these simulations ensure that the simulation core of this study considers both the engagement level and the engineering level, and features the flexibility and reusability of models. The following would show these simulations.

4.1 Case study for detection performance simulation

The detection performance simulations were carried out by changing the specifications of the passive sonars of a submarine in different scenarios.

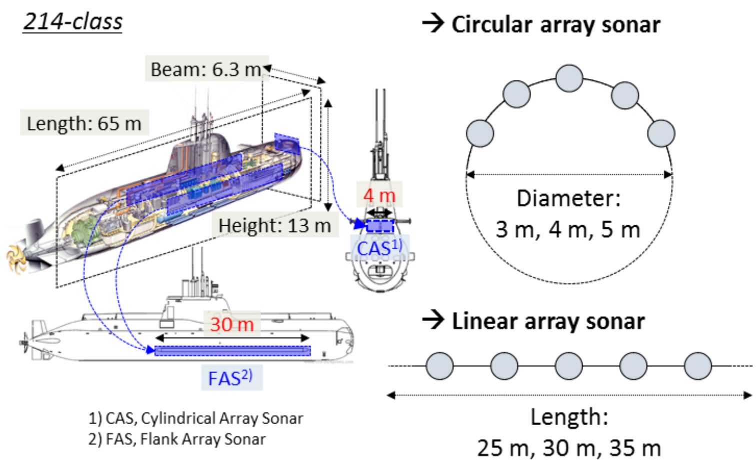

Fig. 4 Specifications of the passive sonars of a submarine

Fig. 4 shows that this study referred to the 214-class submarine, and the diameter of Cylindrical Array Sonar (CAS) and the length of Flank Array Sonar (FAS) were estimated to be 4 m and 30 m, respectively. In the detection performance simulations, the CAS and the FAS were assumed to be a circular array sonar and a linear array sonar. Then, the diameter of the circular array sonar was changed from 3 to 5 m, and the length of the linear array sonar was changed from 25 to 35 m. Fig. 5-10 show the beam patterns of the circular array sonar and the linear array sonar according to the diameter and the length. These figures show that the longer the diameter and the length, the wider the beam width. The width in which the maximum value decreases to 3 dB is called the beam width.

The beam width corresponds to the resolution, which is the ability to resolve adjacent targets. The narrower the beam width, the better the resolution.

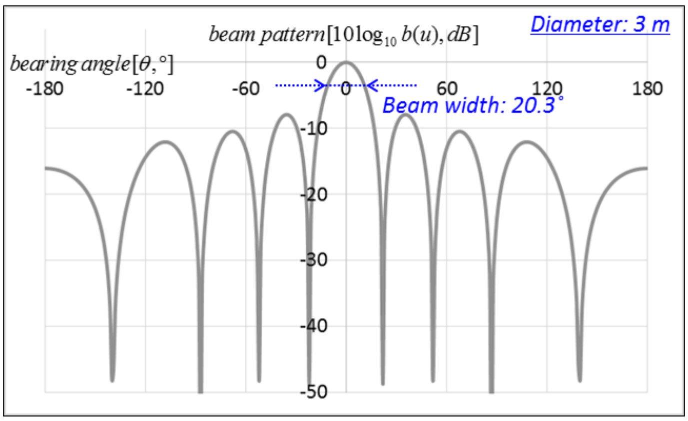

Fig. 5 Beam pattern of a circular array sonar (diameter: 3 m)

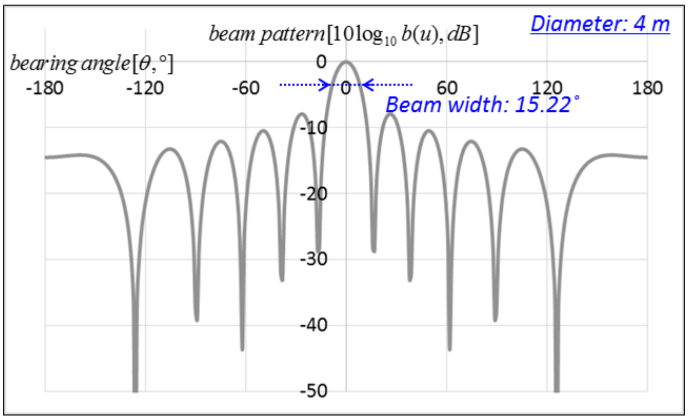

Fig. 6 Beam pattern of a circular array sonar (diameter: 4 m)

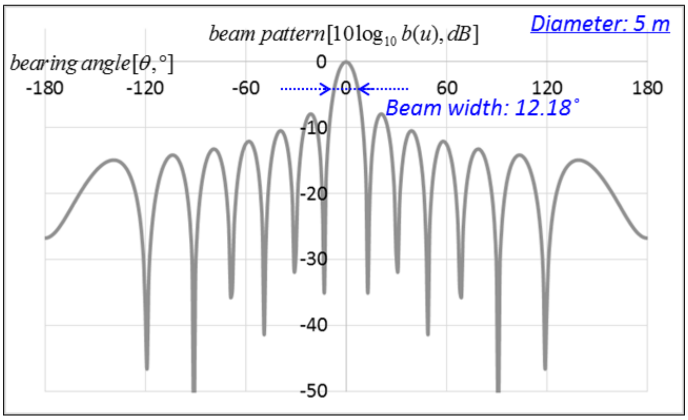

Fig. 7 Beam pattern of a circular array sonar (diameter: 5 m)

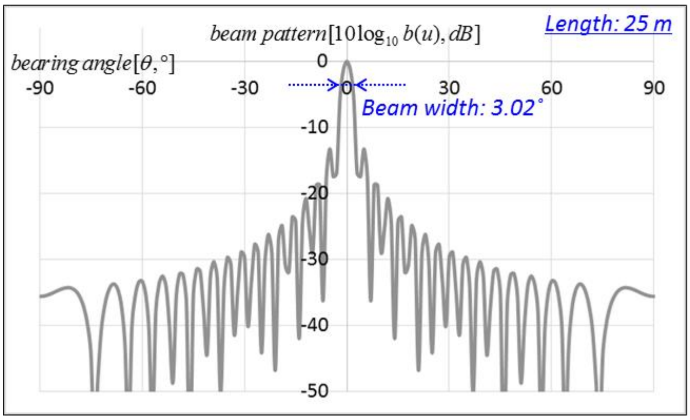

Fig. 8 Beam pattern of a linear array sonar (length: 25 m)

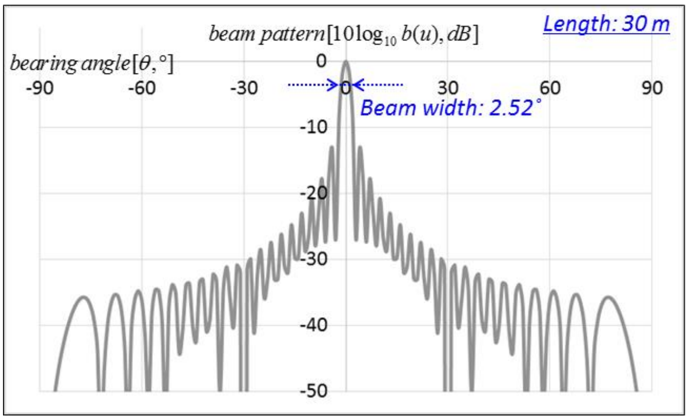

Fig. 9 Beam pattern of a linear array sonar (length: 30 m)

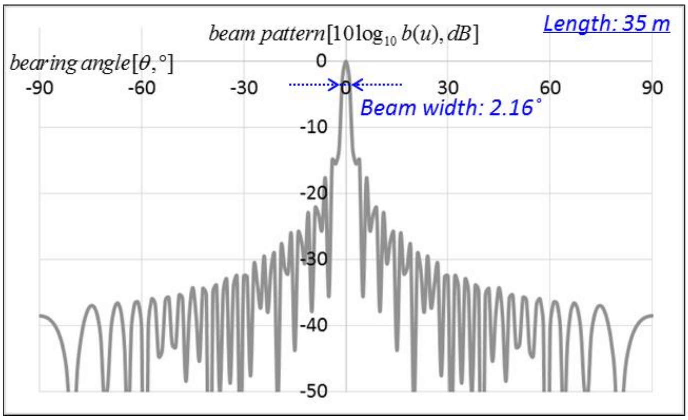

Fig. 10 Beam pattern of a linear array sonar (length: 35 m)

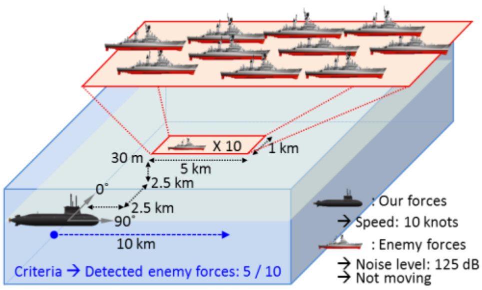

Fig. 11 First scenario for the detection performance simulation

Table 2 Results of the first scenario simulations

Case	Array diameter / length [m]		The number of detected enemy forces
	Circular	Linear	
A1	3	–	0.0
A2	4	–	0.0
A3	5	–	0.0
A4	–	25	4.0
A5	–	30	5.6
A6	–	35	6.3

Fig. 11 shows that the first scenario was that our forces consisted of one submarine that moved along a straight path at a speed of 10 knots, and detected enemy forces. The enemy forces consisted of ten surface ships, which were randomly located in the specified area and did not move, and of which the noise level was 125 dB. The specifications for the submarine referred to the 214-class submarine. The specifications for the surface ships referred to the gearing-class destroyer. The criterion for the detection performance was assumed that the submarine should detect at least five of the ten surface ships.

The first scenario simulations were carried out, using the circular array sonar and the linear array sonar, and changing the diameter and the length as shown in Table 2. The number of detected targets in Table 2 is the mean value of ten simulations of each case. This is because the location of the surface ships was randomized at every simulation.

The results of this scenario are that the linear array sonar is more suitable than the circular array sonar; and the longer the length of the linear array sonar, the more suitable the detection performance. Figs. 12 and 13 show that these results correspond to the Array Gain (AG) at around 0°.

In a passive sonar equation (Section 3.3), the probability of detection becomes higher as the value of the AG becomes larger. The values of AG at around 0° of the linear array sonar are larger than that of the circular array sonar; and the longer the length of the linear array sonar, the larger the values of AG at around 0°. Meanwhile, the values of the AG of the circular array sonar are the same, regardless of the bearing angles, because the array configuration of the circular array sonar is the circle.

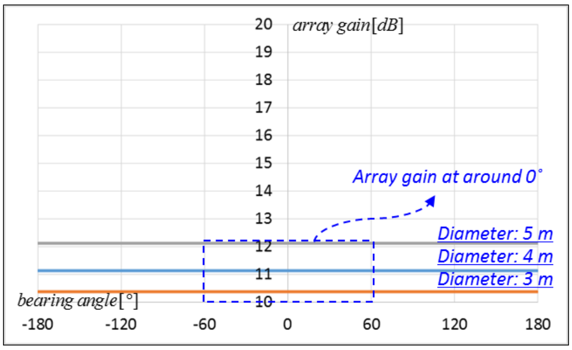

Fig. 12 Array gain of the circular array sonar

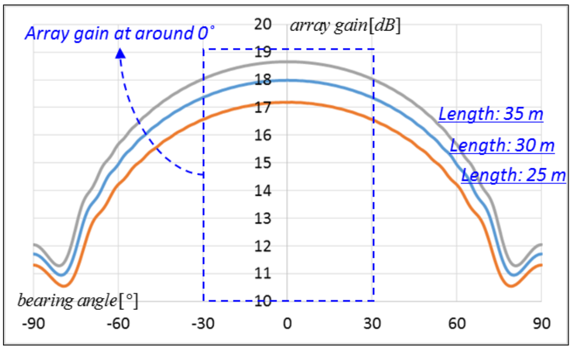

Fig. 13 Array gain of the linear array sonar

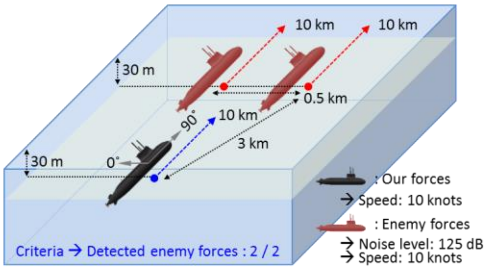

Fig. 14 Second scenario for the detection performance simulation

Among these six cases, Case A5 and Case A6 satisfy the criterion for the detection performance. Considering that the length of the FAS of the 214-class submarine is 30 m, Case A5 is the most suitable case.

Fig. 14 shows the second scenario, which was that our forces consisted of one submarine that moved along a straight path at speed 10 knots, and detected enemy forces. The enemy forces consisted of two submarines that moved along adjacent parallel straight paths in the same direction at a speed of 10 knots, and of which the noise level was 125 dB. The specifications for the submarines referred to the 214-class submarine. The criterion for the detection performance was assumed to be that the submarine should detect both of the adjacent surface ships.

The second scenario simulations were carried out using the circular array sonar and the linear array sonar, and changing the diameter and the length as shown in Table 3.

Table 3 Results of the second scenario simulations

Case	Array diameter / length [m]		The number of detected enemy forces
	Circular	Linear	
B1	3	–	1
B2	4	–	2
B3	5	–	2
B4	–	25	1
B5	–	30	1
B6	–	35	2

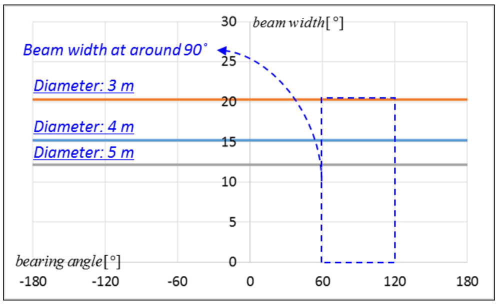

Fig. 15 Beam width of the circular array sonar

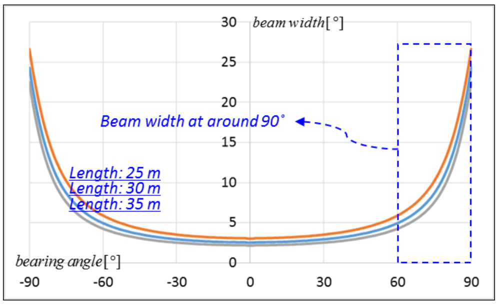

Fig. 16 Beam width of the circular array sonar

The results of this scenario are that the circular array sonar is more suitable than the linear array sonar; and the longer the diameter of the circular array sonar, the more suitable the detection performance. Figs. 15 and 16 show that these results correspond to the beam width at around 90°.

The resolution, which is the ability to resolve adjacent targets, becomes better as the beam width decreases. The values of the beam width at around 90° of the circular array sonar are smaller than those of the linear array sonar; and the longer the diameter of the circular array sonar, the smaller the beam width at around 90°. Meanwhile, the values of the beam width of the circular array sonar are the same, regardless of the bearing angles, because the array configuration of the circular array sonar is a circle.

Among these six cases, Cases B2, B3 and B6 satisfy the criterion for the detection performance. Considering that the diameter and length of the CAS and the FAS of the 214-class submarine are 4 and 30 m, respectively, the results show that Case B2 is the most suitable.

4.2 Case study for maneuvering performance simulation

The maneuvering performance simulations were carried out by changing the specifications of the hydroplanes of a submarine in different scenarios.

Fig. 17 shows that this study referred to the 214-class submarine. In the maneuvering performance simulations, the areas of the hydroplanes were changed to be half times, and one-and-one-half times. The hydrodynamic coefficients could be determined by Eqs. (8)-(11) (Bohlmann 2003)

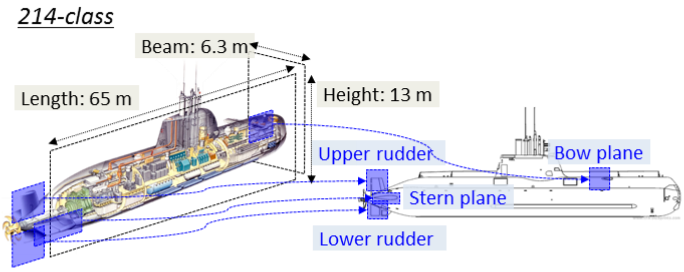

Fig. 17 Specifications of the hydroplanes of a submarine

$$Z_{\delta(P)} = -\frac{S_{(P)}}{L^2} \times a_{2(P)} \times k_{(P)} \tag{8}$$

$$M_{\delta(P)} = -Z_{\delta(P)} \times \frac{x_{(P)}}{L} \tag{9}$$

$$Y_{\delta(R)} = -\frac{S_{(R)}}{L^2} \times a_{2(R)} \times k_{(R)} \tag{10}$$

$$N_{\delta(R)} = Y_{\delta(R)} \times \frac{x_{(R)}}{L} \tag{11}$$

where, *(P)* is a bow or stern plane, and *(R)* is an upper or lower rudder. $Z_{\delta(P)}$, $M_{\delta(P)}$, $Y_{\delta(R)}$, and $N_{\delta(R)}$ are hydrodynamic coefficients representing normal force, pitching moment, lateral force, and yawing moment as a function of the hydroplanes, respectively. $\delta(P)$ is the deflection of a bow or stern plane, and $\delta(R)$ is the deflection of an upper or lower rudder. L is the length of a submarine. $S_{(P)}$ is the area of a bow or stern plane, and $S_{(R)}$ is the area of an upper or lower rudder. $x_{(P)}$ is the lever arm from the center of gravity to a bow or stern plane, and $x_{(R)}$ is the lever arm from the center of gravity to an upper or lower rudder. $a_{2(P)}$ is the lift slope of a bow or stern plane, and $a_{2(R)}$ is the lift slope of an upper or lower rudder.

Table 4 shows the values of the hydrodynamic coefficients. It was assumed that the values of the other hydrodynamic coefficients, which referred to the values from Babaoglu (1998), would not be changed.

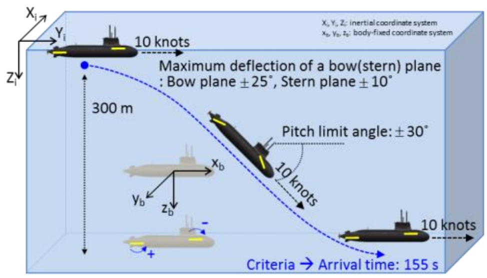

Fig. 18 First scenario for the maneuvering performance simulation

Table 4 Hydrodynamic coefficients according to the area of the hydroplanes

Area of hydroplanes	0.5 times	1 times	1.5 times
$Z_{\delta b}$	-0.002540	-0.005080	-0.007620
$Z_{\delta s}$	-0.002200	-0.004400	-0.008800
$M_{\delta b}$	0.000586	0.001172	0.001758
$M_{\delta s}$	-0.001083	-0.002165	-0.003248
$Y_{\delta r}= Y^{Upper}{}_{\delta r}+ Y^{Lower}{}_{\delta r}$	0.001886	0.003772	0.005658
$Y^{Upper}{}_{\delta r}$	0.000952	0.001904	0.002856
$Y^{Lower}{}_{\delta r}$	0.000934	0.001867	0.002801
$N_{\delta r}= N^{Upper}{}_{\delta r}+ N^{Lower}{}_{\delta r}$	-0.000929	-0.001858	-0.002787
$N^{Upper}{}_{\delta r}$	-0.000469	-0.000938	-0.001407
$N^{Lower}{}_{\delta r}$	-0.000460	-0.000919	-0.001379

Table 5 Results of the first scenario simulations

Case	Array of the hydroplanes [m^2]		The arrival time [s]
	Bow plane	Stern plane	
C1	2.08	13.98	253.8
C2		27.95	196.1
C3		41.93	173.5
C4	4.16	13.98	234.3
C5		27.95	153.6
C6		41.93	183.1
C7	6.24	13.98	232.3
C8		27.95	152.9
C9		41.93	186.1

Fig. 18 shows the first scenario, in which a submarine dived on changing its pitch angle, by controlling the deflection of the bow plane and the stern plane. The forward speed of the submarine was 10 knots. The specifications for the submarine referred to the 214-class submarine. The maximum deflection of the bow plane and the stern plane were assumed to be 25° and 10°, respectively; and the limit of the pitch angle was assumed to be 30°. The criterion for the maneuvering performance was assumed that the submarine should dive to the target depth 300 m within 155 s. The tolerance of the target depth was assumed to be 1 m.

The areas of the bow plane and the stern plane of the 214-class submarine were estimated to be 4.16 and 27.95 m^2, respectively. Table 5 shows the first scenario simulations that were carried out, by changing the areas of the bow plane and the stern plane to be half times, and one-and-one-half times. The arrival time in Table 5 is the time for the submarine to dive to the target depth 300 m.

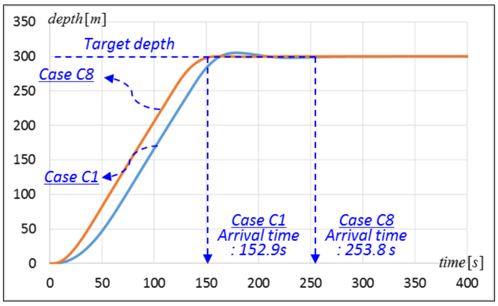

Fig. 19 Depth variations in Cases C1 and C8

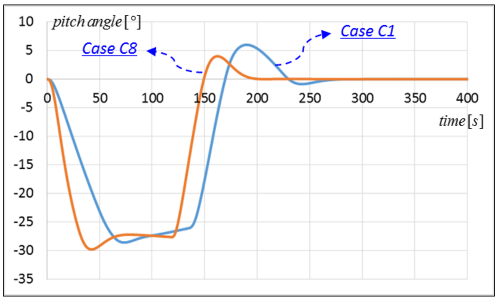

Fig. 20 Pitch angle variations in Cases C1 and C8

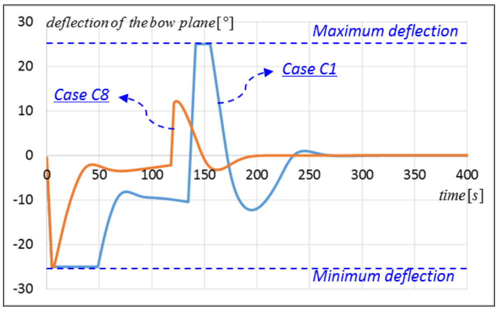

Fig. 21 Deflection of the bow plane in Cases C1 and C8

The results of this scenario are that the wider the areas of the bow plane and the stern plane, the shorter the arrival time. The following would explain this tendency through Cases C1 and C8. The arrival time of Case C1, 253.8 s, is the longest, while that of Case C8, 152.9 s, is the shortest; and the areas of the bow plane and the stern plane of Case C8 are wider than those of Case C1. Fig. 19 shows the depth variations of the submarine in Cases C1 and C8.

Fig. 20 shows the pitch angle variations in Cases C1 and C8. The pitch angle in Case C1 was changed more slowly than in Case C8.

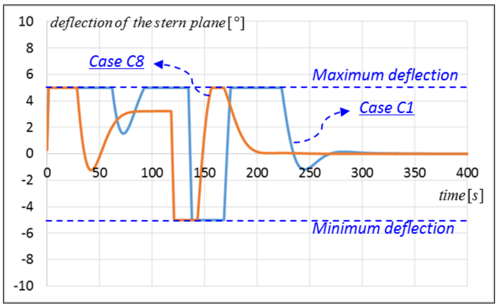

Fig. 22 Deflection of the stern plane in Cases C1 and C8

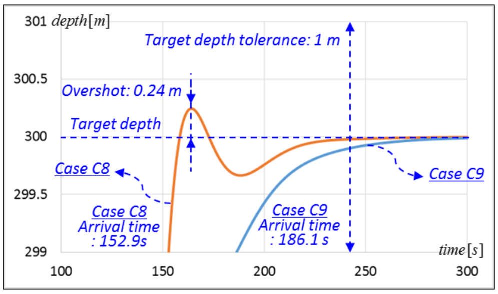

Fig. 23 Depth variations in Cases C8 and C9

Figs. 21 and 22 show the deflection of the bow plane and the stern plane in Cases C1 and C8. These two figures show that the time during which the deflection was the maximum value or the minimum value was longer in Case C1 than in Case C8.

Overall, the smaller the areas of the bow plane and the stern plane, the longer the time for the bow plane and the stern plane to be held at the maximum or minimum deflection. Then, the pitch angle would change slowly, and the depth would change slowly. As a result, the smaller the areas of the upper rudder and the lower rudder, the longer it takes for the submarine to dive to the target depth.

However, this tendency does not hold for Cases C6 and C9. This is because there was no overshoot in Cases C6 and C9. Fig. 23 shows that the depth variation of the submarine in Case C9 had no overshoot, compared to that of the submarine in Case C8.

Among these nine cases, Cases C5 and C8 satisfy the criterion for the maneuvering performance. Considering that the areas of the bow plane and the stern plane of the 214-class submarine are 4.16 and 27.95 m^2, respectively, the results show that Case C5 is the most suitable case.

Fig. 24 shows the second scenario, in which a submarine patrolled along the ten positions by changing the yaw angle of the submarine, by controlling the deflection of the upper rudder and the lower rudder. The forward speed of the submarine was 10 knots. The specifications for the submarine referred to the 214-class submarine. It was assumed that the deflection of the upper rudder and the lower rudder would be changed equally. The maximum deflections of the upper rudder and the lower rudder were assumed to be 40°. The criterion for the maneuvering performance was assumed that the submarine should patrol along the ten positions within 2,210 s.

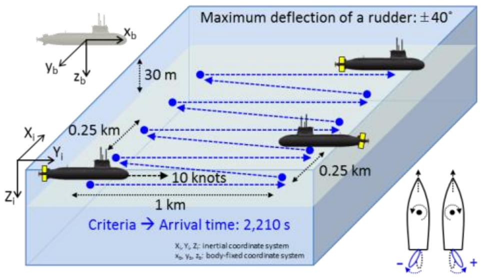

Fig. 24 Second scenario for the maneuvering performance simulation

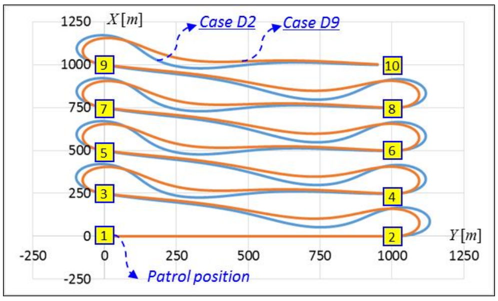

Fig. 25 Trajectories in Cases D2 and D9

Table 6 Results of the second scenario simulations

Case	Array of the rudders [m^2]		The arrival time [s]
	Upper rudder	Lower rudder	
D1		6.47	–
D2	5.62	12.94	2,289.2
D3		19.41	2,210.0
D4		6.47	2,285.0
D5	11.23	12.94	2,209.0
D6		19.41	2,176.8
D7		6.47	2,208.4
D8	16.85	12.94	2,176.4
D9		19.41	2,156.5

The areas of the upper rudder and the lower rudder of the 214-class submarine were estimated to be 11.23 and 12.94 m^2, respectively. Table 6 shows the second scenario simulations that were carried out, by changing the areas of the upper rudder and the lower rudder to be half times, and one-and-one-half times. The arrival time in Table 6 is the time for the submarine to patrol along the ten positions. The dash, –, in Table 6 means that the submarine failed to patrol along the ten positions in Case D1.

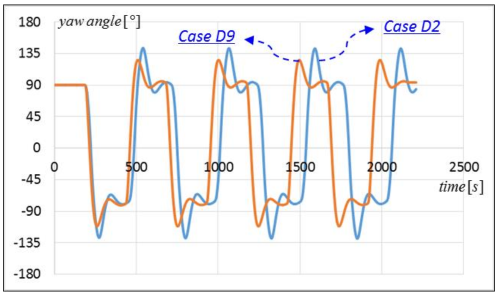

Fig. 26 Yaw angle variations in Cases D2 and D9

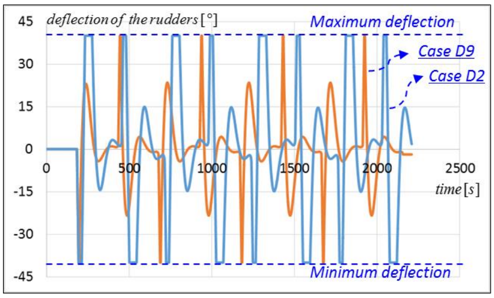

Fig. 27 Deflection of the upper rudder and the lower rudder in Cases D2 and D9

The results of this scenario are that the wider the areas of the upper rudder and the lower udder, the shorter the arrival time. The following would explain this tendency through Cases D2 and D9.

The arrival time of Case D2, 2,289.2 s, is the longest, while that of Case D9, 2,156.5 s, is the shortest; and the areas of the upper rudder and the lower rudder of Case D9 are wider than those of Case D2. Fig. 25 shows the trajectories of the submarines in Cases D2 and D9. The submarine got further away from the position in Case D2 than in Case D9.

Fig. 26 shows the yaw angle variations in Cases D2 and D9. The yaw angle in Case D2 changed more slowly than in Case D9.

Fig. 27 shows the deflection of the upper rudder and lower rudder in Cases D2 and D9. The times during which the deflection was the maximum value or the minimum value were longer in Case D2 than in Case D9.

Overall, the smaller the areas of the upper rudder and the lower rudder, the longer the time for the upper rudder and the lower rudder to be held at the maximum or minimum deflection. Then, the yaw angle would change slowly, and the submarine would get further away from the patrol position. As the result, the smaller the areas of the upper rudder and the lower rudder, the longer for the submarine to patrol along the ten positions.

4.3 Case study for the engagement simulation of submarines and surface ships

The simulation core of this study features the flexibility and reusability of models, so that it is easier to simulate various engagement situations with various naval ship models, which consist of different command systems, weapon systems, detection systems, and maneuver systems, as shown in Fig. 28. Applying such simulation core, the engagement simulations were carried out by changing the engagement situations, such as the number of naval ships engaged, the tactics of the naval ships, and the weapons of the naval ships.

Table 7 shows the engagement simulations that were carried out for the five cases, checking whether or not our forces would succeed in attacking the enemy forces. Table 8 shows the properties of torpedoes. In these cases, the specifications for the maneuvering and detection performance of the submarines and the surface ships referred to the 214-class submarine and the gearing-class surface ship, respectively. The following would explain these cases.

Table 7 Variations of the engagement situations

Case	Number		Tactics		Weapon				Success
	Our forces	Enemy forces	Our forces	Enemy forces	Our forces			Enemy forces	
E1	1	1	Attack	Patrol	Torpedo1			-	O
E2				Evade				Decoy	X
E3					Torpedo2				O
E4	3	2			Torpedo1	Torpedo1	Torpedo1		X
E5					Torpedo1	Torpedo3	Torpedo1		O

Table 8 Variations of the engagement situations

Torpedo	Speed [knot]	Lifespan [min]
Torpedo1	20	20
Torpedo2	20	30
Torpedo3	30	30

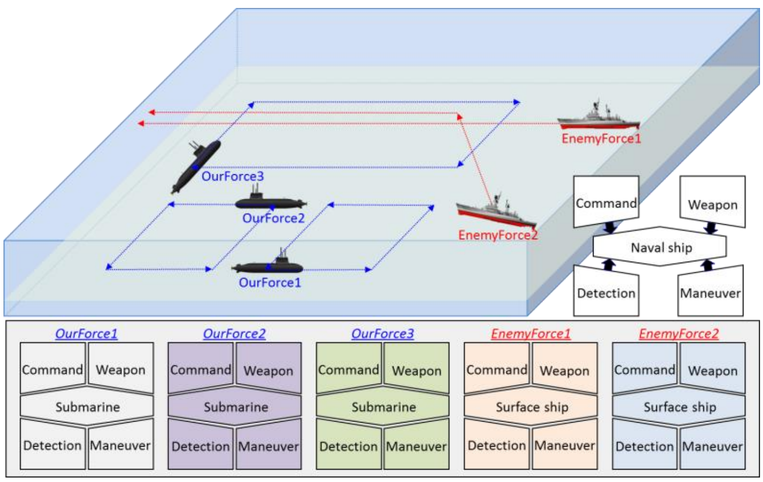

Fig. 28 Variations of the engagement situations

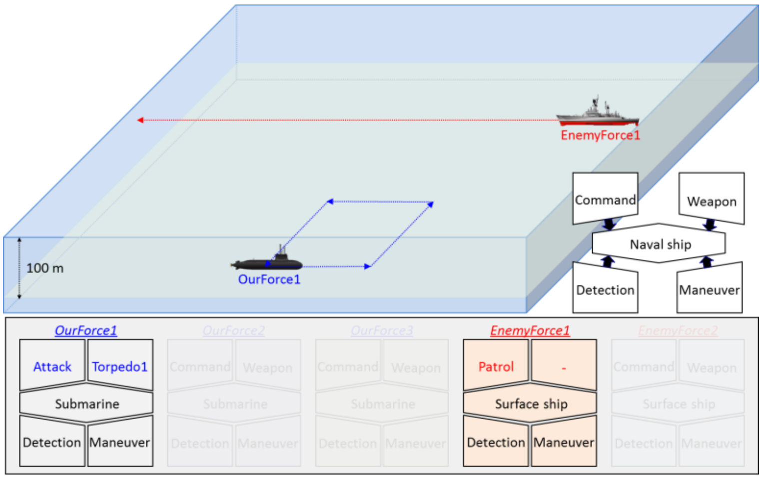

Fig. 29 Progress of Case E1 (1)

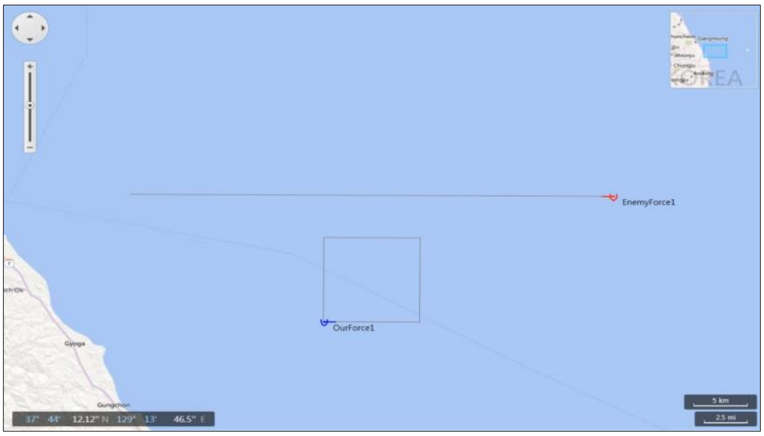

Fig. 30 Map view of Case E1

[Case E1] The scenario of Case E1 was that our forces consisted of one submarine that would attack the enemy forces, and enemy forces consisted of one surface ship that would patrol along the defined path. First, as shown in Figs. 29 and 30 the submarine and the surface ship moved along the defined path.

Next, as shown in Fig. 31, the submarine detected and tracked the surface ship.

Then, as shown in Fig. 32, the submarine launched a torpedo, and succeeded in attacking the surface ship.

[Case E2 & Case E3] The scenario of Cases E2 and E3 was that our forces consisted of one submarine that would attack the enemy forces, and the enemy forces consisted of one surface ship that after detecting our forces, would evade. The progression of Cases E2 and E3 were identical with that of Case E1, until the surface ships launched their decoys, as shown in Fig. 33.

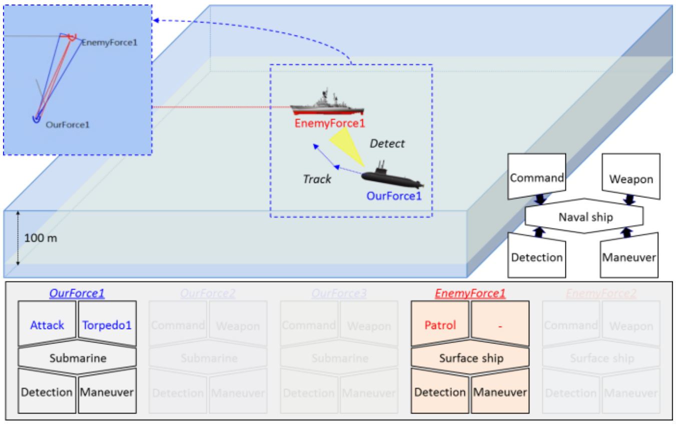

Fig. 31 Progress of Case E1 simulation (2)

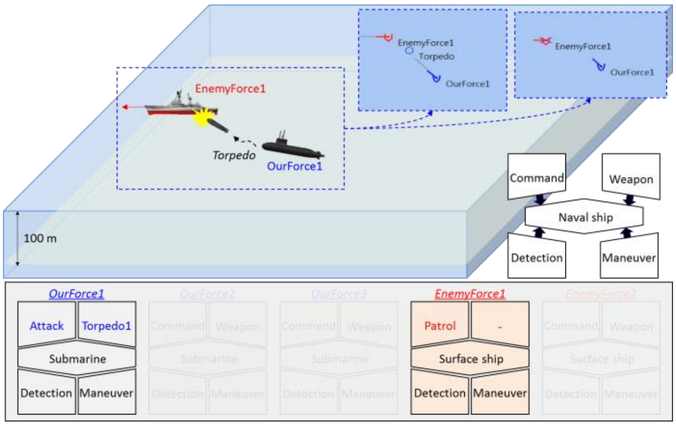

Fig. 32 Progress of Case E1 simulation (3)

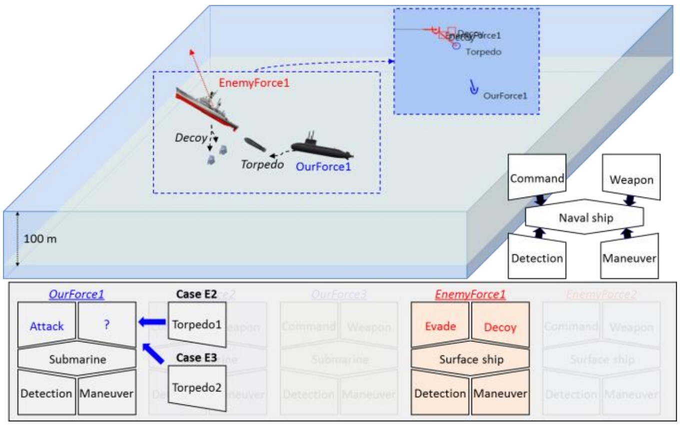

Fig. 33 Progressions of Cases E2 and E3 (1)

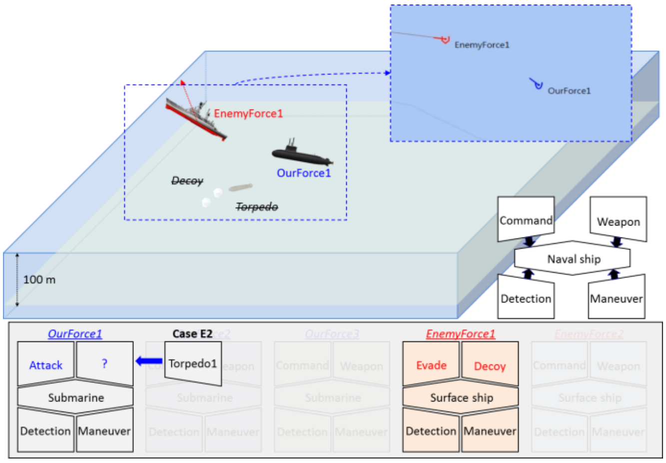

Fig. 34 Progress of Case E2 simulation (2)

Next, in Case E2, the submarine failed to attack the surface ship, because the decoys succeeded in interrupting the torpedo, as shown in Fig. 34. On the other hand, in Case E3, the submarine succeeded in attacking the surface ship, because the decoys failed to interrupt the torpedo, as shown in Fig. 35. The lifespan of the torpedo in Case E3 was longer than that of the torpedo in Case E2, which was the reason why the submarine in Case E3 succeeded in attacking the surface ship.

[Case E4 & Case E5] The scenario of Cases E4 and E5 was that our forces consisted of three submarines that would attack the enemy forces, and the enemy forces consisted of two surface ships that would evade, after detecting our forces. For convenience to indicate the submarines and the surface ships, the submarines are indicated as OurForce1, OurForce2, and OurForce3, and the surface ships are indicated as EnemyForce1 and EnemyForce2. First, as shown in Figs. 36 and 37, the submarines and the surface ships moved along the defined paths.

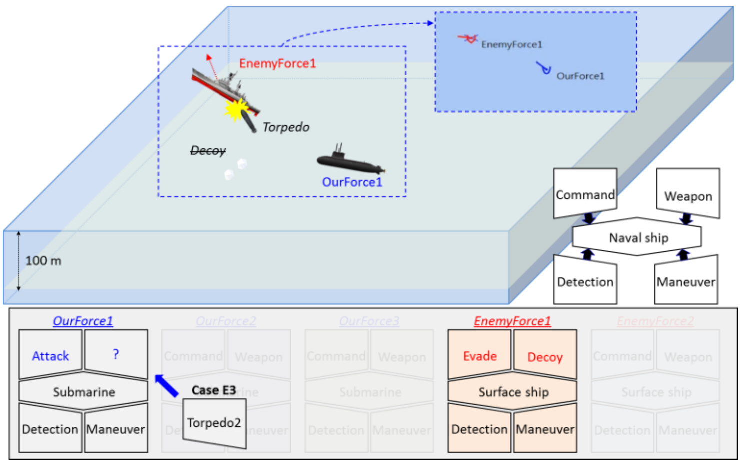

Fig. 35 Progress of Case E3 simulation (3)

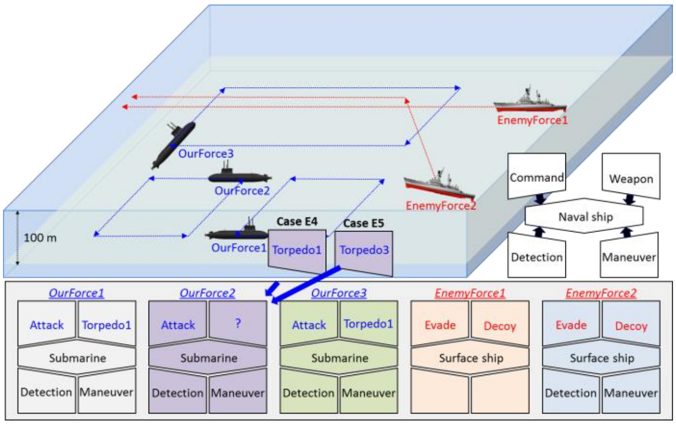

Fig. 36 Progressions of Cases E4 and E5 (1)

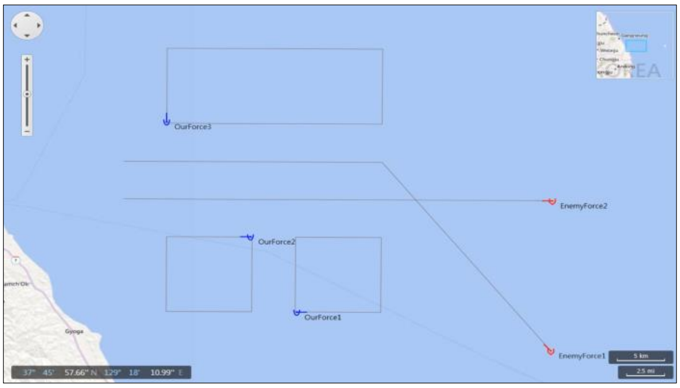

Fig. 37 Map view of Cases E4 and E5

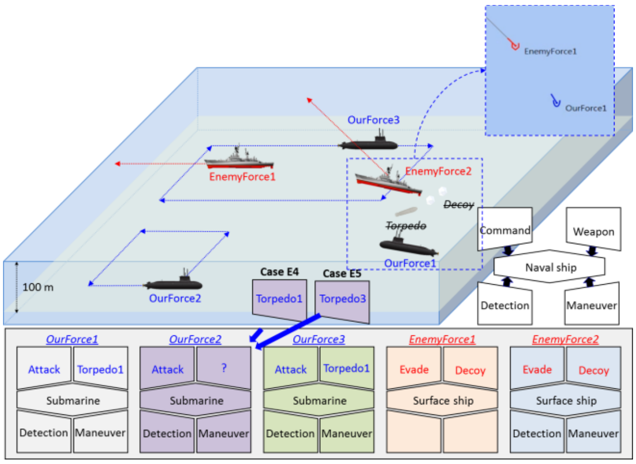

Fig. 38 Progressions of Cases E4 and E5 (2)

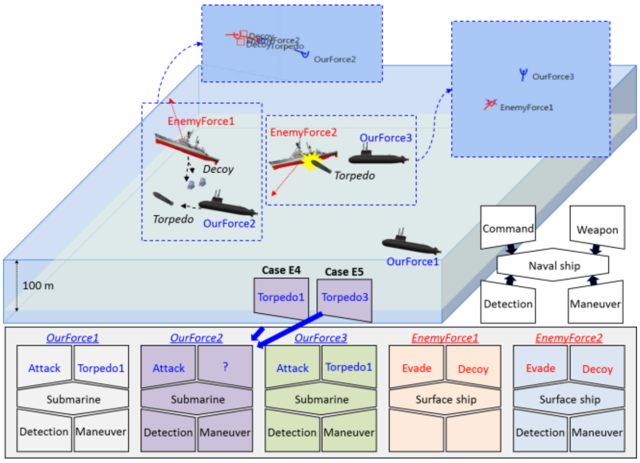

Fig. 39 Progressions of Cases E4 and E5 (3)

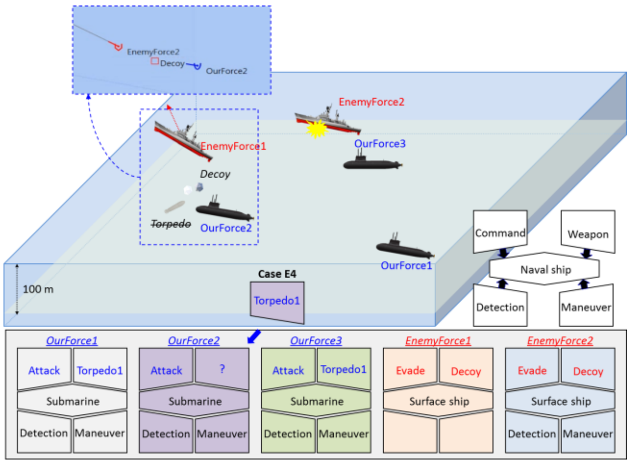

Fig. 40 Progress of Case E4 (1)

Next, as shown in Fig. 38, OurForce1 failed to attack EnemyForce2.

Then, as shown in Fig. 39, OurForce3 succeeded in attacking EnemyForce2, and EnemyForce1 launched the decoys after detecting the torpedo launched by OurForce2. Until this situation, the progressions of Cases E4 and E5 were identical to each other.

In Case E4, OurForce2 failed to attack EnemyForce1, because the decoys succeeded in interrupting the torpedo, as shown in Fig. 40. On the other hand, in Case E5, OurForce2 succeeded in attacking EnemyForce1, because the decoys failed to interrupt the torpedo, as shown in Fig. 41.

The lifespan of the torpedo of OurForce2 in Case E5 was longer than that of OurForce2 in Case E4, and the speed of the torpedo of OurForce2 in Case E5 was faster than that of OurForce2 in Case E4, which was the reason why our forces in Case E5 succeeded in attacking all the enemy forces.

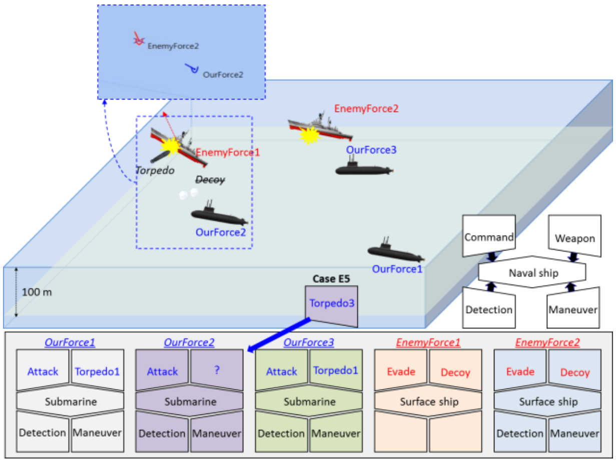

Fig. 41 Progress of Case E5 (2)

From these five cases, whether or not our forces would succeed in attacking the enemy forces was checked according to the engagement situations, such as the number of naval ships engaged, the tactics of the naval ships, and the weapons of the naval ships.

5. Conclusions

This study conducted three case studies using the engagement simulation of the engineering level to check the performance of the related parameters. First, the detection performance simulations were carried out by changing the specifications of the passive sonars of a submarine in different scenarios. The maneuvering performance simulations were carried out by changing the specification of the hydroplanes of a submarine in different scenarios. Lastly, in order to check whether or not our forces would succeed in attacking the enemy forces, we conducted the engagement simulation with various naval ship models, which consisted of several engineering level models, such as command systems, weapon systems, detection systems, and maneuver systems. As a result, the performance according to the specifications of the naval ships and weapons was evaluated.

The simulation core makes it possible to consider the engagement level and the engineering level at the same time. In addition, the simulation core features the flexibility and reusability of models, so that it is easier to simulate various engagement situations with various naval ships.

In the near future, we will upgrade the engineering models for more realistic engagement simulation. It is also planned to improve the performance, so that the speed does not become slow, even if more than 10 models participate together.

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