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Analysis of the dynamic characteristics for the change of design parameters of an underwater vehicle using sensitivity analysis

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ABSTRACT

In order to design the hull form of an underwater vehicle in the conceptual design phase, the dynamic characteristics depending on the hull form parameters should be identified. Course-keeping stability, turning ability, yaw-checking ability, and mission competence are set to be the indices of the dynamic characteristics, and the geometric parameters for the bare hull and rudder are set to be the hull form design parameters. The total sensitivity of the dynamic characteristics with respect to the hull form parameters is calculated by the chain rule of the partial sensitivity of the dynamic characteristics with respect to the hydrodynamic coefficients, and the partial sensitivity of the hydrodynamic coefficients with respect to the hull form parameters. Based on the sensitivity analysis, important hull form parameters are selected, and those optimal values to satisfy the required intercept time of mission competence of a specific underwater vehicle and turning rate are estimated.

1. Introduction

The underwater vehicle is widely used in the fields of military weaponry and commercial use, such as exploitation of mineral resources, seabed surveying, and investigation of offshore pipelines (Kim, 2011). Many kinds of underwater vehicles, like torpedo, anti-torpedo torpedo, and self-propulsive mine, run very fast, and they require excellent dynamic characteristics. When a military underwater vehicle is designed in the conceptual design phase, principal dimensions, like length-to-diameter ratio, nose shape, tailcone angle, total fin area, and movable fin area, should be determined only from the inputs of the running speed and the maximum turn rate.

Dynamic characteristics of an underwater vehicle consist of course-keeping stability and maneuverability. In general, these would be estimated by the sign of the solution of the characteristic equation, and maneuvering simulation after establishing the six Degrees of Freedom (DOF) equations of motion. Gertler and Hagen (1967) and Feldman (1979) suggested the hydrodynamic force model acting on a maneuvering submarine. Healey and Lienard (1993) and Prestero (2001) established the equations of motion of the Autonomous Underwater Vehicle (AUV). While most of the hydrodynamic force models acting on an underwater vehicle are described as first or higher order polynomial functions, some of them are modeled using the neural network method (Yoon et al., 2006; Ahn, 2005). When the model structure of hydrodynamic force is adopted as the polynomial functions, the parameters, the so-called hydrodynamic coefficients, should be estimated theoretically or experimentally. In order to experimentally estimate the hydrodynamic coefficients of an underwater vehicle, the Vertical Planar Motion Mechanism (VPMM) (Jung et al., 2014a,b), rotating arm (Lewis, 1989), and coning motion (Park et al., 2015; Lewandowski, 1991) tests are performed. Since a large budget would be required to perform the model test, empirical formulae to estimate the hydrodynamic coefficients developed using many model test results are used in the conceptual design phase, when many design parameters could be changed (Jeon et al., 2016; HDW, 2002; Prestero, 2001; Fossen, 1994).

Many researches to relate the dynamic characteristics to the design hull form parameters and the hydrodynamic coefficients using sensitivity analysis have been performed (Sen, 2000; Kim et al., 2014). Bae et al. (2007) analyzed the sensitivity of maneuvering characteristics of a Manta-type underwater vehicle due to the hydrodynamic coefficients. Yeo et al. (2006) identified the most

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Nomenclature

A	Cross-sectional area of bare hull
A_E^{rd}	Effective aspect ratio of rudder
A_{tot}^{rd}, A_{mp}^{rd}	Total and movable areas of rudder, respectively
b^{rd}	Span length of rudder
c_t^{rd}, c_r^{rd}	Tip and root chord lengths, respectively, of rudder
D	Diameter of bare hull
G_h	Stability gain margin
L	Length of bare hull
L_{midd}	Length of parallel middle body
m, I_z	Mass and mass moment of inertia, respectively
$O-x_0y_0$	Earth-fixed coordinate
$o-xy$	Body-fixed coordinate
R'	Nondimensional turning radius
r_{ss}	Steady turning rate
S_G^M	Total sensitivity of dynamic characteristics with respect to hull form parameter
S_H^M	Partial sensitivity of dynamic characteristics with respect to hydrodynamic coefficient
S_G^H	Partial sensitivity of hydrodynamic coefficient with respect to hull form parameter
T_{op}	Intercept time
U	Speed of underwater vehicle
u, v, r	Surge and sway velocities, respectively, and yaw rate
X, Y, N	External force and moment
x_G	x coordinate of center of gravity of a vehicle
x_{tot}^{rd}, x_{mp}^{rd}	x coordinates of centers of total area and movable area of rudder, respectively
β	Drift angle
δ_r	Rudder angle
λ^{rd}	Taper ratio of rudder ($= c_t^{rd}/c_r^{rd}$)
ψ	Yaw or heading angle
ψ_1, ψ_2	1st and 2nd overshoot yaw angle, respectively
ρ	Fluid density
Θ	Tailcone angle

effective design parameters of a submarine on the stability indices, and Yeo and Rhee (2006) designed the most sensitive inputs for identifying the hydrodynamic coefficients by the genetic algorithm. Kim et al. (2014) investigated the effect on the maneuvering characteristics due to the appendage of a war ship by sensitivity analysis. However, previous researches have been conducted to analyze

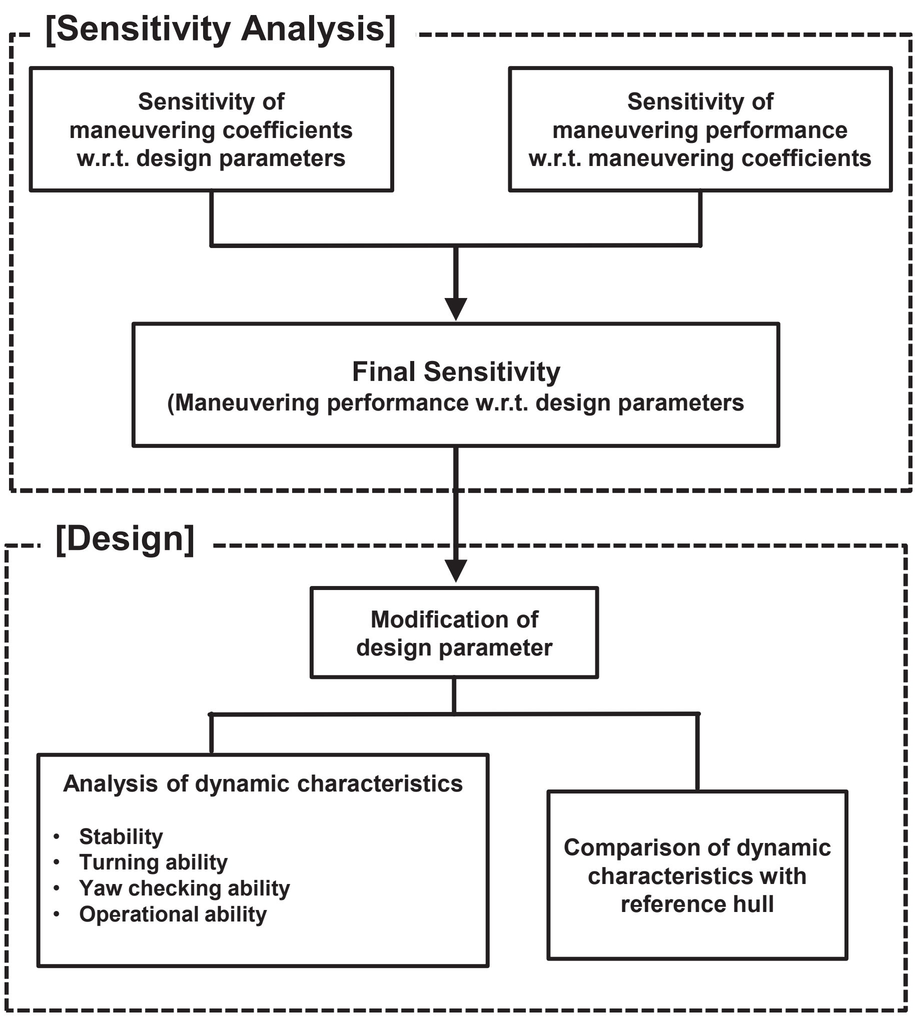


Fig. 1. Procedure for the optimal hull form design of an underwater vehicle.

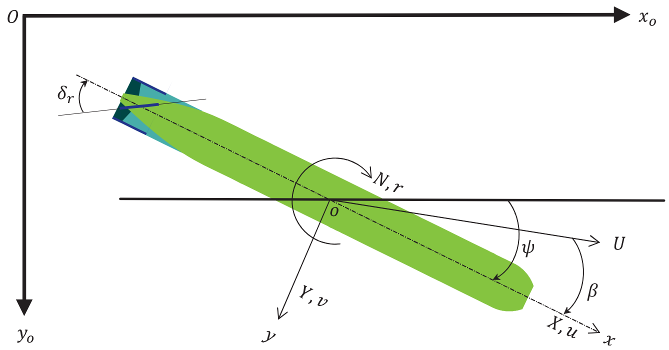


Fig. 2. Coordinate systems.

the general trend of the dynamic characteristics due to the changes of design parameters and hydrodynamic coefficients. In contrast, we selected the most effective design parameters for the dynamic characteristics by sensitivity analysis. Regression analysis between the steady turning rate and movable rudder area ratio has been performed to decide the optimal value of a fast running cylindrical type underwater vehicle, as shown in Fig. 1 (Jeon, 2017). In addition, the special mission scenario of the target underwater vehicle for applying the sensitivity analysis was established, which is necessary to design the target underwater vehicle in the conceptual design phase.

In this paper, three DOF horizontal equations of motion, including an external force model, are described. We selected the anti-torpedo torpedo as the target underwater vehicle, and show its dynamic characteristics. Since its shape is axisymmetric except fins, and fin geometries of rudders and elevators are all the same, the coupling effect of vertical and horizontal motion is small. In addition, the horizontal moving range and maneuvering style of an underwater vehicle is much larger and highly maneuverable than the vertical ones because the depth is limited compared to the total running distance. So, horizontal motion is more critical for a designer of anti-torpedo torpedo. The total sensitivity consisting of two partial sensitivities is defined and calculated, and then the most effective design parameters are selected. Finally, correlation between the required performance of the dynamic characteristics and the design parameters are analyzed, and the optimal movable rudder area ratio is suggested.

Table 1
Principal dimensions of the basic target hull form parameter.

Part	Parameter	Value
Hull	L	1.94 m
	L_{nose}	0.12 m
	L_{midd}	1.38 m
	L_{tail}	0.44 m
	D	0.21 m
	Θ	18.0°
Rudder	A^{rd}_{tot}	1.684E-2 m^2
	A^{rd}_{mp}	6.602E-3 m^2
	C^{rd}_t	3.000E-2 m
	C^{rd}_r	5.900E-2 m
	b^{rd}	9.300E-2 m

Table 2
Hydrodynamic coefficients of the basic target.

Class	Coefficient	Dimension	Value
Added mass	$X'_{\dot{u}}$	$\frac{\rho}{2}L^3$	−1.2765E-3
	$Y'_{\dot{v}}$	$\frac{\rho}{2}L^3$	−2.9736E-2
	$Y'_{\dot{r}}$	$\frac{\rho}{2}L^4$	1.5294E-3
	$N'_{\dot{v}}$	$\frac{\rho}{2}L^4$	0.0000E+0
	$N'_{\dot{r}}$	$\frac{\rho}{2}L^5$	−1.8042E-3
Resistance	X'_{uu}	$\frac{\rho}{2}A$	−9.2693E-4
Damping	Y'_v	$\frac{\rho}{2}L^2U$	−6.0464E-2
	Y'_r	$\frac{\rho}{2}L^3U$	2.5313E-2
	N'_v	$\frac{\rho}{2}L^3U$	3.0351E-4
	N'_r	$\frac{\rho}{2}L^4U$	−1.1221E-2
Control	Y'_{δ_r}	$\frac{\rho}{2}L^2u^2$	−1.0939E-3
	N'_{δ_r}	$\frac{\rho}{2}L^2u^2$	5.0748E-4

2. Equations of motion

2.1. Coordinate systems

Since a cylindrical type underwater vehicle has port-starboard and fore-aft symmetries, we considered only the horizontal motion, which is more critical for accomplishing its anti-torpedo mission. In addition, roll is assumed to be completely controlled by a well-tuned controller.

In order to analyze the dynamic characteristics of an

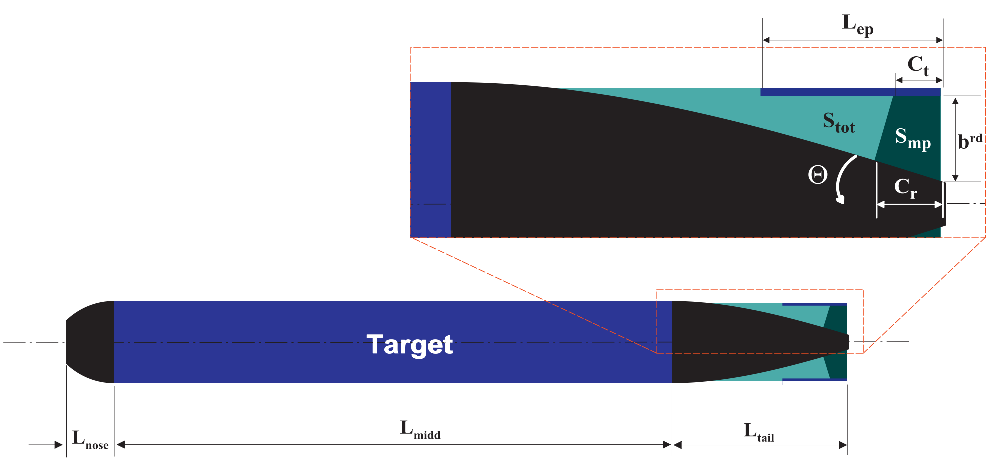


Fig. 3. Target hull shape and symbol definitions.

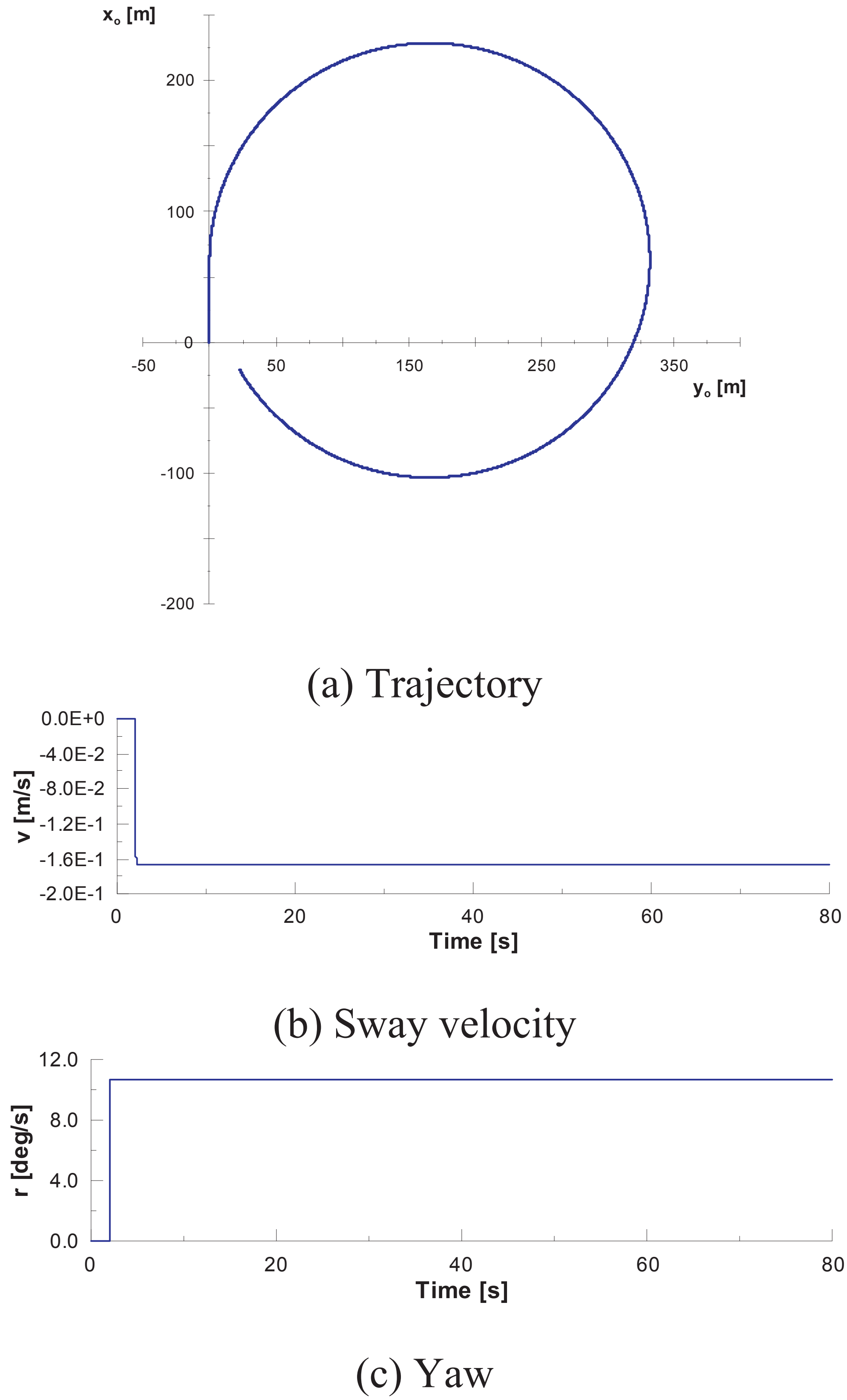


Fig. 4. Turning maneuver.

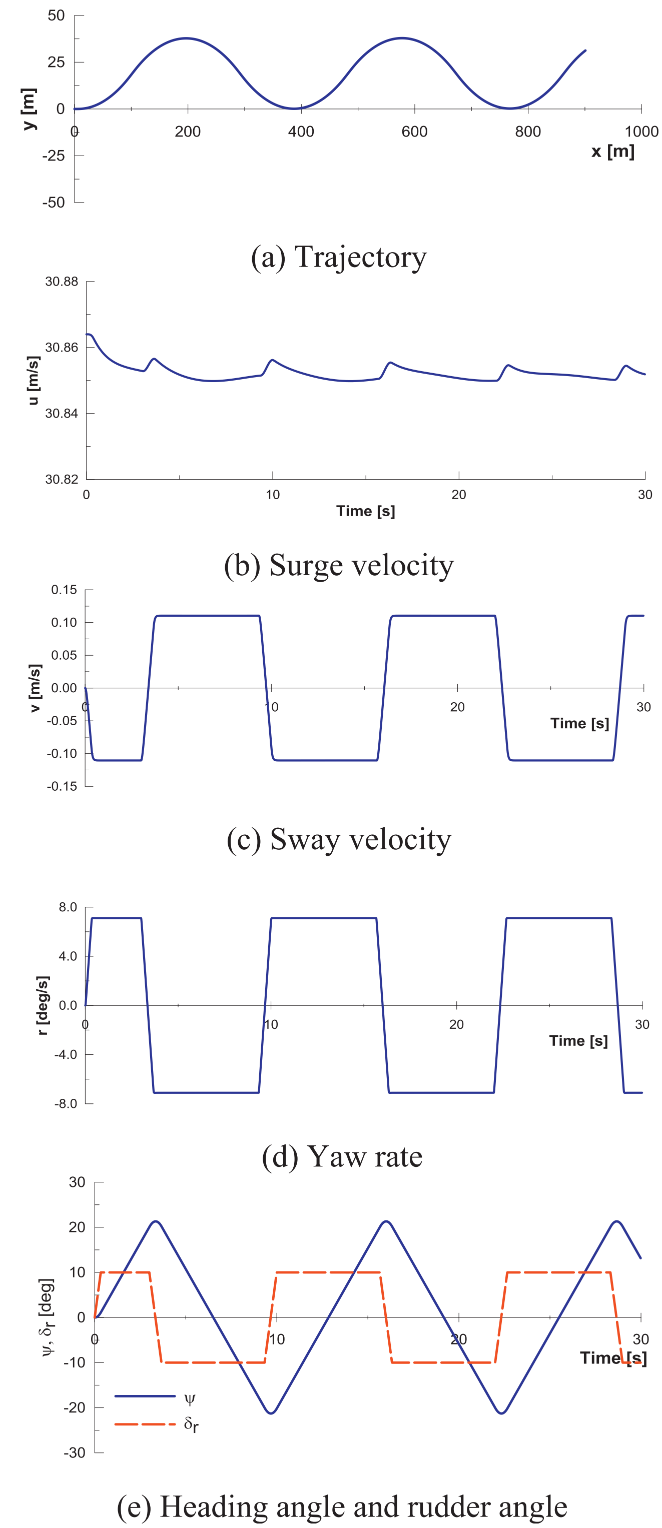


Fig. 5. The 10–20 Zig-zag maneuver.

underwater vehicle in the horizontal plane, three DOF equations of motion, such as surge, sway, and yaw, should be described with respect to a coordinate system. Two coordinate systems were adopted. One is the earth-fixed frame ($O - x_0 y_0$) for representing the trajectory and heading angle, while the other is the body-fixed frame ($O - xy$) for describing the equations of motion, as shown in Fig. 2. The origin of the earth-fixed frame is an arbitrary point in space, and the origin of the body-fixed frame is defined at the geometric center, like the cross-sectional point of center plane and midship plane. x and y axes are positive in the fore and starboard directions, respectively.

2.2. Equations of horizontal motion

Since the hydrodynamic force and moment acting on a maneuvering underwater vehicle are easily modeled from the viewpoint of its body, the equations of horizontal motion are described as follows:

$$\begin{aligned} & m\left(\dot{u} - vr - x_G r^2\right) = X_{HD} + X_T \\ & m(\dot{v} + ur + x_G \dot{r}) = Y_{HD} + Y_\delta \\ & I_z \dot{r} + m x_G (\dot{v} + ur) = N_{HD} + N_\delta \end{aligned} \tag{1}$$

where, subscripts HD, T, and δ mean the hydrodynamic force, thrust, and rudder force, respectively. The dot over the motion variable is the time derivative.

2.3. Modeling of external force

The target underwater vehicle moves so rapidly that the drift angle is very small during its maneuvering, and the hydrodynamic force could be modeled by linear stability and control coefficients.

Hydrodynamic force and moment are modeled using added mass coefficients and linear damping coefficients, which are the so-called stability coefficients, as follows:

$$\begin{aligned} & X_{HD} = X_{\dot{u}} \dot{u} + X_{uu} u^2 \\ & Y_{HD} = Y_{\dot{v}} \dot{v} + Y_{\dot{r}} \dot{r} + Y_v v + Y_r r \\ & N_{HD} = N_{\dot{v}} \dot{v} + N_{\dot{r}} \dot{r} + N_v v + N_r r \end{aligned} \tag{2}$$

$X_{\dot{u}}$, $Y_{\dot{v}}$, …, N_r are estimated by the empirical formula suggested by Lamb (Fossen, 1994) and HDW (2002). Horizontal gain margin (HDW, 2002) which is calculated by stability coefficients such as Y'_v, Y'_r, N'_v, and N'_r in Table 2 is 1.0015 and it is larger than the recommended value 0.2–0.4 for a submarine. So, target torpedo is highly straight-line stable and the linearity of its nominal dynamics can be guaranteed. If the $X_{uu}u^2$ term, which is the drag acting on an underwater vehicle, does not change much during maneuvering, its magnitude can be assumed to be the same as the thrust X_T, and the direction is opposite to the thrust.

Similarly, the control force can be modeled using control coefficients, as follows:

$$\begin{aligned} & X_\delta = 0 \\ & Y_\delta = Y_{\delta_r} \delta_r \\ & N_\delta = N_{\delta_r} \delta_r \end{aligned} \tag{3}$$

Y_{δ_r} and N_{δ_r} are estimated by the empirical formula suggested by HDW (2002).

The empirical formulae of the damping coefficients and control coefficients are estimated after assuming that the body, including rudder, is regarded as an equivalent fin.

3. Dynamic characteristics

3.1. Target underwater vehicle

Myring (1976) suggested the cylindrical-type underwater vehicle that has the smallest drag. Its bare hull consists of nose, parallel middle body, and tailcone, and its control fin of fixed and movable parts is attached on the end of the tailcone, as shown in

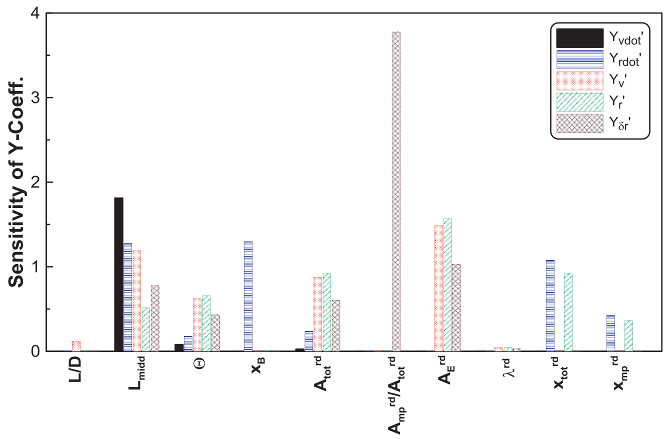


Fig. 6. Sensitivity of the sway hydrodynamic coefficients with respect to the hull form parameters.

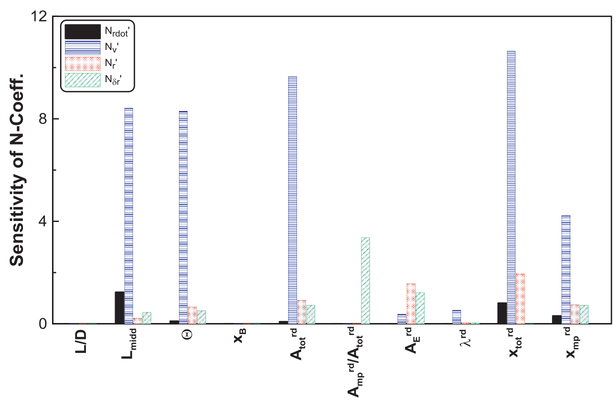


Fig. 7. Sensitivity of the yaw hydrodynamic coefficients with respect to the hull form parameters.

Fig. 3. We adopted this hull form as the basic target underwater vehicle.

Table 1 lists the basic principal dimensions, and the symbols are defined in Fig. 3. Table 2 lists the nondimensional hydrodynamic coefficients estimated by the empirical formulae in HDW (2002).

3.2. Turning and course changing ability

Fig. 4 shows the turning simulation result for 15° rudder deflection. The steady turning rate is 10.6°/s, and the sway velocity is about 0.16 m/s. Fig. 5 shows the 10–20 zig-zag simulation result. The 10–20 zig-zag means that the rudder is deflected first to 10°, and waits up to 20° of heading angle, and then the rudder is deflected to the opposite 10°, and so on, as shown in Fig. 5 (e). The indices representing course changing ability are the 1st and 2nd overshoot angles, which are defined as the difference between the heading angle and the predefined heading angle, which is 20° in this 10-20 zig-zag maneuver. These overshoot angles are 1.312° and 1.310°, respectively.

4. Sensitivity analysis

Sensitivity analysis is widely used to estimate how much the output would be changed by uncertain change of input, or what is the input that would most affect the output. Since most natural systems are not modeled by linear systems, there are two kinds of sensitivities: global, and local ones. In our case, the change of optimal design hull form parameters near the basic values are decided, so the local sensitivity is considered, which is represented by the partial derivative of the output variable with respect to the input variable.

The partial derivative could be directly derived from the explicit function form, while sometimes it could be numerically derived from the implicit relationship between input and output, as follows:

$$\frac{\partial y}{\partial x} \approx \frac{y(x+\Delta x) - y(x)}{\Delta x} \tag{4}$$

where, x and y are the input and output, respectively.

Fig. 1 shows that the final sensitivity of the dynamic characteristics with respect to the hull form design parameters is calculated by the chain rule of partial sensitivities of the hydrodynamic coefficients with respect to the hull form parameters, and the dynamic characteristics with respect to the hydrodynamic coefficients, as follows:

$$S_G^M = S_H^M S_G^H \tag{5}$$

The hull form parameter vector consists of two sub-vectors, i.e. the bare hull and rudder related ones, as follows;

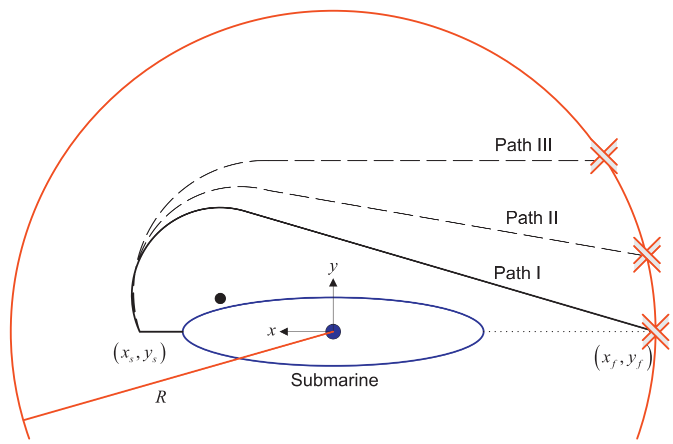


Fig. 8. Mission scenario of the target underwater vehicle.

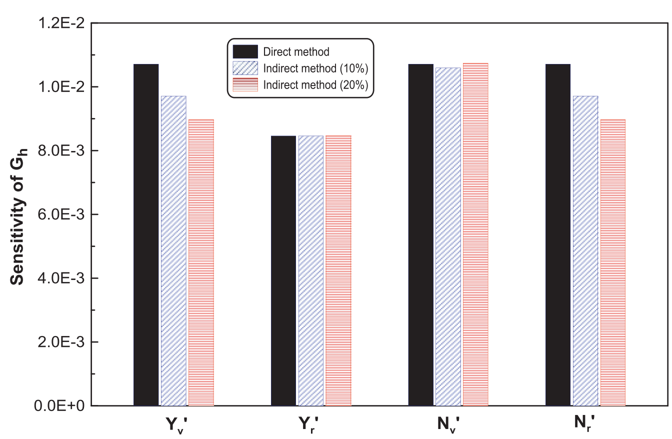


Fig. 9. Sensitivity of the course-keeping stability margin with respect to the hydrodynamic coefficients.

$$\underline{G} = \begin{bmatrix} \underline{G}_{bh}^{T} & \underline{G}_{rd}^{T} \end{bmatrix}^{T} \tag{6}$$

where,

$$\underline{G}_{bh} = [L/D \quad L_{midd} \quad \Theta \quad x_B]^T$$
$$\underline{G}_{rd} = \begin{bmatrix} A_{tot}^{rd} & A_{mp}^{rd}/A_{tot}^{rd} & A_E^{rd} & \lambda^{rd} & x_{tot}^{rd} & x_{mp}^{rd} \end{bmatrix}^T$$

4.1. Partial sensitivity of the hydrodynamic coefficient

The hydrodynamic coefficients in Eqs. (2) and (3) are defined as the outputs of the empirical formula or tables (Fossen, 1994; HDW, 2002) from the inputs of the hull form parameters, as follows:

$$\underline{H} = \begin{bmatrix} Y'_{\dot v} & Y'_{\dot r} & Y'_v & Y'_r & Y'_{\delta_r} & N'_{\dot v} & N'_{\dot r} & N'_v & N'_r & N'_{\delta_r} \end{bmatrix}^T \tag{7}$$

Partial sensitivity of the hydrodynamic coefficient with respect to the hull form parameter is defined as the Jacobian matrix and normalizing matrices, as:

$$S_G^H = N_H^{-1} \frac{\partial \underline{H}}{\partial \underline{G}} N_G \tag{8}$$

$$\text{where, } N_H = \begin{bmatrix} |Y'_{\dot v}| & 0 & \cdots & 0 \\ 0 & |Y'_{\dot r}| & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & \cdots & |N'_{\delta_r}| \end{bmatrix}$$

$$\frac{\partial \underline{H}}{\partial \underline{G}} = \begin{bmatrix} \frac{\partial Y'_{\dot v}}{\partial (L/D)} & \frac{\partial Y'_{\dot v}}{\partial L_{midd}} & \cdots & \frac{\partial Y'_{\dot v}}{\partial x_{mp}^{rd}} \\ \frac{\partial Y'_{\dot r}}{\partial (L/D)} & \frac{\partial Y'_{\dot r}}{\partial L_{midd}} & \cdots & \frac{\partial Y'_{\dot r}}{\partial x_{mp}^{rd}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial N'_{\delta_r}}{\partial (L/D)} & \frac{\partial N'_{\delta_r}}{\partial L_{midd}} & \cdots & \frac{\partial N'_{\delta_r}}{\partial x_{mp}^{rd}} \end{bmatrix}$$

$$N_G = \begin{bmatrix} |L/D| & 0 & \cdots & 0 \\ 0 & |L_{midd}| & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & \cdots & |x_{mp}^{rd}| \end{bmatrix}$$

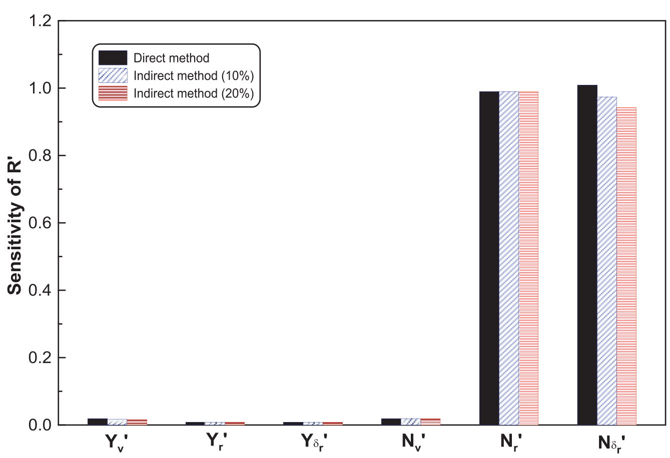


Fig. 10. Sensitivity of the nondimensional turning radius with respect to the hydrodynamic coefficients.

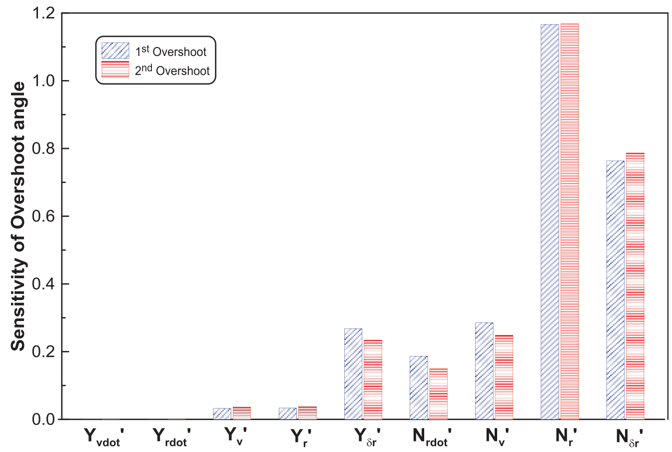


Fig. 11. Sensitivity of the overshoot yaw angle with respect to the hydrodynamic coefficients.

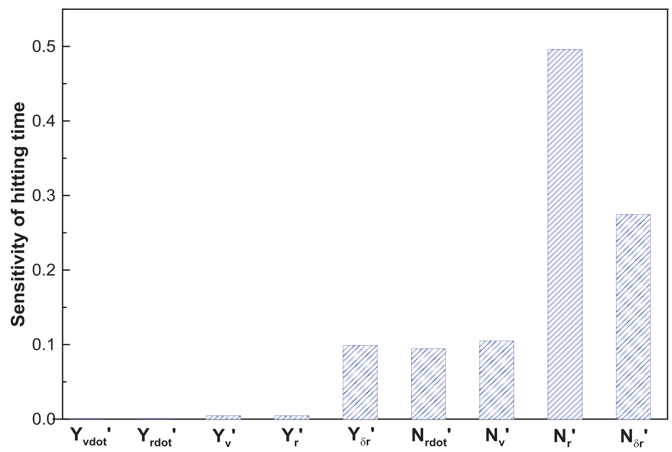


Fig. 12. Sensitivity of the intercept time with respect to the hydrodynamic coefficients.

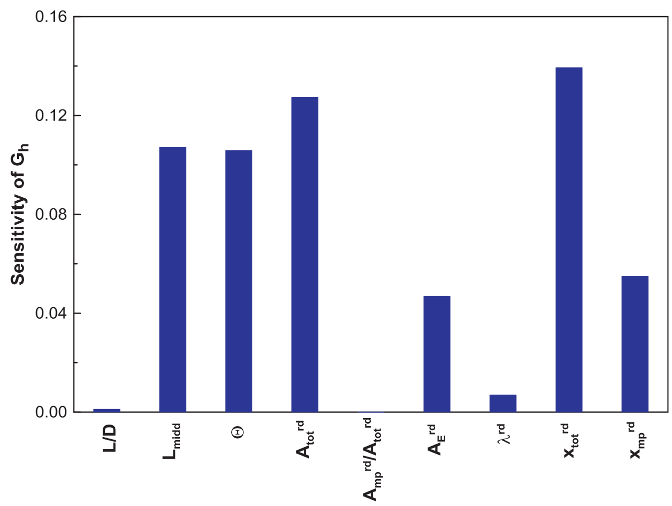


Fig. 13. Sensitivity of the course-keeping stability margin with respect to the hull form parameters.

Normalizing matrices N_H and N_G should be defined, in order to compare the sensitivities of different magnitude values of the hydrodynamic coefficients and the hull form parameters. The

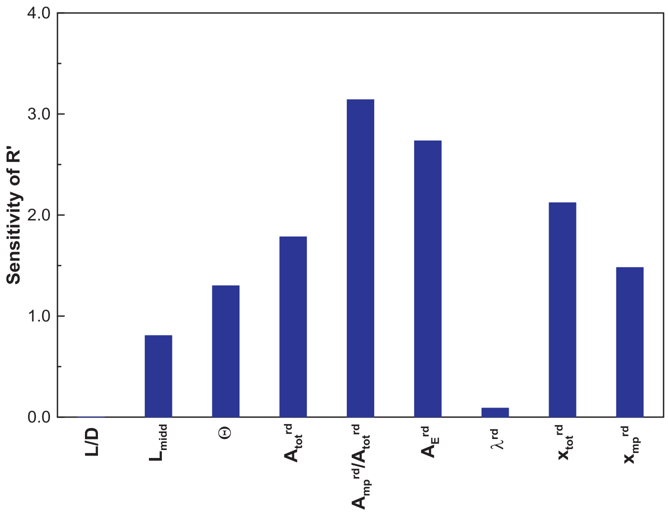


Fig. 14. Sensitivity of the nondimensional turning radius with respect to the hull form parameters.

elements of the matrices are set as the nominal values of the target underwater vehicle.

Fig. 6 shows the sensitivity of Y hydrodynamic coefficients with respect to the hull form parameters. The sway added mass coefficients, such as $Y'_{\dot{v}}$ and $Y'_{\dot{r}}$, are sensitive to the length of the parallel middle body, while the stability coefficients of Y'_v and Y'_r are sensitive to the tailcone angle, total rudder area, aspect ratio, and the distance of the center of rudder. In addition, the effect of rudder related parameters on the sensitivities of Y'_v and Y'_r are a little greater than the effect of the bare hull related parameters. Y'_{δ_r} shows the largest sensitivity to the movable rudder area ratio.

Fig. 7 shows the sensitivity of the N hydrodynamic coefficient with respect to the hull form parameters. The added mass moment of inertia coefficient of $N'_{\dot{r}}$ is not sensitive to any hull form parameters, which means that it cannot be changed so much, despite any changes of the hull form parameters. The most important stability coefficient of N'_v is sensitive to the length of the parallel middle body, tailcone angle, total rudder area and the distance to the center of the rudder area. If the parallel middle body becomes longer, the distance to the center of the rudder area is also longer; and if the tailcone angle becomes smaller, the total rudder area is also greater. Therefore, N'_v is considered to be very sensitive to the rudder related parameters. Naturally, N'_{δ_r} is mainly affected by the movable rudder area ratio, similar to the case of Y'_{δ_r}.

Since the magnitudes of the sensitivities of N coefficients are greater than those of the Y coefficients, it is more effective that a designer changes the N coefficient in order to achieve the same goal, which could be changed with the same level of combination of sway and yaw coefficients.

4.2. Partial sensitivity of the dynamic characteristics

Dynamic characteristics can be represented by the course-keeping stability, turning ability, yaw-checking ability, and mission competence. We selected the mission of the target underwater vehicle to be the intercept of an attacking underwater vehicle that is approaching us. There could be various situations, depending on the approaching direction. The worst scenario, which is Path I in Fig. 8, is that a threat approaches from our back, and such situation requires the best maneuverability of the target underwater vehicle. The target underwater vehicle exits from the tube of the mother ship, and it moves straight forward to (x_s, y_s). It turns about 180° backward, and intercepts the threat at (x_f, y_f).

Therefore, the performance indices of the course-keeping stability, turning ability, yaw-checking ability, and mission competence are defined as gain margin, steady turning radius, 1st and 2nd overshoot yaw angle, and maximum intercept time, as follows:

$$\underline{M} = \begin{bmatrix} G_h & R' & \psi_1 & \psi_2 & T_{op} \end{bmatrix}^T \tag{9}$$

where, $G_h = 1 - \frac{N'_v(Y'_r - m')}{Y'_v(N'_r - m'x'_G)}$,

$$R' = -\frac{1}{\delta_r}\left\{\frac{Y'_v N'_r - N'_v(Y'_r - m')}{Y'_v N'_{\delta_r} - N'_v Y'_{\delta_r}}\right\}$$

Partial sensitivity of the dynamic characteristics with respect to the hydrodynamic coefficient is defined as the Jacobian matrix and normalizing matrices, as:

$$S_H^M = M_H^{-1}\frac{\partial \underline{M}}{\partial \underline{H}} N_H \tag{10}$$

where, $M_H = \begin{bmatrix} |G_h| & 0 & \cdots & 0 \\ 0 & |R'| & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & \cdots & |T_{op}| \end{bmatrix}$

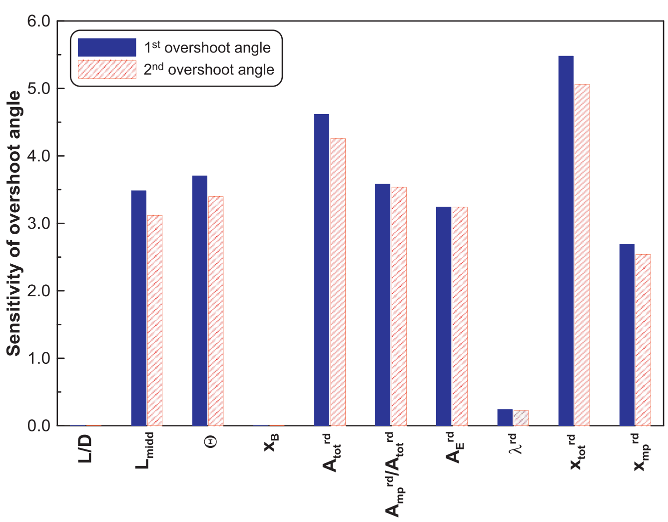


Fig. 15. Sensitivity of the overshoot yaw angle with respect to the hull form parameters.

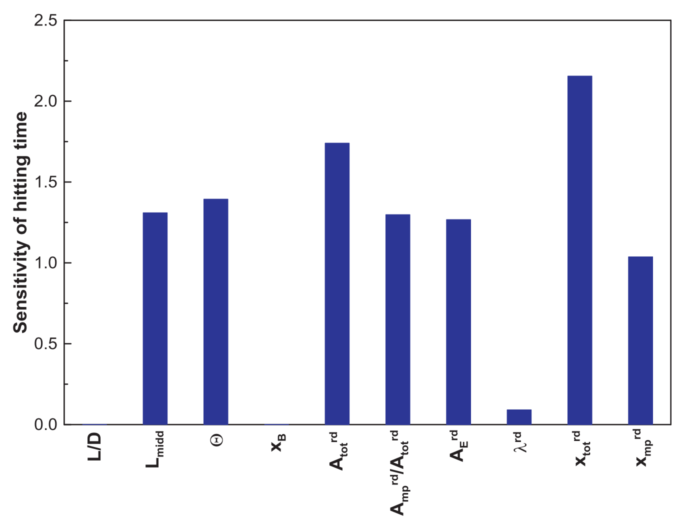


Fig. 16. Sensitivity of the intercept time with respect to the hull form parameters.

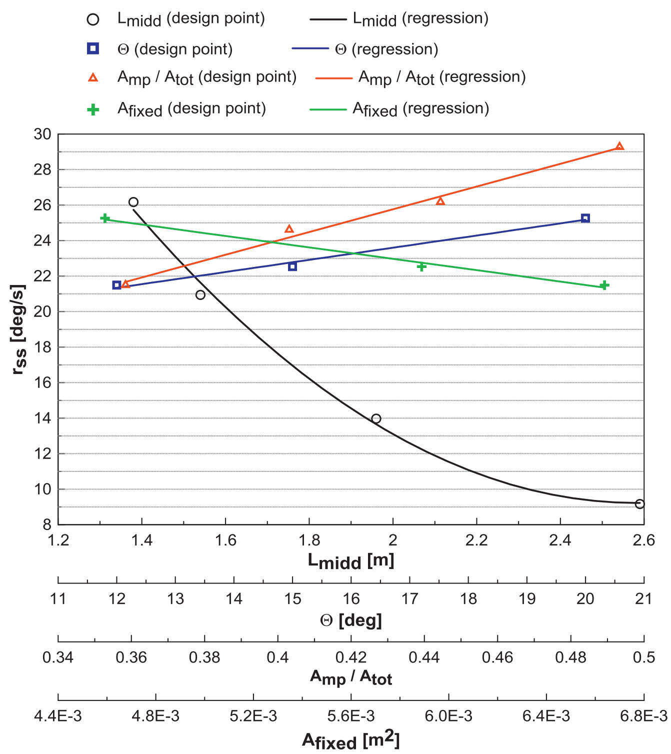


Fig. 17. Regression results of the steady turning rate with respect to the design parameters.

$$\frac{\partial \underline{M}}{\partial \underline{H}} = \begin{bmatrix} \frac{\partial G_h}{\partial Y'_{\dot{v}}} & \frac{\partial G_h}{\partial Y'_{\dot{r}}} & \cdots & \frac{\partial G_h}{\partial N'_{\delta_r}} \\ \frac{\partial R'}{\partial Y'_{\dot{v}}} & \frac{\partial R'}{\partial Y'_{\dot{r}}} & \cdots & \frac{\partial R'}{\partial N'_{\delta_r}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial T_{op}}{\partial Y'_{\dot{v}}} & \frac{\partial T_{op}}{\partial Y'_{\dot{r}}} & \cdots & \frac{\partial T_{op}}{\partial N'_{\delta_r}} \end{bmatrix}$$

The sensitivities of the dynamic characteristics with respect to the hydrodynamic coefficients are calculated by the so-called direct method and indirect method. The direct method can be applied to the case where the explicit formula for dynamic characteristics depending on the hydrodynamic coefficients exist, for example, the gain margin and steady turning radius, as described in Eq. (9). In this case, sensitivity is defined by the partial derivative of a performance index with respect to a hydrodynamic coefficient. Since there are not any explicit formulae for the overshoot yaw angles of the zig-zag test and intercept time for the mission scenario shown in Fig. 8, the change of a performance index due to the change of hydrodynamic coefficient is calculated by numerical simulation.

Figs. 9–12 show the sensitivities of dynamic characteristics with respect to the hydrodynamic coefficients. Both the direct method and the indirect method are applied in the case of the gain margin and the steady turning radius, and the indirect method only is applied to the overshoot yaw angles and intercept time.

Fig. 9 shows that the hydrodynamic coefficients, Y'_v, N'_v, and N'_r, are more sensitive than Y'_r. In addition, the difference between the direct method and the indirect method was analyzed. Since the maximum error of the indirect method is within about 15%, the indirect method can be assumed to give valid approximate sensitivity values. The magnitude of the difference depends on the

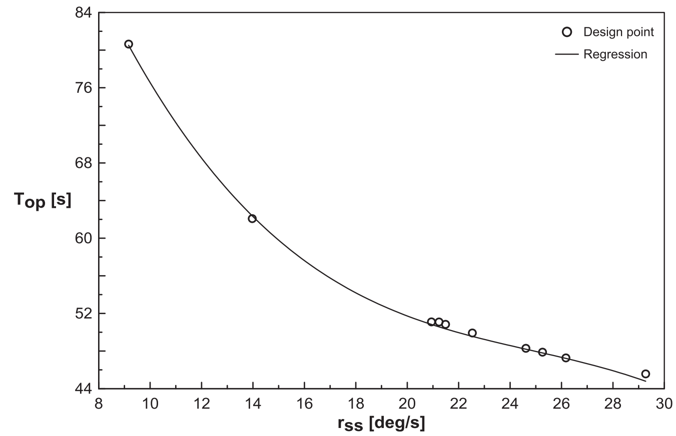


Fig. 18. Regression result of the intercept time with respect to the steady turning rate.

Table 3
Values of design parameters of the target and candidate underwater vehicles.

Name	$\Theta[^\circ]$	L_{midd}[m]	A^{rd}_{mp}/A^{rd}_{tot}	x^{rd}_{tot}[m]
Target	18	1.38	0.392	−0.90
SB_Opt1	12	1.38	0.567	−0.90
SB_Opt2	12	1.54	0.606	−0.98

hydrodynamic coefficient, and a 10% change of the hydrodynamic coefficient is more consistent with the result of the direct method. Therefore, 10% change has been applied to calculate the sensitivity using the indirect method.

The turning ability is mainly influenced by the yaw moment related coefficients, such as N'_r and N'_δ, as shown in Fig. 10. This means that in order to increase the turning ability, a designer should make an effort to increase N'_r and N'_δ. Fig. 11 shows the sensitivity of the yaw-checking ability, and it is mainly affected by the yaw moment related coefficients, as well. The sensitivity of the mission competence is very similar to the sensitivity of the yaw-checking ability, and both performance indices are the most sensitive to N'_r and N'_δ, as in the case of the turning ability.

4.3. Total sensitivity of the dynamic characteristics

The sensitivity of the dynamic characteristics with respect to the hull form parameter is defined as the total sensitivity of the partial sensitivities of the hydrodynamic coefficients and the dynamic characteristics. The total sensitivity is calculated by a chain rule, as follows:

$$S^M_G = S^H_G S^M_H \tag{11}$$

Figs. 13–16 show the sensitivities of the dynamic characteristics with respect to the hull form parameters.

In order to increase the course-keeping stability, it is most

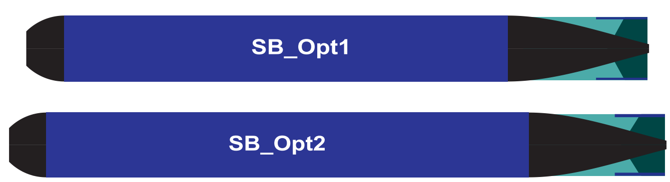
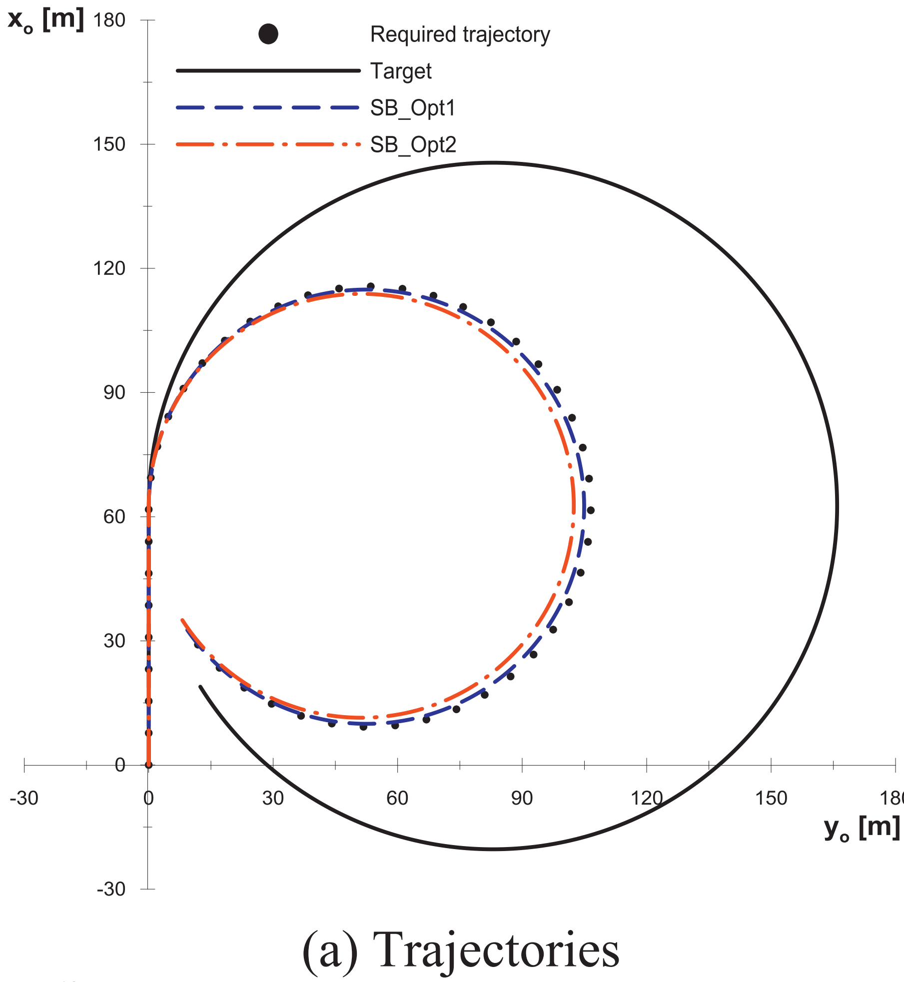


Fig. 19. Hull forms of candidate underwater vehicles.



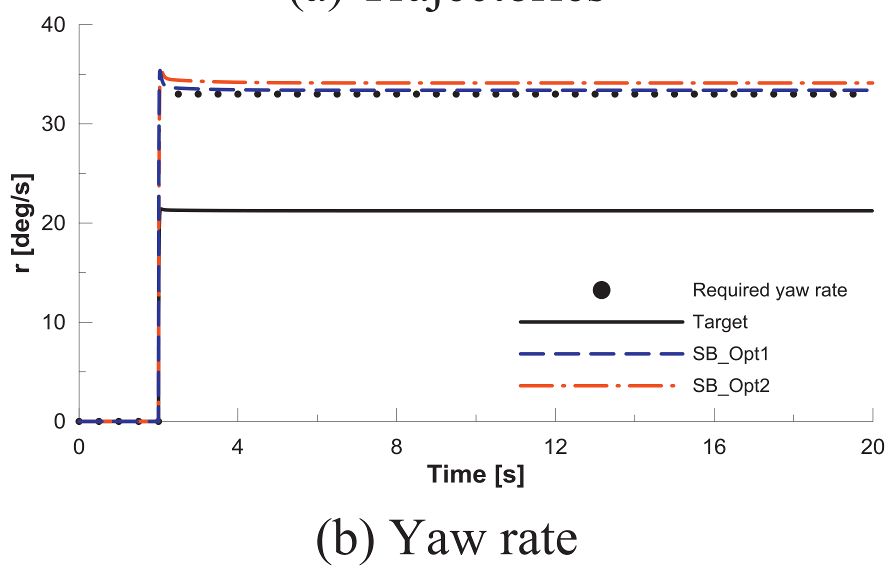
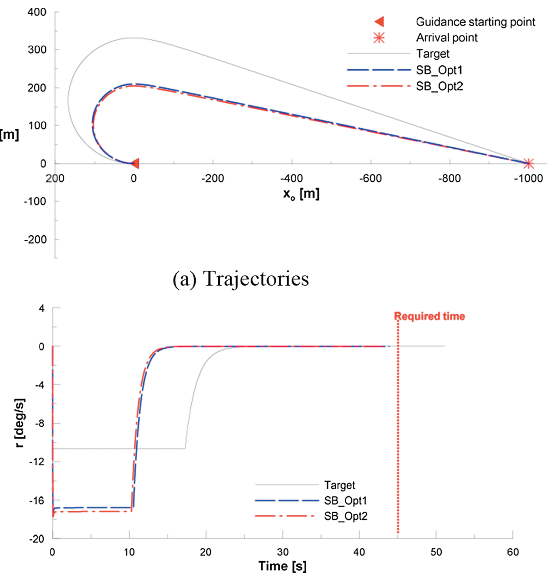


Fig. 20. Simulation results of the turning maneuver.

effective to increase the distance from the origin to the center of rudder area. In addition, the larger the rudder area is, the better the course-keeping stability is. Fig. 14 shows that the movable rudder area and its aspect ratio are sensitive to the turning ability. Fig. 15 shows that the sensitivity changing characteristics of both the 1st and the 2nd overshoot yaw angles are the same, and the length of the parallel middle body and the tailcone angle, as well as the rudder-related parameters, also affect the yaw-checking ability. Fig. 16 shows again that the current mission competence is very similar to the yaw-checking ability.



(a) Trajectories

(b) Yaw rate

Fig. 21. Simulation results of the mission scenario.

5. Design of the underwater vehicle

5.1. Performance criterion and design parameters

In order to optimally design the principal dimensions of the hull form parameters, the performance criterion should be defined. The mission competence is chosen as the representative of the performance, and its quantity is set to be the intercept time. It was assumed that the target underwater vehicle should intercept a threat within at least 45 s. The intercept time of the original target underwater vehicle, of which the principal dimensions are listed in Table 1, is 51.1 s.

Based on the sensitivity analysis, the length of the parallel middle body, tailcone angle, movable area ratio, and fixed rudder area were selected as design parameters. The length of the parallel middle body could include the effect of the distance of center of rudder area, which is the most important parameter for the dynamic characteristics.

5.2. Regression analysis

We changed the nominal values listed in Table 1 of the design parameters, and calculated the steady turning rate, and the intercept time of mission scenario. Fig. 17 shows the relationship between the design parameters and the steady turning rate, which is the conventional system requirement, and those regression formulae are as follows:

$$\begin{aligned} r_{ss} &= 0.48\Theta + 15.59 \\ r_{ss} &= 11.41L_{midd}^2 - 58.93L_{midd} + 85.34 \\ r_{ss} &= 55.96A_{mp}^{rd}\Big/A_{tot}^{rd} + 1.61 \\ r_{ss} &= -1872.5A_{fixed}^{rd} + 33.78 \end{aligned} \tag{12}$$

Since one design parameter is correlated to the other design parameter, it is more convenient for a designer to decide one parameter by using a single variate regression formula like Eq. (12), instead of a multivariate regression formula.

Fig. 18 shows the relationship between the intercept time, which was decided as the performance criterion, and the steady turning rate, which is the output of the regression formula in Eq. (12). The intercept time is nonlinearly related to the steady turning rate, and this relationship is regressed as follows;

$$T_{op} = -0.006r_{ss}^3 + 0.44r_{ss}^2 - 11.43r_{ss} + 153.87 \tag{13}$$

In order to satisfy the performance criterion of the intercept time at mission scenario, the maximum steady turning rate should be 33°/s.

5.3. Optimal movable rudder area ratio

The values of several design parameters are dependent. For example, if the tailcone angle decreases, the fixed rudder area increases, and their effects on the steady turning rate are opposite, as shown in Fig. 17. For this reason, we set that the tailcone angle to be 12° to remove both parameters of tailcone angle and fixed rudder area. The length of parallel middle body should be selected after considering the length of the firing tube, and the system constraints, like enduring time. We set two cases. One is the same value as the target underwater vehicle (SB_Opt1), and the other one (SB_Opt2) is the value where L/D is 10. If the length of the parallel middle body increases, the steady turning rate decreases, as shown in Fig. 17. Since the amount of increasing value of the parallel middle body is small, it is assumed that the reduced rate can be compensated by the increase of movable rudder area ratio using Eq. (12).

Table 3 lists the design parameters of the target and candidate upgrade underwater vehicles of which the hull forms are shown in Fig. 19. The distance of the center of the fixed rudder area is simultaneously extended with the extension of the length of the parallel middle body.

Figs. 20 and 21 show the simulation results of the turning test and the mission scenario of the target and candidate underwater vehicles. Both candidate underwater vehicles satisfy the requirements of the maximum steady turning rate in turning maneuver, and the intercept time of the mission scenario.

6. Conclusion

In this paper, the changes of the dynamic characteristics of an underwater vehicle performing a specific mission due to the change of the design parameters are estimated by sensitivity analysis. The dynamic characteristics are classified into course-keeping stability, turning ability, yaw-checking ability, and mission competence. Mission competence is assumed to be the intercept of a threat within the required time. The sensitivities of the dynamic characteristics with respect to the hull form parameters are calculated by the chain rule, using the partial sensitivity of the dynamic characteristics with respect to the hydrodynamic coefficients, and the partial sensitivity of the hydrodynamic coefficients with respect to the hull form parameters.

The turning ability and mission competence are mainly affected by the yaw moment related coefficients, such as N'_r and N'_{δ_r}, and these coefficients are mainly affected by the movable rudder area ratio, and the distance from the origin to the center of the rudder area. Based on these sensitivity analyses, we selected four design parameters, i.e. the tailcone angle, the length of the parallel middle body, the movable rudder area ratio, and the fixed rudder area. In addition, the intercept time of the specific mission scenario is regressed by the steady turning rate, and the steady turning rates are regressed by the candidate hull form parameters. The movable rudder area ratios of the candidate underwater vehicles were calculated by regression formula, and it was confirmed that the candidate underwater vehicles satisfy the required intercept time.

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