Elsevier Editorial System(tm) for European Journal of Mechanics - B/Fluids
Manuscript Draft

Manuscript Number: EJMFLU-D-15-00015R1

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Article Type: Original Research Paper

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Experimental study on the hydrodynamic forces and moments acting on a ROV with an asymmetrical shapes moving in a vertical plane

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ABSTRACT

Hydrodynamic models and coefficients are important parameters for predicting the maneuverability of the ROV (Remotely Operated Vehicle). This paper will present an experimental study on the hydrodynamic behaviors of a new ROV that has an asymmetrical shape but has a large capacity holding more instruments on board than other ROVs. A series towing tests has been carried out on this ROV moving in a vertical plane. This paper will give the fitting formulae of forces and moments, and corresponding hydrodynamic coefficients, which can be used for simulating the motions and so for predicting the maneuverability of the ROV, and will also discuss the effects of asymmetry in its shapes on its hydrodynamic coefficients.

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1. Introduction

Underwater vehicles can be applied to ocean resource exploration and exploitation, pipeline inspection and offshore structure maintenance, seafloor geography mapping, and so on. There are two kinds of underwater vehicles for such applications: Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) [1]. Generally speaking, AUVs have simple and watertight hulls, similar in many cases to conventional submarines, operating at relatively high speeds; in contrast, ROVs have relatively complex and open-frame hulls, operating at relatively low speed. This paper is mainly concerned about ROVs.

Hydrodynamics of ROVs are important for controlling their motions and predicting their performances in sea. At present, their hydrodynamic properties are mainly studied by carrying out experiments. That is perhaps because their hull geometries are generally very complex and it is difficult and very time consuming to perform numerical computations. In addition, unlike conventional submarines having roughly similar hulls, each ROV has its unique hull geometry that is generally different from others. Due to this, there are no common hydrodynamic properties that can apply to all ROVs. One needs to carry out study on hydrodynamics for each ROV. Due also to this, there is lack of common dynamics mathematical models that can be applied to all ROVs [2].

The most commonly accepted dynamics model for conventional submarines can be traced to a series of studies performed at DTNSRDC (David Taylor Naval Ship Research and Development Centre) [3] [4]. This dynamical model (known as the DTNSRDC standard submarine equations of motion) has been used for predicting the motions of not only conventional submarines, but also some underwater vehicles such as [5] for AUV and [6], [7] and [8] for the ROVs. However, the DTNSRDC dynamical model is originally proposed for conventional submarines, where the hydrodynamic forces are assumed to be related to the square of velocities. For ROVs, it may move at a low speed and the linear part (proportional to the one order of speed) of hydrodynamic force and moment may play a role and may not be ignored.

In many publications, the dynamic model for ROV was simplified as one without off-diagonal drag entries and ignores influence of motion in one direction on the hydrodynamics in other directions by assuming that vehicles have three symmetrical planes, e.g., [9][10] and [11]. Associated hydrodynamic coefficients were obtained by model tests (e.g.[12][13][14][15][16]) and computational fluid dynamics (e.g. [17]). Besides, the reference [18] discussed the hydrodynamic properties of a submersible with an aerofoil for forward and backward motions, and the work in [6] and [19] conducted towing tests for ROV models moving in forward and backward, starboard and portside, upward and downward directions. In these papers and others in literature, the effects of asymmetrical ROV shape on its hydrodynamic properties are rarely studied as far as we know.

This paper will present an experimental study on the hydrodynamic behaviors of a new ROV similar to the Quantum designed by SMD [20]. This ROV has more capacity than others and allows additional sensors and equipments to be mounted on board. The vehicle has a complex open-framed hull and is front-rear and top-bottom asymmetrical. In this paper, we will present the study on the hydrodynamics associated with surge and heave motions with particular attention on the effects of the front-rear and top-bottom asymmetry of its hull, and suggest a dynamic model which takes into account of the front-rear and top-bottom asymmetry.

The remainder of this paper is organized as follows. In Section 2, the model and test facilities and procedure will be described. Section 3 presents the data processing method. Then the experimental results is given and discussed in Section 4. Finally, the conclusions are summarized in Section 5.

2. Test model, experimental facilities and procedures

The test model of the ROV is illustrated in Fig. 1. The frame structure is made of steel, while the other components within the frame, such as thruster and equipment blocks are made of buoyancy material. Its main parameters are summarized in Table 1. The test model is front-rear and top-bottom asymmetrical (more details may be found in Fig. 4).

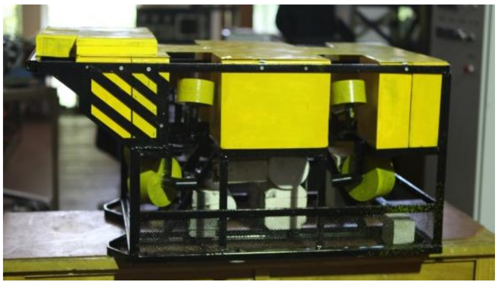


Fig. 1. Test model

Table 1
Parameters of test model

Physical property	Value
Scale ratio	1:4
length, m	0.875
width, m	0.5
height, m	0.5
mass in air, kg	78

In many situations, the ROV will be operated to move up and down (referred as to the heave direction), such as during the launch stage, and forward and backward (referred as to the surge direction), such as during the search stage on the sea bed. This paper will mainly study the properties of forces and moments acting on the ROV in such situations. For this purpose, a series of model tests in surge and heave directions with constant towing speeds have been carried out. The experiments are carried out in two facilities of Harbin Engineering University. The surge tests are undertaken in circulating water channel (the model placed in it as shown in Fig. 2), which has a cross-section of 1.7m wide and 1.5m deep with the velocity of flow. During the surge tests, the test model is stationary and water flows forward or backward relative to the model. The heave towing tests are carried out in a large water tank of 50m long, 30m wide and 10m deep (the model placed in it as shown in Fig. 3). During the tests, water was stationary, while the test model is towed with constant speeds. In both kinds of the tests, the relative speeds between water and the model are changed in a range (specific values are given below), and the tests are repeated several times at each value of speeds. The forces and moments acting on the test model are measured using a six-component force transducer.

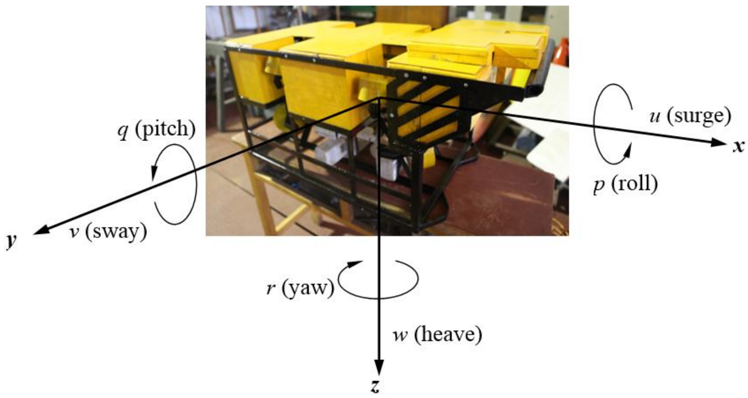
Fig. 2. Model test in circulating water channel

Fig. 3. Model test in a tank

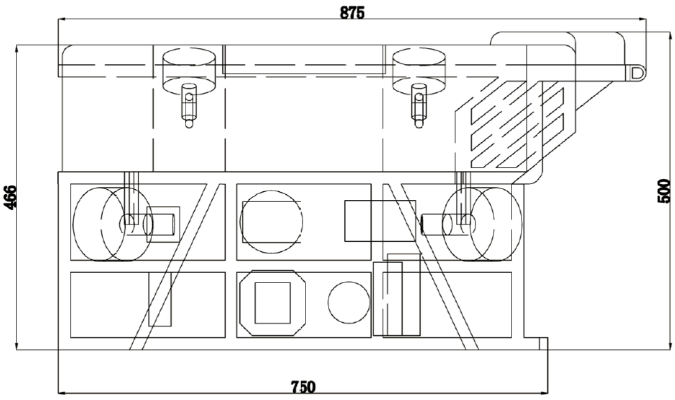
3. Data processing

3.1 Expressions of forces and moments on the model

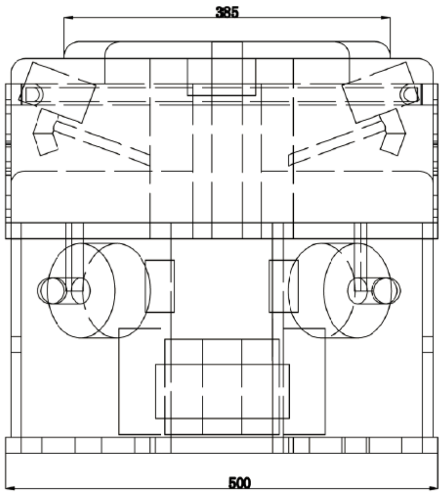
For convenience of describing the forces and motions, the coordinate system is set up as shown in Fig. 4. In the figure, u, v and w denotes the linear velocities in the surge, sway and heave directions with their corresponding forces represented by X, Y and Z, respectively. In addition, p, q and r denote the angular velocities in roll, pitch and yaw directions with K, M and N to be corresponding moments, respectively.



(a) Coordinate system



(b) Section at y=0



(c) Section as x=0

Fig. 4. Coordinate system and illustration of two mid-plane sections

For an underwater vehicle moving in the deep water at a constant speed, without taking the surface water effect into consideration, the hydrodynamic forces and moments are caused by the fluid viscosity, depending on its geometry and its motion velocities. Generally, they may be expressed as:

$$\vec{F}_D = \vec{F}_D(\vec{U}) \quad (\vec{F}_D = \{X, Y, Z, K, M, N\};\ \vec{U} = \{u, v, w, p, q, r\}).$$

Using the similar method to that in [21], the components of the forces and moments can be expressed by the multivariate Taylor series of the velocities. If we may just take the series to the second order, the forces and moments due to the motion in the surge and heave motions may be expressed as

$$X = X_u u + X_{uu} u^2 + X_w w + X_{ww} w^2 \tag{1a}$$
$$Z = Z_u u + Z_{uu} u^2 + Z_w w + Z_{ww} w^2 \tag{1b}$$
$$M = M_u u + M_{uu} u^2 + M_w w + M_{ww} w^2 \tag{1c}$$

As indicated above, the vehicle is front-rear and top-bottom asymmetrical, which is further illustrated in Fig. 4 by using two mid-plan, the motion in the surge direction may induce the force in the vertical (heave) direction and the moment in the pitch direction. Similarly, the motion in the heave direction can also induce the force in the surge direction and the moment in the pitch direction. These effects have been reflected in Eq. (1). The comments of the forces and moments due to asymmetry are often ignored in literature. Their properties are particularly interested in this paper.

For the motion only in one direction, the forces and moments acting on the vehicle can be reduced to

$$y(U) = y_U U + y_{UU} U^2 \tag{2a}$$

where, y generally denotes one of X, Z and M in Eq. (1) and U represents either u or w in Eq. (1).

Considering the direction of the velocity, the force may also be written as

$$y(U) = \begin{cases} y_U^{(+)}|U| + y_{UU}^{(+)}U^2, & (U \geq 0) \\ -y_U^{(-)}|U| + y_{UU}^{(-)}U^2, & (U < 0) \end{cases} \tag{2b}$$

Because of its front-rear and top-bottom asymmetry of the vehicle, $y_U^{(+)} \neq y_U^{(-)}$, $y_{UU}^{(+)} \neq y_{UU}^{(-)}$. This is not convenient for practical engineering applications. Therefore, Eq.(2) is better to be written in the other form. We know that any function can be written uniquely as a sum of an even function and an odd function, hence $y(U)$ in Eq. (2) can be rewritten as:

$$y(U) = \bar{y}_{|U|}|U| + \bar{y}_U U + \bar{y}_{U|U|}U|U| + \bar{y}_{UU}U^2 \tag{3}$$

where $\bar{y}_{|U|}$, $\bar{y}_U$, $\bar{y}_{U|U|}$ and $\bar{y}_{UU}$ do not depend on the direction of the velocity and so $\bar{y}_{|U|}|U| + \bar{y}_{UU}U^2$ is even while $\bar{y}_U U + \bar{y}_{U|U|}U|U|$ is odd. In order to examine the relationship between the coefficients in Eqs. (2) and (3), one may re-write Eq. (3) as

$$y(U) = \begin{cases} (\bar{y}_{|U|} + \bar{y}_U)|U| + (\bar{y}_{U|U|} + \bar{y}_{UU})U^2, & (U \geq 0) \\ -(\bar{y}_U - \bar{y}_{|U|})|U| + (\bar{y}_{UU} - \bar{y}_{U|U|})U^2, & (U < 0) \end{cases} \tag{4}$$

Compared with Eq. (2b), we should have

$$y_U^{(+)} = \bar{y}_{|U|} + \bar{y}_U,\ y_U^{(-)} = \bar{y}_U - \bar{y}_{|U|},\ y_{UU}^{(+)} = \bar{y}_{U|U|} + \bar{y}_{UU},\ y_{UU}^{(-)} = \bar{y}_{UU} - \bar{y}_{U|U|},$$

such that

$$\bar{y}_{|U|} = \frac{1}{2}\left(y_U^{(+)} - y_U^{(-)}\right), \quad \bar{y}_U = \frac{1}{2}\left(y_U^{(+)} + y_U^{(-)}\right)$$

$$\bar{y}_{U|U|} = \frac{1}{2}\left(y_{UU}^{(+)} - y_{UU}^{(-)}\right),\ \bar{y}_{UU} = \frac{1}{2}\left(y_{UU}^{(+)} + y_{UU}^{(-)}\right)$$

In the following sections, Eq. (3) will be employed to process the experimental data but the bar over the force and moment coefficient will be dropped from now without confusion. Correspondingly, the force and moment in Eq. (1) can be rewritten as:

$$X = X_{|u|}|u| + X_u u + X_{u|u|}u|u| + X_{uu}u^2 + X_{|w|}|w| + X_w w + X_{w|w|}w|w| + X_{ww}w^2 \tag{5a}$$
$$Z = Z_{|u|}|u| + Z_u u + Z_{u|u|}u|u| + Z_{uu}u^2 + Z_{|w|}|w| + Z_w w + Z_{w|w|}w|w| + Z_{ww}w^2 \tag{5b}$$
$$M = M_{|u|}|u| + M_u u + M_{u|u|}u|u| + M_{uu}u^2 + M_{|w|}|w| + M_w w + M_{w|w|}w|w| + M_{ww}w^2 \tag{5c}$$

It is indicated that the force coefficients should be understood as these with a bar as those in Eq. (3), meaning that they do not depend on the direction of the velocity.

In order to be able to apply the force/moment coefficients to prototype vehicles, it may be better to convert the coefficients into dimensionless form. For this purpose, the coefficients of the forces proportional to the velocity will be nondimensionalized by $\frac{1}{2}\rho l^2\sqrt{gl}$, these proportional to the square of the velocity by $\frac{1}{2}\rho l^2$, the coefficients of moments proportional to the velocity by $\frac{1}{2}\rho l^3\sqrt{gl}$ and these moment coefficients proportional to the square of the velocity by $\frac{1}{2}\rho l^3$, where *l* is the model length, ρ is the water density and g is the gravitational acceleration. For examples, $X'_U = X_U/\frac{1}{2}\rho l^2\sqrt{gl}$, $X'_{UU} = X_{UU}/\frac{1}{2}\rho l^2$, $M'_U = M_U/\frac{1}{2}\rho l^3\sqrt{gl}$, $M'_{UU} = M_{UU}/\frac{1}{2}\rho l^3$. These with a dash as superscript represent the non-dimensional coefficients.

3.2. Least squares method

The least square method is employed to find the hydrodynamic coefficients in Eq. (3) or (5) from corresponding tests. For any test case with a velocity in one direction, one expects that the following expression has a minimum error.

$$S = \sum_{i=1}^{N}\left[y_{mi} - \left(y_{|U|}|U_i| + y_U\, U_i + y_{U|U|}\, U_i|U_i| + y_{UU}\, {U_i}^2\right)\right]^2 \tag{6}$$

where y_{mi} is the measured force or moment corresponding to the velocity U_i and *y* denotes any of *X*, *Z* and *M* in Eq.5). In other words, the following equations need to be satisfied.

$$\frac{\partial S}{\partial y_{|U|}} = -2\sum_{i=1}^{N}\left[y_{mi} - \left(y_{|U|}|U_i| + y_U\, U_i + y_{U|U|}\, U_i|U_i| + y_{UU}\, {U_i}^2\right)\right]|U_i| = 0$$

$$\frac{\partial S}{\partial y_{U}} = -2\sum_{i=1}^{N}\left[y_{mi} - \left(y_{|U|}|U_i| + y_U\, U_i + y_{U|U|}\, U_i|U_i| + y_{UU}\, {U_i}^2\right)\right]U_i = 0$$

$$\frac{\partial S}{\partial y_{U|U|}} = -2\sum_{i=1}^{N}\left[y_{mi} - \left(y_{|U|}|U_i| + y_U\, U_i + y_{U|U|}\, U_i|U_i| + y_{UU}\, {U_i}^2\right)\right]U_i|U_i| = 0$$

$$\frac{\partial S}{\partial y_{UU}} = -2\sum_{i=1}^{N}\left[y_{mi} - \left(y_{|U|}|U_i| + y_U\, U_i + y_{U|U|}\, U_i|U_i| + y_{UU}\, {U_i}^2\right)\right]{U_i}^2 = 0$$

Then

$$y_{|U|}\sum_{i=1}^{N}{U_i}^2 + y_U\sum_{i=1}^{N}U_i|U_i| + y_{U|U|}\sum_{i=1}^{N}{U_i}^3 + y_{UU}\sum_{i=1}^{N}{U_i}^2\,|U_i| = \sum_{i=1}^{N}y_{mi}|U_i|$$

$$y_{|U|}\sum_{i=1}^{N}U_i|U_i| + y_U\sum_{i=1}^{N}{U_i}^2 + y_{U|U|}\sum_{i=1}^{N}{U_i}^2\,|U_i| + y_{UU}\sum_{i=1}^{N}{U_i}^3 = \sum_{i=1}^{N}y_{mi}U_i$$

$$y_{|U|}\sum_{i=1}^{N}{U_i}^3 + y_U\sum_{i=1}^{N}{U_i}^2|U_i| + y_{U|U|}\sum_{i=1}^{N}{U_i}^4 + y_{UU}\sum_{i=1}^{N}{U_i}^3\,|U_i| = \sum_{i=1}^{N}y_{mi}\,U_i|U_i|$$

$$y_{|U|}\sum_{i=1}^{N}{U_i}^2|U_i| + y_U\sum_{i=1}^{N}{U_i}^3 + y_{U|U|}\sum_{i=1}^{N}{U_i}^3\,|U_i| + y_{UU}\sum_{i=1}^{N}{U_i}^4 = \sum_{i=1}^{N}y_{mi}\,{U_i}^2$$

The force or moment coefficients are found by solving the following equations.

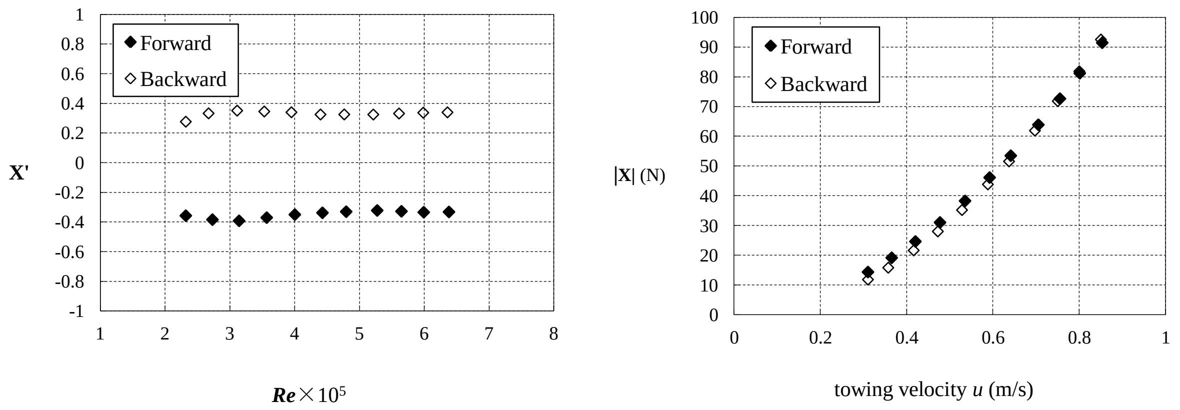
$$\begin{bmatrix} \sum_{i=1}^{N} U_i^{\,2} & \sum_{i=1}^{N} U_i|U_i| & \sum_{i=1}^{N} U_i^{\,3} & \sum_{i=1}^{N} U_i^{\,2}\,|U_i| \\ \sum_{i=1}^{N} U_i|U_i| & \sum_{i=1}^{N} U_i^{\,2} & \sum_{i=1}^{N} U_i^{\,2}\,|U_i| & \sum_{i=1}^{N} U_i^{\,3} \\ \sum_{i=1}^{N} U_i^{\,3} & \sum_{i=1}^{N} U_i^{\,2}|U_i| & \sum_{i=1}^{N} U_i^{\,4} & \sum_{i=1}^{N} U_i^{\,3}\,|U_i| \\ \sum_{i=1}^{N} U_i^{\,2}|U_i| & \sum_{i=1}^{N} U_i^{\,3} & \sum_{i=1}^{N} U_i^{\,3}\,|U_i| & \sum_{i=1}^{N} U_i^{\,4} \end{bmatrix} \begin{bmatrix} y_{|U|} \\ y_U \\ y_{U|U|} \\ y_{UU} \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{N} y_{mi}|U_i| \\ \sum_{i=1}^{N} y_{mi}U_i \\ \sum_{i=1}^{N} y_{mi}\,U_i|U_i| \\ \sum_{i=1}^{N} y_{mi}\,U_i^{\,2} \end{bmatrix} \tag{7}$$

4. Results and discussions

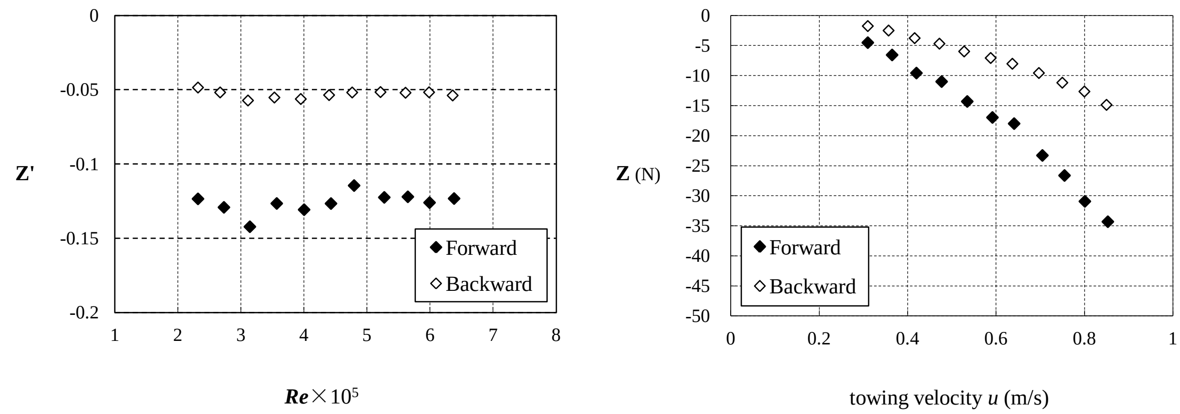
In this section, the experimental results are presented, analyzed and discussed for towing tests in surge and heave directions, respectively.

4.1. Constant velocity towing tests in the surge direction

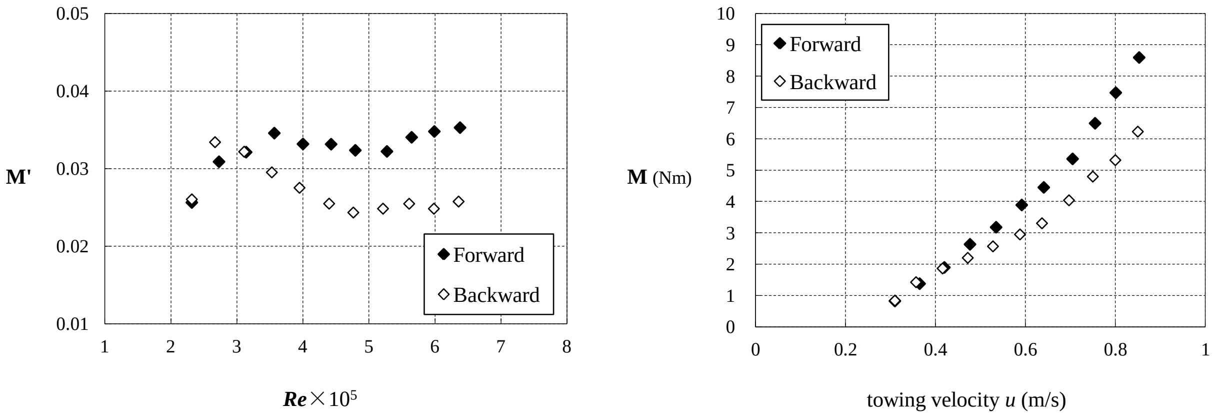
Fig. 5 shows the forces and moments measured for the constant velocities in a range of 0.3m/s to 0.85 m/s when the model is towed in the surge direction (i.e., forward and backward). The figures on the left give the non-dimensional force or moment against the Reynolds number while these on the right plot corresponding dimensional forces or moments. The absolute value of the force in the surge direction is depicted in Fig. 5(a), where the Reynolds number is defined as $Re = Ul/\nu$ with the water kinematic viscosity taken $\nu = 1.1696 \times 10^{-6} m^2 \cdot s^{-1}$ based on the water temperature of 14℃ in the test. It is first pointed out that the variation of the non-dimensional force and moment (X', Z' and M') is not significant in the range of Reynolds number tested; in other words they do not strongly depend on the Reynolds number in the range. It is secondly pointed out that no matter which direction the vehicle moves (forward or backward), the force in surge direction (Fig. 5(a)) has very close magnitude, meaning that the asymmetry of the ROV viewed from the front or rear does not cause difference in the surge forces. Thirdly, as one can see in Fig. 5(b), the vertical force (*Z*) magnitudes in the heave direction are considerable different, though they always point upward (i.e., in the negative direction of z-axis), indicating that the front-rear and top-bottom asymmetry of the ROV does affect the vertical forces. Similarly, the curves for the moments *M* in the pitching direction (Fig. 5(c)) are apart from each other, in particular for the larger towing velocity, though their direction is the same (rotating about positive direction of y-axis).



(a) Force in surge direction (left: non-dimensional force; right: dimensional)



(b) Force in heave direction (left: non-dimensional; right: dimensional)



(c) Moment in pitch direction (left: non-dimensional; right: dimensional)

Fig. 5. Measured forces and moments for constant speed towing in the surge direction

The forces and moments in Fig. 5 can be fitted into formulae such as Eq. (3) using the least square method in Eq. (7). In order to obtain more reliable fitting results, the tests for each towing velocity are repeated several times. As a result, there are several values of forces available corresponding to each value of the velocity. Due to this, when carrying out the fitting, one may have two options. One is to apply the least square method to all the measured forces or moments at the same time while the other one is to calculate the average values for each towing velocity firstly before applying the least square method. Table 2 shows the force or moment coefficients. The values in brackets are obtained by using the second option. As observed from Table 2, the coefficients obtained by two methods agree very well. Hence, in the following analysis, we only apply the second option for fitting curves. In addition, the force coefficients corresponding to the square of the velocity are generally much larger than these corresponding to the linear terms. However, this does not means that one can ignore the linear terms. That is because the ROV may operate with a very slow motion. In such cases, the linear terms may be significant. To check how well the force or moment formulae expressed by Eq. 3 with the coefficients in Table 2, the comparison between measured values and fitting curves is made in Fig. 6. The agreement between them is almost perfect.

Table 2

Hydrodynamic coefficients obtained by fitting the test results for towing in the surge direction

X_u	$X_{\|u\|}$	X_{uu}	$X_{u\|u\|}$	$X'_u \times 10^3$	$X'_{\|u\|} \times 10^3$	$X'_{uu} \times 10^2$	$X'_{u\|u\|}$
-4.46	-7.00	9.40	-122	-3.98	-6.24	2.455	-0.317
(-4.24)	(-6.77)	(9.00)	(-122)	(-3.78)	(-6.04)	(2.351)	(-0.319)
Z_u	$Z_{\|u\|}$	Z_{uu}	$Z_{u\|u\|}$	$Z'_u \times 10^4$	$Z'_{\|u\|} \times 10^4$	$Z'_{uu} \times 10^2$	$Z'_{u\|u\|} \times 10^2$

-0.663	-1.09	-32.3	-12.7	-5.91	-9.75	-8.43	-3.31
(-0.611)	(-1.04)	(-32.3)	(-12.7)	(-5.45)	(-9.29)	(-8.44)	(-3.32)
M_u	$M_{\|u\|}\times10^3$	M_{uu}	$M_{u\|u\|}$	$M'_u\times10^3$	$M'_{\|u\|}\times10^6$	$M'_{uu}\times10^2$	$M'_{u\|u\|}\times10^3$
-1.02	8.21	9.96	2.84	-1.04	8.37	2.97	8.47
(-1.09)	(66.2)	(10.0)	(2.93)	(-1.12)	(-67.4)	(3.00)	(8.74)

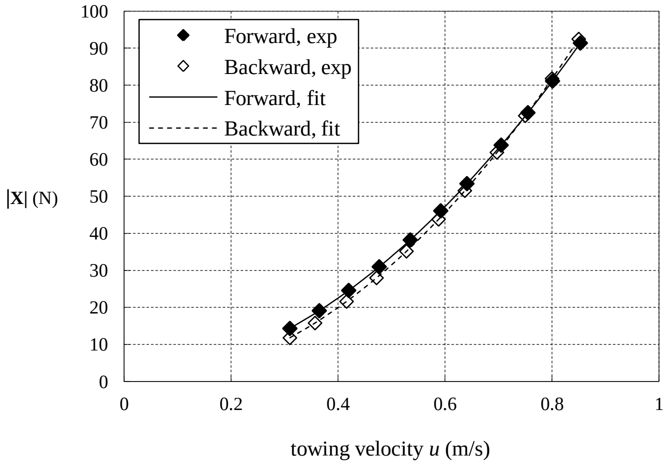


Fig. 6a Force in surge direction

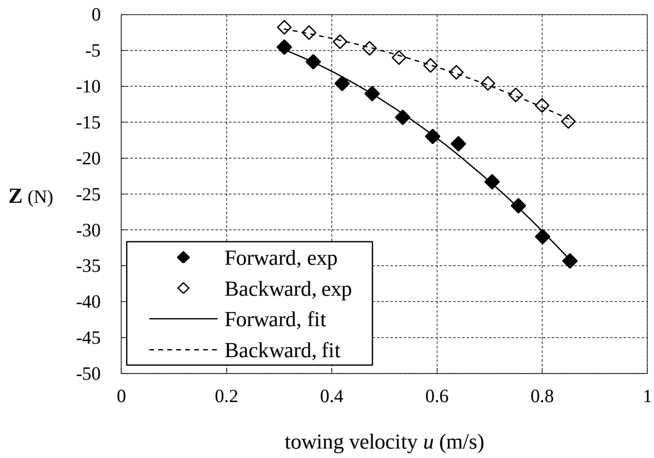


Fig. 6b Force in heave direction

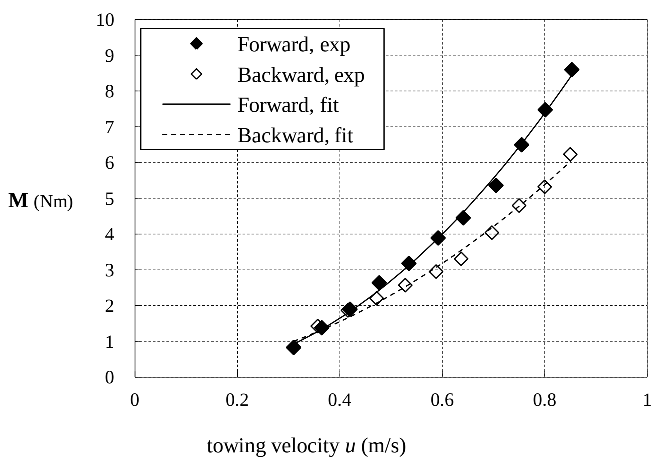


Fig. 6c Moment in pitch direction

Fig. 6. Comparison between fitting results and measured data for the surge tests

Furthermore, to quantitatively assess the error between the fitted curves of forces and moment and the measured values, two parameters are introduced and examined. One of them is relative error, *E*, reflecting the differences between the fitted curves and the measured values at each velocity, defined by Eq.(8).

$$E = \left|\frac{y_m - y_c}{y_m}\right| \times 100\% \tag{8}$$

where y_m represents the measured forces or moments while y_c is the values by Eq. (3) using the coefficients in Table 2. As mentioned before, there are several values of force or moments at each value of the velocity due to repeating testes, and so the range of errors at each velocity would be obtained. In addition, one can also obtain the error based on the average measured value of force and moments. To do so, y_m in Eq. (8) should be replaced by an average value ($\breve{y}_{mi}$) corresponding to the speed concerned. The other parameter is the standard deviation, σ, defined in Eq. (9).

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\breve{y}_{mi} - y_{ci})^2} \tag{9}$$

where $\breve{y}_{mi}$ is the mean values of measured forces or moments at each velocity and y_{ci} is the value calculated by using the fitted formulae at the same velocity.

For the towing tests with constant velocity in the surge direction, Fig.7 presents the variation of relative error, *E*. In the figure, the solid dots represent the error using the mean value of measured force or moment while the solid vertical lines represent the error using the values of forces at each velocity. Fig. 8 shows the variation of the standard deviation. It can be seen that the maximum relative error is less than 10% while the mean error is less than 5% in the cases. The standard deviation has the similar trends and values for the backward and forward motion.

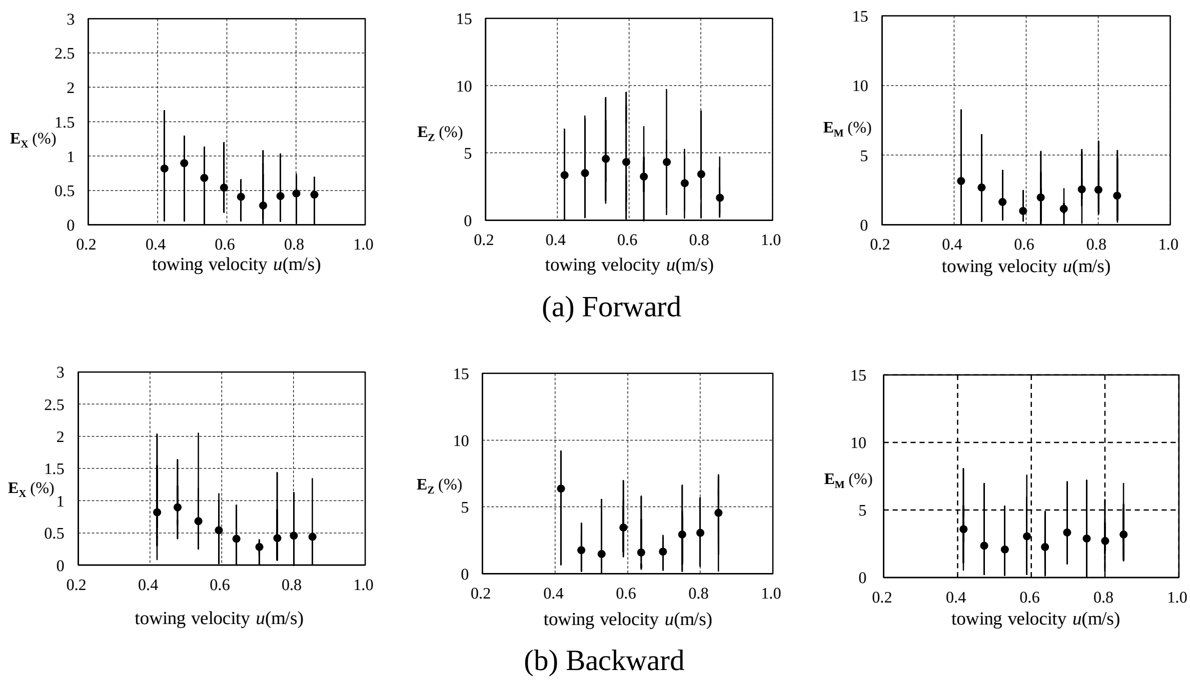


Fig. 7. Relative error (E) for the surge tests (the dots is calculated by mean velocity)

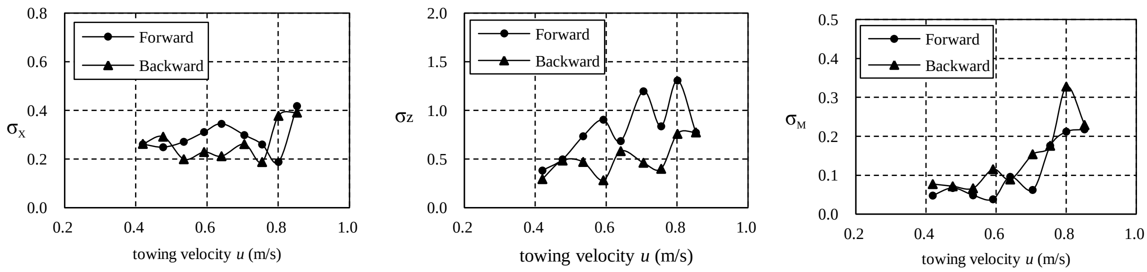
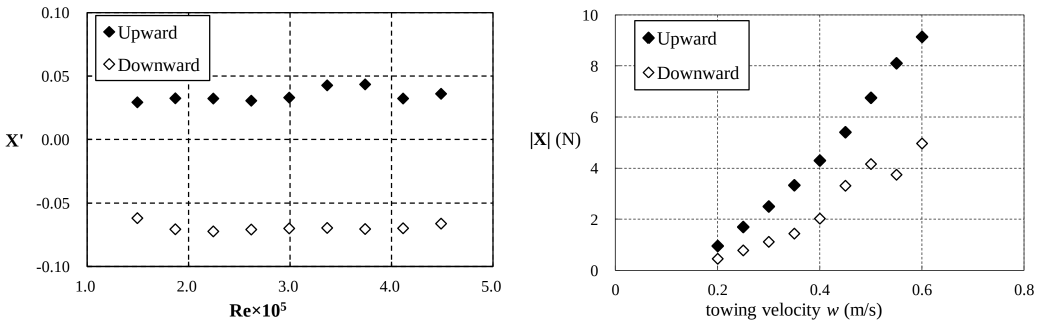


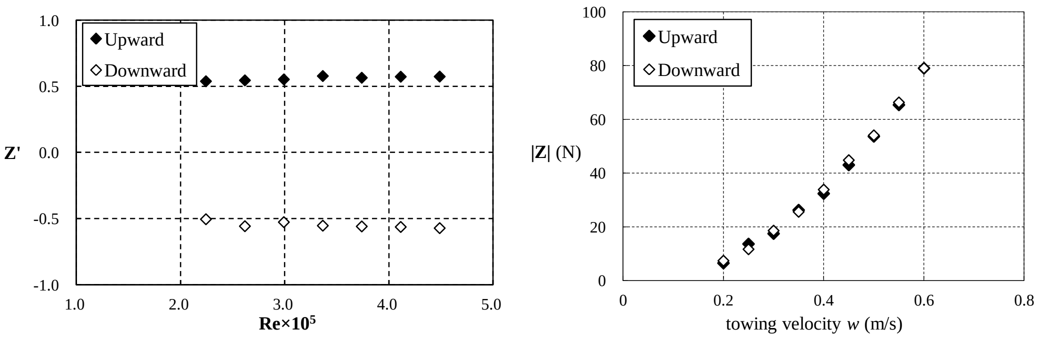
Fig. 8. Standard deviation for the surge tests

4.2. Constant velocity towing tests in the heave direction

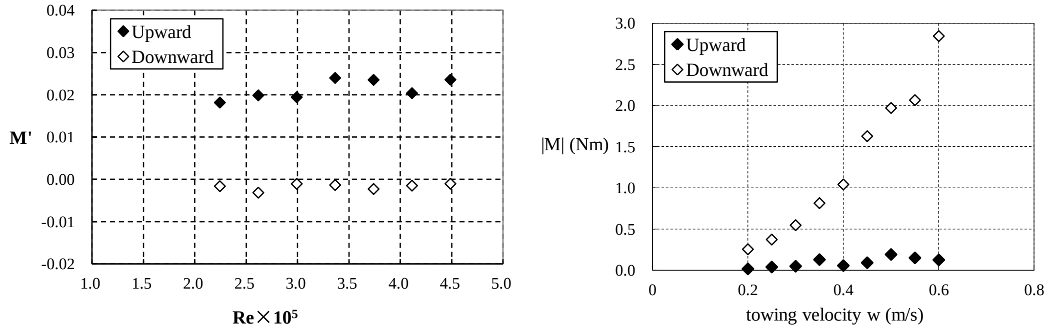
Fig. 9 shows the forces and moments for constant velocity towing in the heave direction. Similar to Fig. 5, the figures on the left are the non-dimensional force or moment against the Reynolds number while these on the right plot the absolute value of corresponding dimensional forces or moments. Again one can see that the variation of the non-dimensional force and moment (X', Z' and M') with the Reynolds number is not significant in the range of Reynolds number tested. As shown in Fig. 9(a), the surge forces for the upward and downward motions are considerable different not only in their magnitudes but also in their direction. Specifically, the upward motion generates a force in the positive surge direction while the downward motion causes a force in the negative surge direction. In addition, the moments in the pitch direction caused by the upward and downward motions are also very different as depicted in Fig. 9(c). When the ROV is towed upward, the moment significantly increases with the velocity but the moment is almost zero when it is towed downward. Figs. 9(a) and 9(c) demonstrates that the front-rear asymmetry viewed from the top or bottom strongly affect the surge forces and pitch moment. Fig. 9 (b) shows the forces in the heave direction when the vehicle moves upward or downward. The vertical forces (Z) for the motion in different directions with the same speed have very close magnitude, meaning that the top-bottom asymmetry of the ROV does not cause much difference in the vertical force.



(a) Force in surge direction (left: non-dimensional force; right: dimensional)



(b) Force in heave direction (left: non-dimensional force; right: dimensional)



(c) Moment in pitch direction (left: non-dimensional; right: dimensional)

Fig. 9. Forces and moments for constant velocity towing in the heave direction

The forces and moments in Fig. 9 can also be fitted into a formula using the Eq. (3) as what was done for Fig. 5. After doing so, the force or moment coefficients are listed in Table 3. The comparison between measured values and fitting curves (Eq. 3 with coefficient in Table 3) is given in Fig. 10. The agreement between them is again very good.

Table 3

Hydrodynamic coefficients tested by towing in the vertical direction

X_w	$X_{\|w\|}$	X_{ww}	$X_{w\|w\|}$	$X'_w\times10^4$	$X'_{\|w\|}\times10^4$	$X'_{ww}\times10^2$	$X'_{w\|w\|}\times10^2$
0.181	-0.584	-5.03	19.8	1.61	-5.21	-1.31	5.17
Z_w	$Z_{\|w\|}$	Z_{ww}	$Z_{w\|w\|}$	$Z'_w\times10^3$	$Z'_{\|w\|}\times10^4$	$Z'_{ww}\times10^4$	$Z'_{w\|w\|}$
10.4	-0.459	-0.297	-237	9.30	-4.09	-7.77	-0.618
M_w	$M_{\|w\|}$	M_{ww}	$M_{w\|w\|}$	$M'_w\times10^4$	$M'_{\|w\|}\times10^4$	$M'_{ww}\times10^2$	$M'_{w\|w\|}\times10^2$
-0.276	-0.430	4.33	4.52	-2.81	-4.38	1.29	1.35

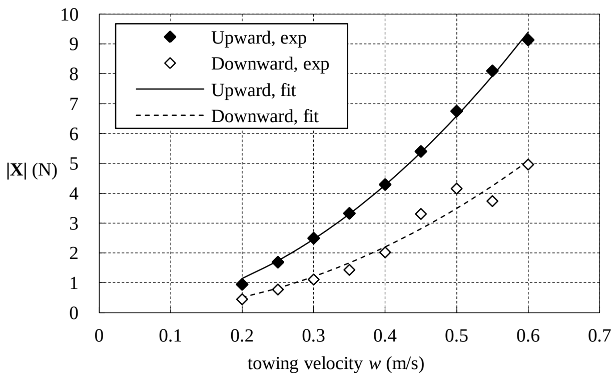


Fig. (10) Force in the surge direction

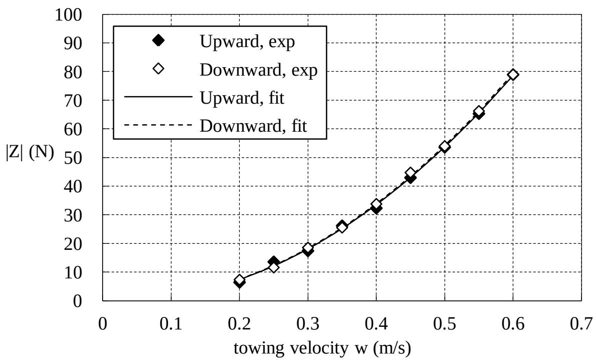


Fig. (10) Force in the heave direction

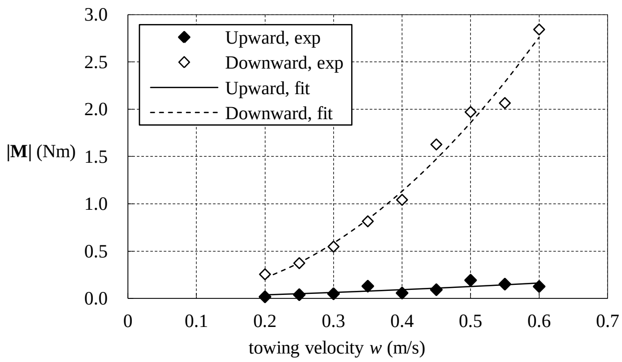


Fig. (10) Moment in the pitch direction

Fig. 10. Comparison between fitting results and measured data for the heave tests

4.3. Comparing coefficients in different directions

As has been demonstrated, the force X, Z and moment M can be induced by the motions in both surge and heave directions. It may be interesting to show the relative importance of different components due to the motions in different directions. For this purpose, the ratios of force coefficients corresponding to different components are shown in Table 4. As can be seen, the liner force coefficients in surge direction caused by the heave motion are only about 4 to 8% of these by the surge motion, but the 2nd order force coefficients can be about 54%. In contrast, the value of $\left|Z'_{|u|}/Z'_{|w|}\right|$ (the ratio of the linear vertical coefficient due to the surge motion to that due to the vertical motion) can be more than 2. This means that asymmetrical effects are particular important when the ROV moves slowly. More interesting point is that the linear coefficient ratio ($\left|M'_{|w|}/M'_{|u|}\right|$) of the pitch moment can be more than 52 but the second order force coefficient ratio $\left|M'_{w|w|}/M'_{u|u|}\right|$ is only about 1.59. The data given here clearly shows that the forces induced by the motion in other directions and the pitch moment induced by the surge or heave motions are generally not negligible.

Table 4
Comparison of Coefficients

$\lvert X'_w/X'_u\rvert$	$\left\lvert X'_{\lvert w\rvert}/X'_{\lvert u\rvert}\right\rvert$	$\lvert X'_{ww}/X'_{uu}\rvert$	$\left\lvert X'_{w\lvert w\rvert}/X'_{u\lvert u\rvert}\right\rvert$
4.06×10^{-2}	8.34×10^{-2}	0.535	0.163
$\lvert Z'_u/Z'_w\rvert$	$\left\lvert Z'_{\lvert u\rvert}/Z'_{\lvert w\rvert}\right\rvert$	$\lvert Z'_{uu}/Z'_{ww}\rvert$	$\left\lvert Z'_{u\lvert u\rvert}/Z'_{w\lvert w\rvert}\right\rvert$
6.37×10^{-2}	2.38	108	5.35×10^{-2}
$\lvert M'_w/M'_u\rvert$	$\left\lvert M'_{\lvert w\rvert}/M'_{\lvert u\rvert}\right\rvert$	$\lvert M'_{ww}/M'_{uu}\rvert$	$\left\lvert M'_{w\lvert w\rvert}/M'_{u\lvert u\rvert}\right\rvert$
0.271	52.3	0.435	1.59

5. Conclusion

This paper deals with the hydrodynamic behaviors of a new ROV moving in a vertical plane. The ROV is complex and asymmetrical in its shape. A series of model tests are carried out. Based on the test results, the corresponding fitting formulae of the hydrodynamic forces and moments are obtained, which can be used for predicting the motions of the ROV and for validating numerical results. Also based on the test results, the effects of the asymmetry on the vehicle's hydrodynamic forces and moments are discussed and quantified. Some conclusions are summarized as below.

1. For the surge towing tests, the vertical force (Z) magnitudes in the vertical direction are considerably different for different towing direction, though they always point upward (i.e., in the negative direction

of z-axis). Dimensionless vertical force due to forward motion can be twice of that due to backward motion. Similarly, the moments (*M*) in the pitching direction caused by the forward and backward motion are different, particularly for the relatively large towing velocity, though their direction is the same (rotating about positive direction of y-axis). These differences are the results of the front-rear and top-bottom asymmetry of the ROV.

2. For the heave towing tests, the surge forces for the upward and downward motions are considerable different not only in their magnitudes but also in their direction. Specially, the upward motion generates a force in positive surge direction while the downward motion causes a force in negative surge direction. In addition, the moments in the pitch direction caused by the upward and downward motions are also very different. When the ROV is towed upward, the moment significantly increases with the velocity but the moment is almost zero when it is towed downward.

3. For each value of velocity, the tests are repeated several times. Based on the error analysis on the repeated results, the value of forces and moments calculated by the fitted formulae may have accuracy with the maximum error less than 10% and the mean error less than 5%.

4. Nondimensional hydrodynamic coefficients do not vary significantly with the change of Reynolds number. Based on this fact, the nondimensional coefficients may be extrapolated to high Reynolds numbers or speeds.

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Experimental study on the hydrodynamic forces and moments acting on a ROV with an asymmetrical shapes moving in a vertical plane

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ABSTRACT

Hydrodynamic models and coefficients are important parameters for predicting the maneuverability of the ROV (Remotely Operated Vehicle). This paper will present an experimental study on the hydrodynamic behaviors of a new ROV that has an asymmetrical shape but has a large capacity holding more instruments on board than other ROVs. A series towing tests has been carried out on this ROV moving in a vertical plane. This paper will give the fitting formulae of forces and moments, and corresponding hydrodynamic coefficients, which can be used for simulating the motions and so for predicting the maneuverability of the ROV, and will also discuss the effects of asymmetry in its shapes on its hydrodynamic coefficients.

Keywords: ROV (Remotely Operated Vehicle); effects of asymmetrical shapes; scaled model test; hydrodynamics coefficients

1. Introduction

Underwater vehicles can be applied to ocean resource exploration and exploitation, pipeline inspection and offshore structure maintenance, seafloor geography mapping, and so on. There are two kinds of underwater vehicles for such applications: Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) [1]. Generally speaking, AUVs have simple and watertight hulls, similar in many cases to conventional submarines, operating at relatively high speeds; in contrast, ROVs have relatively complex and open-frame hulls, operating at relatively low speed. This paper is mainly concerned about ROVs.

Hydrodynamics of ROVs are important for controlling their motions and predicting their performances in sea. At present, their hydrodynamic properties are mainly studied by carrying out experiments. That is perhaps because their hull geometries are generally very complex and it is difficult and very time consuming to perform numerical computations. In addition, unlike conventional submarines having roughly similar hulls, each ROV has its unique hull geometry that is generally different from others. Due to this, there are no common hydrodynamic properties that can apply to all ROVs. One needs to carry out study on hydrodynamics for each ROV. Due also to this, there is lack of common dynamics mathematical models that can be applied to all ROVs [2].

The most commonly accepted dynamics model for conventional submarines can be traced to a series of studies performed at DTNSRDC (David Taylor Naval Ship Research and Development Centre) [3] [4]. This dynamical model (known as the DTNSRDC standard submarine equations of motion) has been used for predicting the motions of not only conventional submarines, but also some underwater vehicles such as [5] for AUV and [6], [7] and [8] for the ROVs. However, the DTNSRDC dynamical model is originally proposed for conventional submarines, where the hydrodynamic forces are assumed to be related to the square of velocities. For ROVs, it may move at a low speed and the linear part (proportional to the one order of speed) of hydrodynamic force and moment may play a role and may not be ignored.

In many publications, the dynamic model for ROV was simplified as one without off-diagonal drag entries and ignores influence of motion in one direction on the hydrodynamics in other directions by assuming that vehicles have three symmetrical planes, e.g., [9][10] and [11]. Associated hydrodynamic coefficients were obtained by model tests (e.g.[12][13][14][15][16]) and computational fluid dynamics (e.g. [17]). Besides, the reference [18] discussed the hydrodynamic properties of a submersible with an aerofoil for forward and backward motions, and the work in [6] and [19] conducted towing tests for ROV models moving in forward and backward, starboard and portside, upward and downward directions. In these papers and others in literature, the effects of asymmetrical ROV shape on its hydrodynamic properties are rarely studied as far as we know.

This paper will present an experimental study on the hydrodynamic behaviors of a new ROV similar to the Quantum designed by SMD [20]. This ROV has more capacity than others and allows additional sensors and equipments to be mounted on board. The vehicle has a complex open-framed hull and is front-rear and top-bottom asymmetrical. In this paper, we will present the study on the hydrodynamics associated with surge and heave motions with particular attention on the effects of the front-rear and top-bottom asymmetry of its hull, and suggest a dynamic model which takes into account of the front-rear and top-bottom asymmetry.

The remainder of this paper is organized as follows. In Section 2, the model and test facilities and procedure will be described. Section 3 presents the data processing method. Then the experimental results is given and discussed in Section 4. Finally, the conclusions are summarized in Section 5.

2. Test model, experimental facilities and procedures

The test model of the ROV is illustrated in Fig. 1. The frame structure is made of steel, while the other components within the frame, such as thruster and equipment blocks are made of buoyancy material. Its main parameters are summarized in Table 1. The test model is front-rear and top-bottom asymmetrical (more details may be found in Fig. 4).

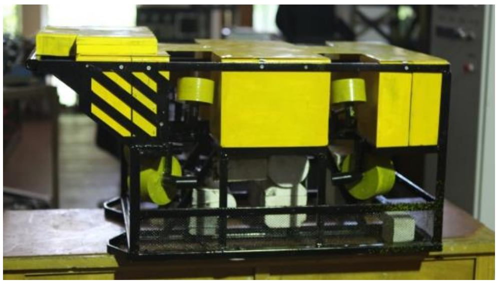


Fig. 1. Test model

Table 1

Parameters of test model

Physical property	Value
Scale ratio	1:4
length, m	0.875
width, m	0.5
height, m	0.5
mass in air, kg	78

In many situations, the ROV will be operated to move up and down (referred as to the heave direction), such as during the launch stage, and forward and backward (referred as to the surge direction), such as during the search stage on the sea bed. This paper will mainly study the properties of forces and moments acting on the ROV in such situations. For this purpose, a series of model tests in surge and heave directions with constant towing speeds have been carried out. The experiments are carried out in two facilities of Harbin Engineering University. The surge tests are undertaken in circulating water channel (the model placed in it as shown in Fig. 2), which has a cross-section of 1.7m wide and 1.5m deep with the velocity of flow. During the surge tests, the test model is stationary and water flows forward or backward relative to the model. The heave towing tests are carried out in a large water tank of 50m long, 30m wide and 10m deep (the model placed in it as shown in Fig. 3). During the tests, water was stationary, while the test model is towed with constant speeds. In both kinds of the tests, the relative speeds between water and the model are changed in a range (specific values are given below), and the tests are repeated several times at each value of speeds. The forces and moments acting on the test model are measured using a six-component force transducer.

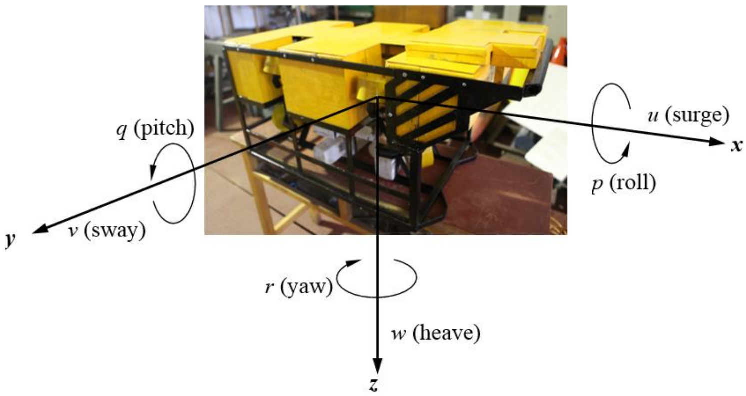
Fig. 2. Model test in circulating water channel

Fig. 3. Model test in a tank

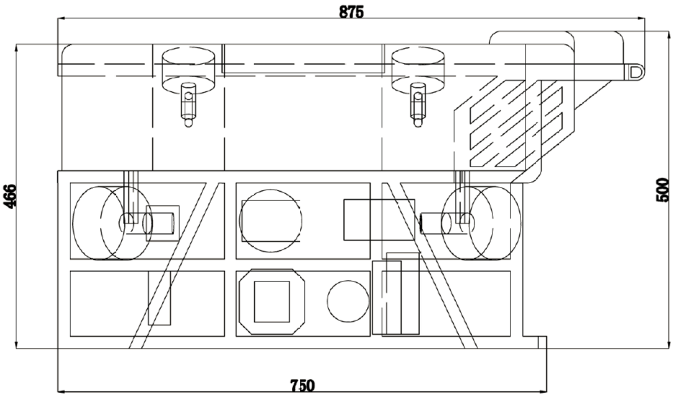
3. Data processing

3.1 Expressions of forces and moments on the model

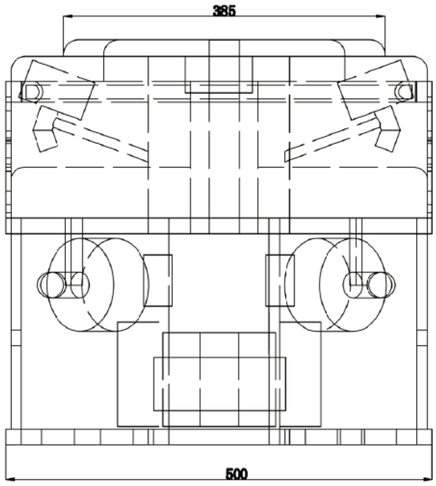
For convenience of describing the forces and motions, the coordinate system is set up as shown in Fig. 4. In the figure, u, v and w denotes the linear velocities in the surge, sway and heave directions with their corresponding forces represented by X, Y and Z, respectively. In addition, p, q and r denote the angular velocities in roll, pitch and yaw directions with K, M and N to be corresponding moments, respectively.



(a) Coordinate system



(b) Section at y=0



(c) Section as x=0

Fig. 4. Coordinate system and illustration of two mid-plane sections

For an underwater vehicle moving in the deep water at a constant speed, without taking the surface water effect into consideration, the hydrodynamic forces and moments are caused by the fluid viscosity, depending on its geometry and its motion velocities. Generally, they may be expressed as:

$$\vec{F}_D = \vec{F}_D(\vec{U}) \quad (\vec{F}_D = \{X, Y, Z, K, M, N\}; \ \vec{U} = \{u, v, w, p, q, r\}).$$

Using the similar method to that in [21], the components of the forces and moments can be expressed by the multivariate Taylor series of the velocities. If we may just take the series to the second order, the forces and moments due to the motion in the surge and heave motions may be expressed as

$$X = X_u u + X_{uu} u^2 + X_w w + X_{ww} w^2 \tag{1a}$$
$$Z = Z_u u + Z_{uu} u^2 + Z_w w + Z_{ww} w^2 \tag{1b}$$
$$M = M_u u + M_{uu} u^2 + M_w w + M_{ww} w^2 \tag{1c}$$

As indicated above, the vehicle is front-rear and top-bottom asymmetrical, which is further illustrated in Fig. 4 by using two mid-plan, the motion in the surge direction may induce the force in the vertical (heave) direction and the moment in the pitch direction. Similarly, the motion in the heave direction can also induce the force in the surge direction and the moment in the pitch direction. These effects have been reflected in Eq. (1). The comments of the forces and moments due to asymmetry are often ignored in literature. Their properties are particularly interested in this paper.

For the motion only in one direction, the forces and moments acting on the vehicle can be reduced to

$$\mathrm{y}(U) = y_U U + y_{UU} U^2 \tag{2a}$$

where, y generally denotes one of *X*, *Z* and *M* in Eq. (1) and *U* represents either *u* or *w* in Eq. (1).

Considering the direction of the velocity, the force may also be written as

$$\mathrm{y}(U) = \begin{cases} y_U{}^{(+)}|U| + y_{UU}{}^{(+)}U^2, & (U \geq 0) \\ -y_U{}^{(-)}|U| + y_{UU}{}^{(-)}U^2, & (U < 0) \end{cases} \tag{2b}$$

Because of its front-rear and top-bottom asymmetry of the vehicle, $y_U{}^{(+)} \neq y_U{}^{(-)}$, $y_{UU}{}^{(+)} \neq y_{UU}{}^{(-)}$. This is not convenient for practical engineering applications. Therefore, Eq.(2) is better to be written in the other form. We know that any function can be written uniquely as a sum of an even function and an odd function, hence $\mathrm{y}(U)$ in Eq. (2) can be rewritten as:

$$\mathrm{y}(U) = \bar{y}_{|U|}|U| + \bar{y}_U U + \bar{y}_{U|U|}U|U| + \bar{y}_{UU}U^2 \tag{3}$$

where $\bar{y}_{|U|}$, $\bar{y}_U$, $\bar{y}_{U|U|}$ and $\bar{y}_{UU}$ do not depend on the direction of the velocity and so $\bar{y}_{|U|}|U| + \bar{y}_{UU}U^2$ is even while $\bar{y}_U U + \bar{y}_{U|U|}U|U|$ is odd. In order to examine the relationship between the coefficients in Eqs. (2) and (3), one may re-write Eq. (3) as

$$\mathrm{y}(U) = \begin{cases} (\bar{y}_{|U|} + \bar{y}_U)|U| + (\bar{y}_{U|U|} + \bar{y}_{UU})U^2, & (U \geq 0) \\ -(\bar{y}_U - \bar{y}_{|U|})|U| + (\bar{y}_{UU} - \bar{y}_{U|U|})U^2, & (U < 0) \end{cases} \tag{4}$$

Compared with Eq. (2b), we should have

$$y_U^{(+)} = \bar{y}_{|U|} + \bar{y}_U,\ y_U^{(-)} = \bar{y}_U - \bar{y}_{|U|},\ y_{UU}^{(+)} = \bar{y}_{U|U|} + \bar{y}_{UU},\ y_{UU}^{(-)} = \bar{y}_{UU} - \bar{y}_{U|U|},$$

such that

$$\bar{y}_{|U|} = \frac{1}{2}\left(y_U^{(+)} - y_U^{(-)}\right), \quad \bar{y}_U = \frac{1}{2}\left(y_U^{(+)} + y_U^{(-)}\right)$$

$$\bar{y}_{U|U|} = \frac{1}{2}\left(y_{UU}^{(+)} - y_{UU}^{(-)}\right),\ \bar{y}_{UU} = \frac{1}{2}\left(y_{UU}^{(+)} + y_{UU}^{(-)}\right)$$

In the following sections, Eq. (3) will be employed to process the experimental data but the bar over the force and moment coefficient will be dropped from now without confusion. Correspondingly, the force and moment in Eq. (1) can be rewritten as:

$$X = X_{|u|}|u| + X_u u + X_{u|u|}u|u| + X_{uu}u^2 + X_{|w|}|w| + X_w w + X_{w|w|}w|w| + X_{ww}w^2 \tag{5a}$$
$$Z = Z_{|u|}|u| + Z_u u + Z_{u|u|}u|u| + Z_{uu}u^2 + Z_{|w|}|w| + Z_w w + Z_{w|w|}w|w| + Z_{ww}w^2 \tag{5b}$$
$$M = M_{|u|}|u| + M_u u + M_{u|u|}u|u| + M_{uu}u^2 + M_{|w|}|w| + M_w w + M_{w|w|}w|w| + M_{ww}w^2 \tag{5c}$$

It is indicated that the force coefficients should be understood as these with a bar as those in Eq. (3), meaning that they do not depend on the direction of the velocity.

In order to be able to apply the force/moment coefficients to prototype vehicles, it may be better to convert the coefficients into dimensionless form. For this purpose, the coefficients of the forces proportional to the velocity will be nondimensionalized by $\frac{1}{2}\rho l^2\sqrt{gl}$, these proportional to the square of the velocity by $\frac{1}{2}\rho l^2$, the coefficients of moments proportional to the velocity by $\frac{1}{2}\rho l^3\sqrt{gl}$ and these moment coefficients proportional to the square of the velocity by $\frac{1}{2}\rho l^3$, where *l* is the model length, ρ is the water density and g is the gravitational acceleration. For examples, $X'_U = X_U/\frac{1}{2}\rho l^2\sqrt{gl}$, $X'_{UU} = X_{UU}/\frac{1}{2}\rho l^2$, $M'_U = M_U/\frac{1}{2}\rho l^3\sqrt{gl}$, $M'_{UU} = M_{UU}/\frac{1}{2}\rho l^3$. These with a dash as superscript represent the non-dimensional coefficients.

3.2. Least squares method

The least square method is employed to find the hydrodynamic coefficients in Eq. (3) or (5) from corresponding tests. For any test case with a velocity in one direction, one expects that the following expression has a minimum error.

$$S = \sum_{i=1}^{N}\left[y_{mi} - \left(y_{|U|}|U_i| + y_U\, U_i + y_{U|U|}\, U_i|U_i| + y_{UU}\, {U_i}^2\right)\right]^2 \tag{6}$$

where y_{mi} is the measured force or moment corresponding to the velocity U_i and *y* denotes any of *X*, *Z* and *M* in Eq.5). In other words, the following equations need to be satisfied.

$$\frac{\partial S}{\partial y_{|U|}} = -2\sum_{i=1}^{N}\left[y_{mi} - \left(y_{|U|}|U_i| + y_U\, U_i + y_{U|U|}\, U_i|U_i| + y_{UU}\, {U_i}^2\right)\right]|U_i| = 0$$

$$\frac{\partial S}{\partial y_U} = -2\sum_{i=1}^{N}\left[y_{mi} - \left(y_{|U|}|U_i| + y_U\, U_i + y_{U|U|}\, U_i|U_i| + y_{UU}\, {U_i}^2\right)\right]U_i = 0$$

$$\frac{\partial S}{\partial y_{U|U|}} = -2\sum_{i=1}^{N}\left[y_{mi} - \left(y_{|U|}|U_i| + y_U\, U_i + y_{U|U|}\, U_i|U_i| + y_{UU}\, {U_i}^2\right)\right]U_i|U_i| = 0$$

$$\frac{\partial S}{\partial y_{UU}} = -2\sum_{i=1}^{N}\left[y_{mi} - \left(y_{|U|}|U_i| + y_U\, U_i + y_{U|U|}\, U_i|U_i| + y_{UU}\, {U_i}^2\right)\right]{U_i}^2 = 0$$

Then

$$y_{|U|}\sum_{i=1}^{N}{U_i}^2 + y_U\sum_{i=1}^{N}U_i|U_i| + y_{U|U|}\sum_{i=1}^{N}{U_i}^3 + y_{UU}\sum_{i=1}^{N}{U_i}^2\,|U_i| = \sum_{i=1}^{N}y_{mi}|U_i|$$
$$y_{|U|}\sum_{i=1}^{N}U_i|U_i| + y_U\sum_{i=1}^{N}{U_i}^2 + y_{U|U|}\sum_{i=1}^{N}{U_i}^2\,|U_i| + y_{UU}\sum_{i=1}^{N}{U_i}^3 = \sum_{i=1}^{N}y_{mi}U_i$$
$$y_{|U|}\sum_{i=1}^{N}{U_i}^3 + y_U\sum_{i=1}^{N}{U_i}^2|U_i| + y_{U|U|}\sum_{i=1}^{N}{U_i}^4 + y_{UU}\sum_{i=1}^{N}{U_i}^3\,|U_i| = \sum_{i=1}^{N}y_{mi}\,U_i|U_i|$$
$$y_{|U|}\sum_{i=1}^{N}{U_i}^2|U_i| + y_U\sum_{i=1}^{N}{U_i}^3 + y_{U|U|}\sum_{i=1}^{N}{U_i}^3\,|U_i| + y_{UU}\sum_{i=1}^{N}{U_i}^4 = \sum_{i=1}^{N}y_{mi}\,{U_i}^2$$

The force or moment coefficients are found by solving the following equations.

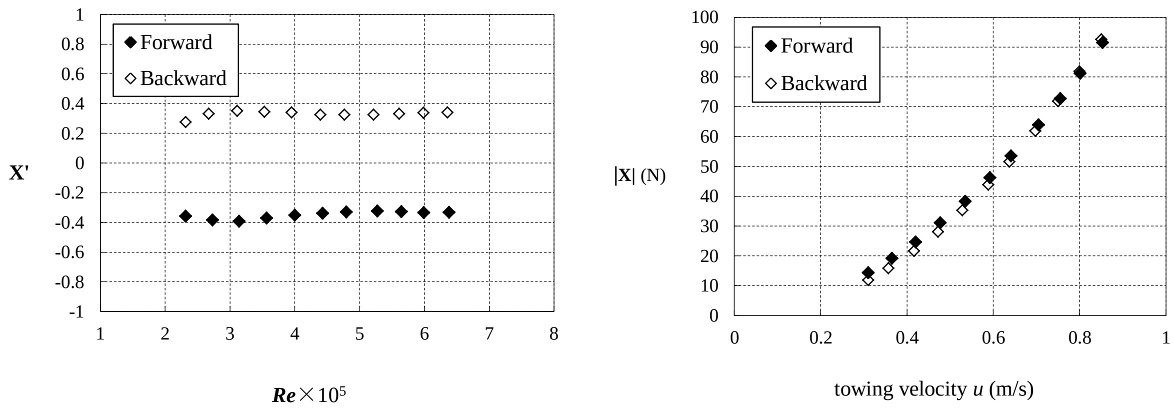
$$\begin{bmatrix} \sum_{i=1}^{N} U_i^{2} & \sum_{i=1}^{N} U_i|U_i| & \sum_{i=1}^{N} U_i^{3} & \sum_{i=1}^{N} U_i^{2}\,|U_i| \\ \sum_{i=1}^{N} U_i|U_i| & \sum_{i=1}^{N} U_i^{2} & \sum_{i=1}^{N} U_i^{2}\,|U_i| & \sum_{i=1}^{N} U_i^{3} \\ \sum_{i=1}^{N} U_i^{3} & \sum_{i=1}^{N} U_i^{2}|U_i| & \sum_{i=1}^{N} U_i^{4} & \sum_{i=1}^{N} U_i^{3}\,|U_i| \\ \sum_{i=1}^{N} U_i^{2}|U_i| & \sum_{i=1}^{N} U_i^{3} & \sum_{i=1}^{N} U_i^{3}\,|U_i| & \sum_{i=1}^{N} U_i^{4} \end{bmatrix} \begin{bmatrix} y_{|U|} \\ y_{U} \\ y_{U|U|} \\ y_{UU} \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{N} y_{mi}|U_i| \\ \sum_{i=1}^{N} y_{mi}U_i \\ \sum_{i=1}^{N} y_{mi}\,U_i|U_i| \\ \sum_{i=1}^{N} y_{mi}\,U_i^{2} \end{bmatrix} \tag{7}$$

4. Results and discussions

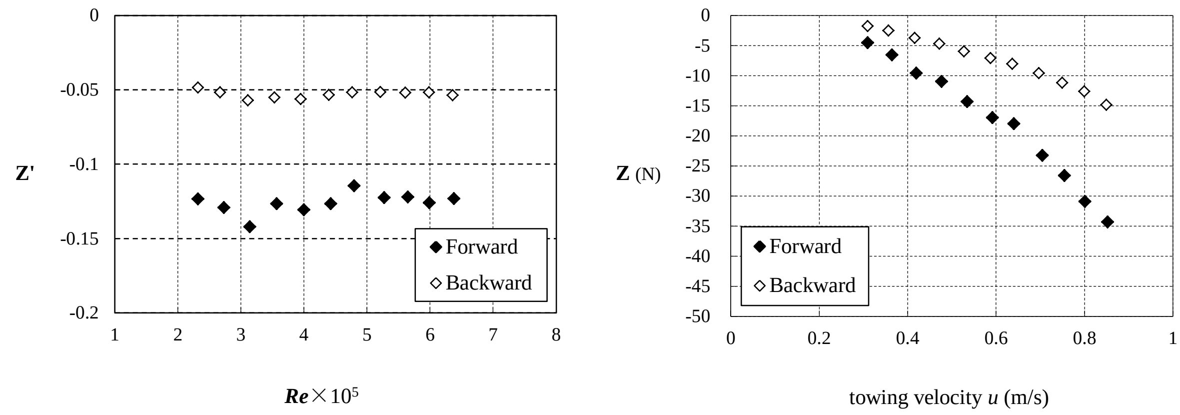
In this section, the experimental results are presented, analyzed and discussed for towing tests in surge and heave directions, respectively.

4.1. Constant velocity towing tests in the surge direction

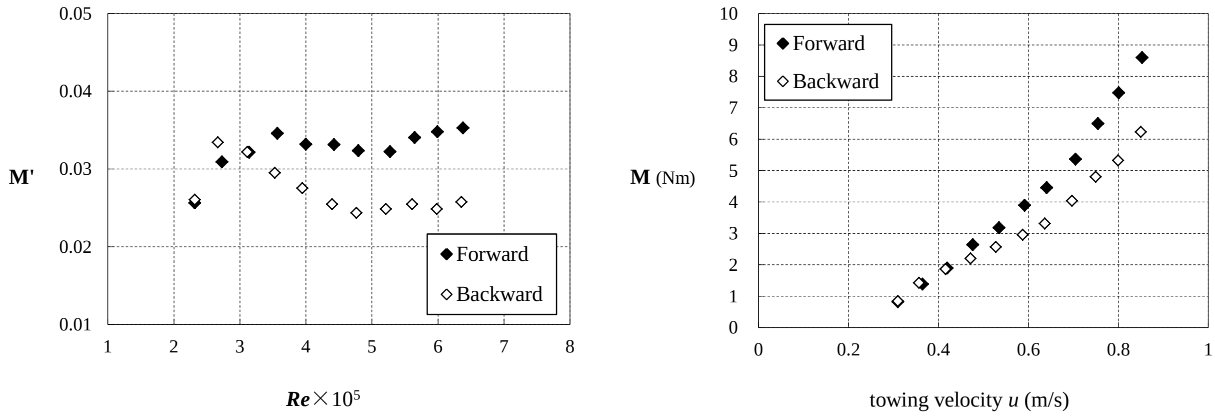
Fig. 5 shows the forces and moments measured for the constant velocities in a range of 0.3m/s to 0.85 m/s when the model is towed in the surge direction (i.e., forward and backward). The figures on the left give the non-dimensional force or moment against the Reynolds number while these on the right plot corresponding dimensional forces or moments. The absolute value of the force in the surge direction is depicted in Fig. 5(a), where the Reynolds number is defined as $Re = Ul/\nu$ with the water kinematic viscosity taken $\nu = 1.1696 \times 10^{-6} m^2 \cdot s^{-1}$ based on the water temperature of 14℃ in the test. It is first pointed out that the variation of the non-dimensional force and moment (X', Z' and M') is not significant in the range of Reynolds number tested; in other words they do not strongly depend on the Reynolds number in the range. It is secondly pointed out that no matter which direction the vehicle moves (forward or backward), the force in surge direction (Fig. 5(a)) has very close magnitude, meaning that the asymmetry of the ROV viewed from the front or rear does not cause difference in the surge forces. Thirdly, as one can see in Fig. 5(b), the vertical force (Z) magnitudes in the heave direction are considerable different, though they always point upward (i.e., in the negative direction of z-axis), indicating that the front-rear and top-bottom asymmetry of the ROV does affect the vertical forces. Similarly, the curves for the moments M in the pitching direction (Fig. 5(c)) are apart from each other, in particular for the larger towing velocity, though their direction is the same (rotating about positive direction of y-axis).



(a) Force in surge direction (left: non-dimensional force; right: dimensional)



(b) Force in heave direction (left: non-dimensional; right: dimensional)



(c) Moment in pitch direction (left: non-dimensional; right: dimensional)

Fig. 5. Measured forces and moments for constant speed towing in the surge direction

The forces and moments in Fig. 5 can be fitted into formulae such as Eq. (3) using the least square method in Eq. (7). In order to obtain more reliable fitting results, the tests for each towing velocity are repeated several times. As a result, there are several values of forces available corresponding to each value of the velocity. Due to this, when carrying out the fitting, one may have two options. One is to apply the least square method to all the measured forces or moments at the same time while the other one is to calculate the average values for each towing velocity firstly before applying the least square method. Table 2 shows the force or moment coefficients. The values in brackets are obtained by using the second option. As observed from Table 2, the coefficients obtained by two methods agree very well. Hence, in the following analysis, we only apply the second option for fitting curves. In addition, the force coefficients corresponding to the square of the velocity are generally much larger than these corresponding to the linear terms. However, this does not means that one can ignore the linear terms. That is because the ROV may operate with a very slow motion. In such cases, the linear terms may be significant. To check how well the force or moment formulae expressed by Eq. 3 with the coefficients in Table 2, the comparison between measured values and fitting curves is made in Fig. 6. The agreement between them is almost perfect.

Table 2

Hydrodynamic coefficients obtained by fitting the test results for towing in the surge direction

X_u	$X_{\lvert u\rvert}$	X_{uu}	$X_{u\lvert u\rvert}$	$X'_u\times10^3$	$X'_{\lvert u\rvert}\times10^3$	$X'_{uu}\times10^2$	$X'_{u\lvert u\rvert}$
-4.46	-7.00	9.40	-122	-3.98	-6.24	2.455	-0.317
(-4.24)	(-6.77)	(9.00)	(-122)	(-3.78)	(-6.04)	(2.351)	(-0.319)
Z_u	$Z_{\lvert u\rvert}$	Z_{uu}	$Z_{u\lvert u\rvert}$	$Z'_u\times10^4$	$Z'_{\lvert u\rvert}\times10^4$	$Z'_{uu}\times10^2$	$Z'_{u\lvert u\rvert}\times10^2$

-0.663	-1.09	-32.3	-12.7	-5.91	-9.75	-8.43	-3.31
(-0.611)	(-1.04)	(-32.3)	(-12.7)	(-5.45)	(-9.29)	(-8.44)	(-3.32)
M_u	$M_{\|u\|}\times10^3$	M_{uu}	$M_{u\|u\|}$	$M'_u\times10^3$	$M'_{\|u\|}\times10^6$	$M'_{uu}\times10^2$	$M'_{u\|u\|}\times10^3$
-1.02	8.21	9.96	2.84	-1.04	8.37	2.97	8.47
(-1.09)	(66.2)	(10.0)	(2.93)	(-1.12)	(-67.4)	(3.00)	(8.74)

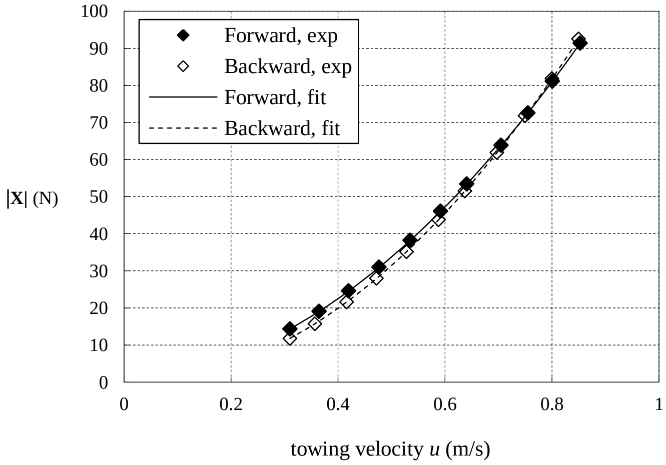


Fig. 6a Force in surge direction

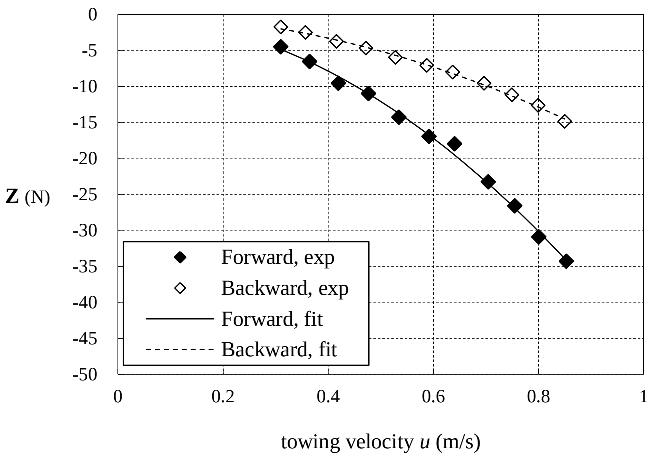


Fig. 6b Force in heave direction

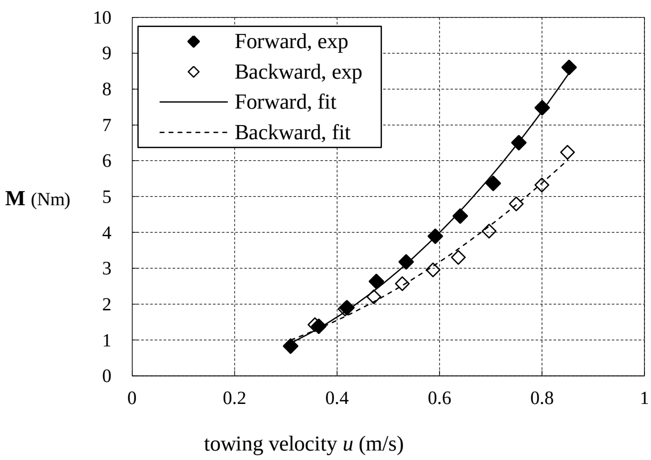


Fig. 6c Moment in pitch direction

Fig. 6. Comparison between fitting results and measured data for the surge tests

Furthermore, to quantitatively assess the error between the fitted curves of forces and moment and the measured values, two parameters are introduced and examined. One of them is relative error, *E*, reflecting the differences between the fitted curves and the measured values at each velocity, defined by Eq.(8).

$$E = \left|\frac{y_m - y_c}{y_m}\right| \times 100\% \tag{8}$$

where y_m represents the measured forces or moments while y_c is the values by Eq. (3) using the coefficients in Table 2. As mentioned before, there are several values of force or moments at each value of the velocity due to repeating testes, and so the range of errors at each velocity would be obtained. In addition, one can also obtain the error based on the average measured value of force and moments. To do so, y_m in Eq. (8) should be replaced by an average value ($\breve{y}_{mi}$) corresponding to the speed concerned. The other parameter is the standard deviation, σ, defined in Eq. (9).

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\breve{y}_{mi} - y_{ci})^2} \tag{9}$$

where $\breve{y}_{mi}$ is the mean values of measured forces or moments at each velocity and y_{ci} is the value calculated by using the fitted formulae at the same velocity.

For the towing tests with constant velocity in the surge direction, Fig.7 presents the variation of relative error, *E*. In the figure, the solid dots represent the error using the mean value of measured force or moment while the solid vertical lines represent the error using the values of forces at each velocity. Fig. 8 shows the variation of the standard deviation. It can be seen that the maximum relative error is less than 10% while the mean error is less than 5% in the cases. The standard deviation has the similar trends and values for the backward and forward motion.

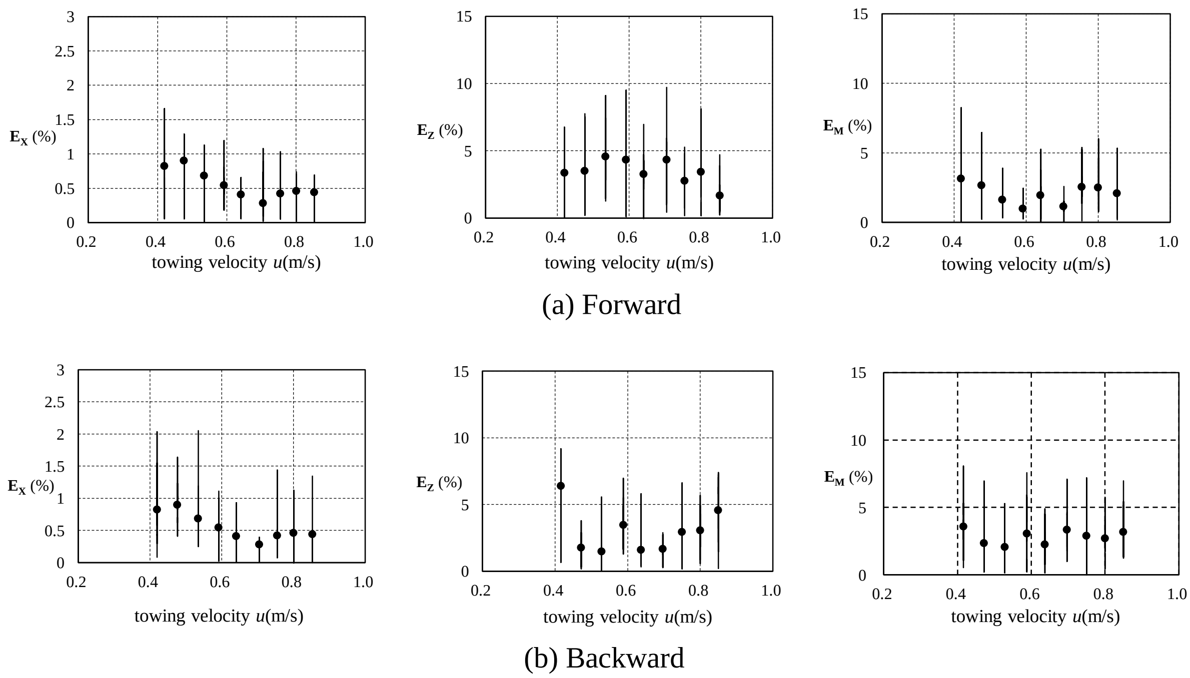


Fig. 7. Relative error (E) for the surge tests (the dots is calculated by mean velocity)

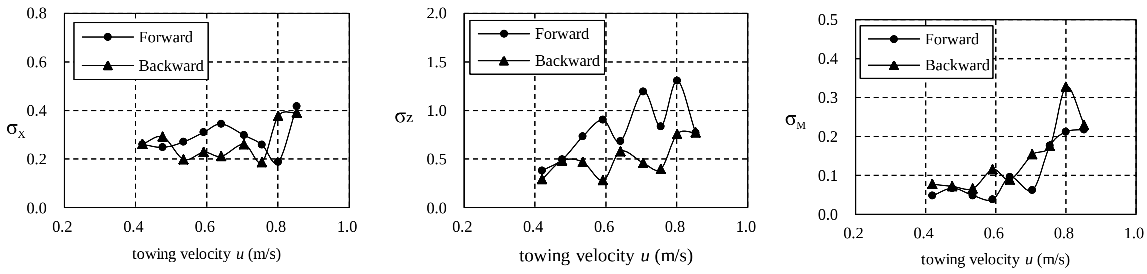
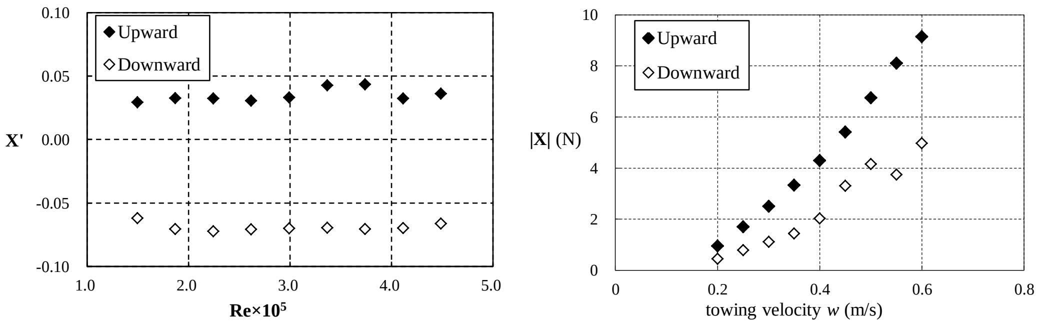


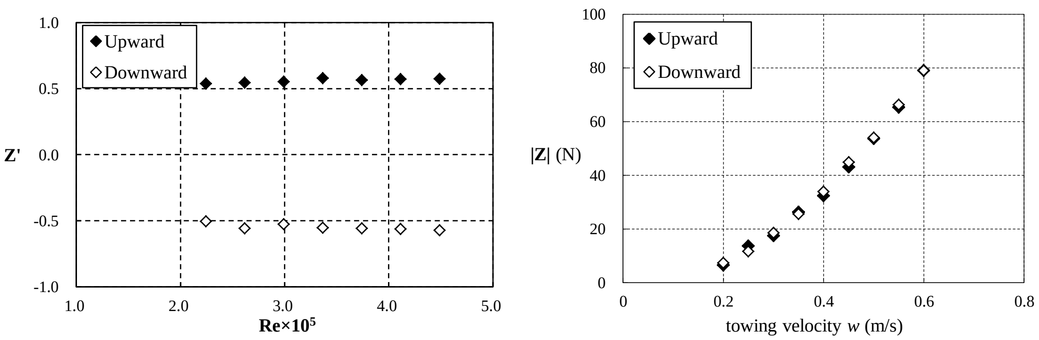
Fig. 8. Standard deviation for the surge tests

4.2. Constant velocity towing tests in the heave direction

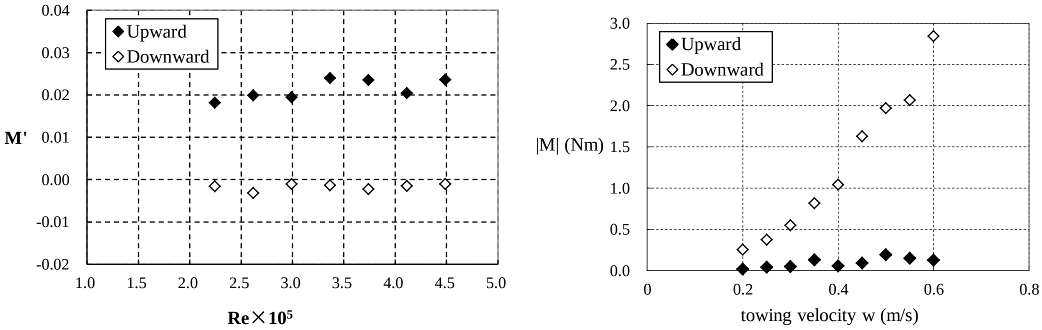
Fig. 9 shows the forces and moments for constant velocity towing in the heave direction. Similar to Fig. 5, the figures on the left are the non-dimensional force or moment against the Reynolds number while these on the right plot the absolute value of corresponding dimensional forces or moments. Again one can see that the variation of the non-dimensional force and moment (X', Z' and M') with the Reynolds number is not significant in the range of Reynolds number tested. As shown in Fig. 9(a), the surge forces for the upward and downward motions are considerable different not only in their magnitudes but also in their direction. Specifically, the upward motion generates a force in the positive surge direction while the downward motion causes a force in the negative surge direction. In addition, the moments in the pitch direction caused by the upward and downward motions are also very different as depicted in Fig. 9(c). When the ROV is towed upward, the moment significantly increases with the velocity but the moment is almost zero when it is towed downward. Figs. 9(a) and 9(c) demonstrates that the front-rear asymmetry viewed from the top or bottom strongly affect the surge forces and pitch moment. Fig. 9 (b) shows the forces in the heave direction when the vehicle moves upward or downward. The vertical forces (Z) for the motion in different directions with the same speed have very close magnitude, meaning that the top-bottom asymmetry of the ROV does not cause much difference in the vertical force.



(a) Force in surge direction (left: non-dimensional force; right: dimensional)



(b) Force in heave direction (left: non-dimensional force; right: dimensional)



(c) Moment in pitch direction (left: non-dimensional; right: dimensional)

Fig. 9. Forces and moments for constant velocity towing in the heave direction

The forces and moments in Fig. 9 can also be fitted into a formula using the Eq. (3) as what was done for Fig. 5. After doing so, the force or moment coefficients are listed in Table 3. The comparison between measured values and fitting curves (Eq. 3 with coefficient in Table 3) is given in Fig. 10. The agreement between them is again very good.

Table 3

Hydrodynamic coefficients tested by towing in the vertical direction

X_w	$X_{\|w\|}$	X_{ww}	$X_{w\|w\|}$	$X'_w\times10^4$	$X'_{\|w\|}\times10^4$	$X'_{ww}\times10^2$	$X'_{w\|w\|}\times10^2$
0.181	-0.584	-5.03	19.8	1.61	-5.21	-1.31	5.17
Z_w	$Z_{\|w\|}$	Z_{ww}	$Z_{w\|w\|}$	$Z'_w\times10^3$	$Z'_{\|w\|}\times10^4$	$Z'_{ww}\times10^4$	$Z'_{w\|w\|}$
10.4	-0.459	-0.297	-237	9.30	-4.09	-7.77	-0.618
M_w	$M_{\|w\|}$	M_{ww}	$M_{w\|w\|}$	$M'_w\times10^4$	$M'_{\|w\|}\times10^4$	$M'_{ww}\times10^2$	$M'_{w\|w\|}\times10^2$
-0.276	-0.430	4.33	4.52	-2.81	-4.38	1.29	1.35

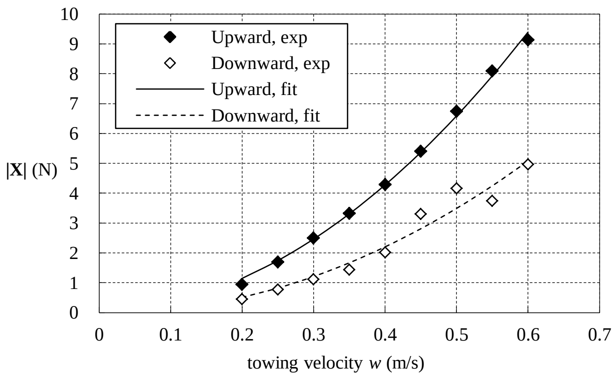


Fig. (10) Force in the surge direction

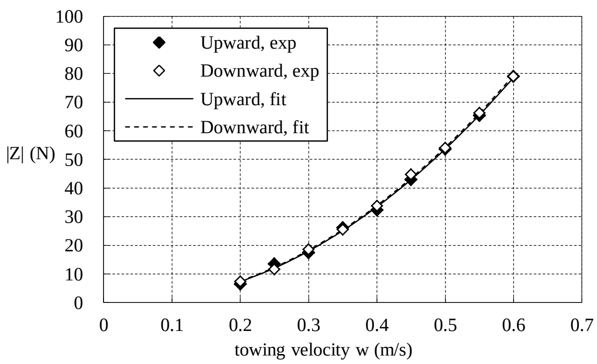


Fig. (10) Force in the heave direction

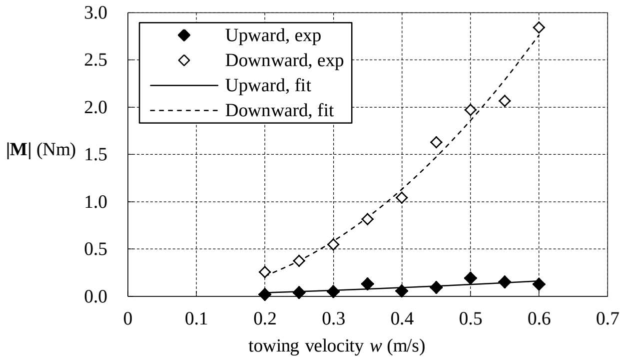


Fig. (10) Moment in the pitch direction

Fig. 10. Comparison between fitting results and measured data for the heave tests

4.3. Comparing coefficients in different directions

As has been demonstrated, the force X, Z and moment M can be induced by the motions in both surge and heave directions. It may be interesting to show the relative importance of different components due to the motions in different directions. For this purpose, the ratios of force coefficients corresponding to different components are shown in Table 4. As can be seen, the liner force coefficients in surge direction caused by the heave motion are only about 4 to 8% of these by the surge motion, but the 2nd order force coefficients can be about 54%. In contrast, the value of $\left|Z'_{|u|}/Z'_{|w|}\right|$ (the ratio of the linear vertical coefficient due to the surge motion to that due to the vertical motion) can be more than 2. This means that asymmetrical effects are particular important when the ROV moves slowly. More interesting point is that the linear coefficient ratio ($\left|M'_{|w|}/M'_{|u|}\right|$) of the pitch moment can be more than 52 but the second order force coefficient ratio $\left|M'_{w|w|}/M'_{u|u|}\right|$ is only about 1.59. The data given here clearly shows that the forces induced by the motion in other directions and the pitch moment induced by the surge or heave motions are generally not negligible.

Table 4

Comparison of Coefficients

$\lvert X'_w/X'_u\rvert$	$\left\lvert X'_{\lvert w\rvert}/X'_{\lvert u\rvert}\right\rvert$	$\lvert X'_{ww}/X'_{uu}\rvert$	$\left\lvert X'_{w\lvert w\rvert}/X'_{u\lvert u\rvert}\right\rvert$
4.06×10^{-2}	8.34×10^{-2}	0.535	0.163
$\lvert Z'_u/Z'_w\rvert$	$\left\lvert Z'_{\lvert u\rvert}/Z'_{\lvert w\rvert}\right\rvert$	$\lvert Z'_{uu}/Z'_{ww}\rvert$	$\left\lvert Z'_{u\lvert u\rvert}/Z'_{w\lvert w\rvert}\right\rvert$
6.37×10^{-2}	2.38	108	5.35×10^{-2}
$\lvert M'_w/M'_u\rvert$	$\left\lvert M'_{\lvert w\rvert}/M'_{\lvert u\rvert}\right\rvert$	$\lvert M'_{ww}/M'_{uu}\rvert$	$\left\lvert M'_{w\lvert w\rvert}/M'_{u\lvert u\rvert}\right\rvert$
0.271	52.3	0.435	1.59

5. Conclusion

This paper deals with the hydrodynamic behaviors of a new ROV moving in a vertical plane. The ROV is complex and asymmetrical in its shape. A series of model tests are carried out. Based on the test results, the corresponding fitting formulae of the hydrodynamic forces and moments are obtained, which can be used for predicting the motions of the ROV and for validating numerical results. Also based on the test results, the effects of the asymmetry on the vehicle's hydrodynamic forces and moments are discussed and quantified. Some conclusions are summarized as below.

1. For the surge towing tests, the vertical force (Z) magnitudes in the vertical direction are considerably different for different towing direction, though they always point upward (i.e., in the negative direction

of z-axis). Dimensionless vertical force due to forward motion can be twice of that due to backward motion. Similarly, the moments (*M*) in the pitching direction caused by the forward and backward motion are different, particularly for the relatively large towing velocity, though their direction is the same (rotating about positive direction of y-axis). These differences are the results of the front-rear and top-bottom asymmetry of the ROV.

2. For the heave towing tests, the surge forces for the upward and downward motions are considerable different not only in their magnitudes but also in their direction. Specially, the upward motion generates a force in positive surge direction while the downward motion causes a force in negative surge direction. In addition, the moments in the pitch direction caused by the upward and downward motions are also very different. When the ROV is towed upward, the moment significantly increases with the velocity but the moment is almost zero when it is towed downward.

3. For each value of velocity, the tests are repeated several times. Based on the error analysis on the repeated results, the value of forces and moments calculated by the fitted formulae may have accuracy with the maximum error less than 10% and the mean error less than 5%.

4. Nondimensional hydrodynamic coefficients do not vary significantly with the change of Reynolds number. Based on this fact, the nondimensional coefficients may be extrapolated to high Reynolds numbers or speeds.

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***Detailed Response to Reviewers**

Responses to the comments of reviewer

The authors are grateful to the constructive suggestions of the reviewer. We have addressed all the issues raised by the reviewer. The changes for addressing the issues are marked as red in the revised manuscript. Details are given below.

Reviewer #1: The paper reports on the outcome of a study aimed at the acquisition and analysis of experimental data on the forces and moments that apply on an asymmetrical underwater vehicle in two different motions.

The paper is well-written and presented. The experiments have clearly been conducted with careful attention to details, and are reported in sufficient detail. The method presented in this paper for data reduction and data analysis is quite novel and will be of value to others engaged in similar experimentation. The presentation and discussion of the test results is quite comprehensive with a quantitative assessment and good discussion of errors. Although the ROV geometry can clearly be seen from the photos presented in Figures 1-3, it may still be helpful to provide a schematic drawing showing the ROV geometry at the two mid-plane sections of x=constant, and y=constant.

This is very valuable suggestions. Two mid-plane sections are added to Fig. 4 and relevant comments are added in the text.