Deep Sea Motion under Higher Sea States

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ABSTRACT: **Surface waves, induced due to different sea states, greatly affect the dynamics and control of the vehicles operating undersea or on the sea surface. In certain missions involving longer operation time, vehicle may encounter disturbances that are induced by higher sea states, forcing to guide the vehicle to safer depths. In the moderate sea states, taken up to sea state 3, these disturbances are accounted for the motion closer to the sea surface and considered negligible as vehicle moves down to few meters. In case of a rough and higher sea states, disturbances may be experienced even down to hundred meters. This paper attempts to provide a three-dimensional generalization of disturbances in deep sea operating vehicles, by simulating their 6dof motion under higher sea states. A sea state model is realized in terms of inertial forces and moments that vehicle would experience during the motion. An analytical formalism is derived to estimate the induced forces and moments integrated over a given vehicle arbitrarily oriented in the motion. Three limiting cases are considered in this work: (1) the deep water waves: $0.5 < ho/\lambda < \infty$ (2) the intermediate depth waves: $0.05 < ho/\lambda < 0.5$ and (3) the shallow water waves: $0 < ho/\lambda < 0.05$. For illustration, derived forces and moments are applied to a well known autonomous underwater vehicle (AUV) known as REMUS (Remote Environmental Monitoring Unit) taken as reference vehicle for the analysis. Slender shape of REMUS closely approximates the known vehicles like submarine, remotely operated vehicle (ROV) and unmanned ocean vehicle (UOV) to which these results are applicable. Numerical results show that in case of deep water wave at lower sea state, the disturbance no longer remains significant after certain depth. On the other hand in shallow and deep water wave case at higher sea states, the disturbance is found significant, affecting the dynamics of the underwater vehicles, down to larger depths of operation. Deep water wave case is further taken up for detailed study of vehicle motion in three dimensions.**

Keywords: Autonomous vehicles, linear theory, environmental modeling, simulation, waves.

I. INTRODUCTION

Under water vehicles serve important purposes in today's world. Besides the wide spread military use, underwater vehicles perform many others tasks such as maintenance and damage of off shore platforms particularly AUV has become increasingly useful tool for oceanographic exploration. AUV operates in deep to shallow water conditions to complete several missions. AUV oceanographic mission are useful such as for pollution analysis, coastal water sampling, etc. Other missions entail coastal engineering, which encompasses everything from dynamical studies to the sampling of sediments. Finally the AUV can be used in military operations like reconnaissance and locating the mines along hostile coastlines.

A major factor in the effectiveness of an AUV is its ability to explore new territory without human control and return to the point at which it was inserted in to the water. Therefore, a capable control system that can anticipate and adapt to its surroundings is crucial. The control of AUV in the shallow and deep waters in higher sea states make it more difficult. In deep water most of the missions take place at depths below the region of surface waves effects.

Sea waves of different amplitudes and wavelength corresponding to different sea states are among the main sources for the sea disturbances [9-14]. These forces have great impact on the ships, ROV, UOV submarine etc. In the literature, the study of underwater disturbance on vehicle motion is investigated with reference to specific application and the design of the vehicle [1,7,8,9,11,12]. This paper attempts to provide a three-dimensional generalization of disturbances affecting the deep sea operating vehicles by simulating a 6dof motion under higher sea states.

Based on the velocity and pressure fields [1,5] of the waves, a linear airy wave theory is used to estimate the induced disturbance. A sea state model is realized here in terms of inertial forces and moments that vehicle would experience during the motion. An analytical formalism is derived to estimate the induced forces and moments integrated over a geometrical configuration of a vehicle arbitrarily oriented during the motion. For the sake of an order of magnitude estimates, reference geometry of the vehicle is considered as a slender shape which approximates the commonly known vehicles like submarine, ROV and UOV. In comparison of wavelength (λ) with the sea depth (h_0) following limiting cases are considered in this work: (1) the deep water waves: 0.5 $h_o/\lambda < \infty$ (2) the intermediate depth waves: 0.05 $h_o/\lambda < 0.5$ and (3) the shallow water waves: $0 < h_o/\lambda < 0.05$. As we will see, the numerical results show that in case of deep water wave at lower sea states (up to 3), the disturbance no longer remains significant after certain depth. On the other hand in deep water at higher sea states and in the shallow water case, the disturbance is found significant, affecting the dynamics of the underwater vehicles. Deep water wave case is further taken up for study of vehicle motion in three dimensions. Two specific vehicle orientations, as envisage in [11], are specifically simulated, analyzed and compared. These are (i) head sea in which the waves is supposedly shine longitudinally to moving body; and (ii) beam sea in which waves shine

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laterally on the vehicle motion. In head sea waves, only the pitch force and moment are experienced by the body; on the other hand, in case of beam sea pitch and yaw forces and moments of equal magnitude are experienced. These effects are profound near the surface and decreases exponentially with the depth.

II. LINEAR WAVE THEORY FOR DEEP, INTERMEDIATE AND SHALLOW WATER WAVES

Gravity waves: The endeavour of gravity to bring the disturbed sea surface (regardless the causes of this disturbance) back to its equilibrium position gives rise to the so called gravity waves. Gravity waves are being taken care of in the present treatment. Following assumptions are made (i) water is ideal, i.e. inviscid, incompressible and irrotational; (ii) the presence of the body i.e. cylinder does not disturb the pressure and velocity fields of wave which is ensured by taking the diameter (D) of the cylinder much smaller than the wave length (λ) of the wave i.e. $ky = 2\pi/\lambda \ll 1$ so does, kz

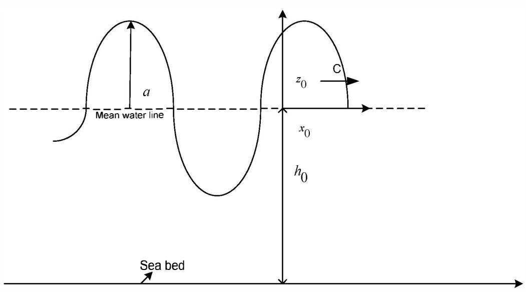

Fig. 1: Shown are a reference frame $x_0y_0z_0$ and a right-running wave.

Linear wave theory gives the solutions [1,5]

$$\eta^- = a\sin(kx_0 + \omega t)$$

$$\eta^+ = a\cos(kx_0 - \omega t)$$

Where the subscripts minus and plus refer to left-running and right-running waves, respectively. Here a is the amplitude of the wave. The velocity potentials corresponding to the above equations are:

$$\phi_w^- = \frac{ag}{\omega}\frac{\cosh[k(z_0 + h_0)]}{\cosh(kh_0)}\cos(kx_0 + \omega t),$$

and

$$\phi_w^+ = \frac{ag}{\omega}\frac{\cosh[k(z_0 + h_0)]}{\cosh(kh_0)}\sin(kx_0 - \omega t),$$

where

$$\omega^2 = gk\tanh(kh_0)$$

There are three types of waves which are the function of h_o/λ.

A. DEEP WATER WAVES $(0.5 < h_0/\lambda < \infty)$

For studying the effects in the deep water waves we assume that the wavelength of the waves is very small compared to the depth of the sea so we can assume that $h_0 \to \infty$ such that [1,3,5]

$$\eta = a\cos(kx_0 - \omega t)$$

$$\phi_w = \frac{ag}{\omega}e^{kz_0}\sin(kx_0 - \omega t)$$

$$\omega^2 = gk$$

Pressure Field of Wave: The total pressure at a point below the water surface according to the linearized Bernoulli equation is [8]

$$p = p_0 - \rho g z_o - \rho\frac{\partial\phi_w}{\partial t},$$

where p_0 is the standard atmospheric pressure the effect of which, when integrated across the whole surface of the body, comes out to be zero, $\rho g z_o$ corresponds to the hydrostatic pressure for the case of calm water, when summed up for the entire body surface, the buoyancy of the body and the last one gives the pressure due to wave. The pressure gradient $\partial p/\partial z_o$ for the hydrostatic case (i.e. in the absence of wave) equals the specific weight of the fluid and causes a buoyant lifting force on the immersed body that equals the weight of displaced water. As we are interested only in the effect of wave pressure on the body so above equation takes the form:

$$p = -\rho\frac{\partial\phi_w}{\partial t}.$$

If we reverse the direction of z_o-axis in the reference system $x_oy_oz_o$-o_o and translate it vertically downward to some depth H then in the expression for the velocity potential of wave z_o needs to be replaced by $-(z_o+H)$ i.e.

$$\phi_w = \frac{ag}{\omega}e^{-k(z_0+H)}\sin(kx_0 - \omega t) \tag{1}$$

which, using the complex number notation, can further be written as [1, 17]

$$\phi_w = -\frac{iag}{\omega}e^{i(kx_0-\omega t)-k(z_0+H)}$$

The wave induced pressure field accordingly takes the shape

$$p = i\omega\rho\phi_w \tag{2}$$

Here are $x_0y_0z_0$ are the inertial coordinates related to the body axes via the transformation [12]:

$$\begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix} = \begin{pmatrix} \overline{x} \\ \overline{y} \\ \overline{z} \end{pmatrix} + [T]\begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

Where, T_{ij} are the direction cosines of the transformation matrix, $[T]$ situated at its ith row and jth column.

Force (per unit length of the body) exerted by the pressure field along the z_0–direction on the cross-sectional area of the body at x in the body frame 0xyz:

$$f_p(x) = \oint jp(y, z; x)(dy + jdz) \tag{3}$$

Now using the Green's theorem [13] on the right hand side of Eq (3):

$$f_p(x) = -\iint_R \left(\frac{\partial}{\partial y} - j\frac{\partial}{\partial z} \right) p(y,z;x)\,dydz \qquad (4)$$

Using (2), Equation (4) takes the form

$$f_p(x) = be^{-kH} g(-1) \times E(-1;x)S(-1;x)a\rho g S(x) \qquad (5)$$

Where

$$b = -a\rho g k e^{-i\omega t}$$
$$E(a;x) = e^{k[i\bar{x} + a\bar{z} + (iT_{11}+T_{31})x]} \qquad (6)$$
$$g(c) = (iT_{12} + cT_{32}) + j(iT_{13} + cT_{33})$$

Velocity Field of Wave: Under the assumption that the velocity field of wave is not affected by the body, the effect of the wave velocity field on the body can be evaluated in planes perpendicular to its symmetry axis i.e. treating as two dimensional flow problem via the Newton's second law of motion:

$$\boldsymbol{F} = -m\left(\frac{\partial \boldsymbol{V}}{\partial t} + \boldsymbol{V} \cdot \nabla \boldsymbol{V} \right) \qquad (7)$$

Since the flow is impinging an area $S(a,x)$ with velocity $v_w + jw_w$ in yz plane, the added mass of water is $\rho_w S(a,x)$ and the corresponding momentum is $-(v_w + jw_w)\rho_w S(x)$. Thus following from (7) and taking $\partial/\partial x \gg \partial/\partial y, \partial/\partial z$, the force per unit length is given by

$$f_w(x) = \left(\frac{\partial}{\partial t} - u\frac{\partial}{\partial x} \right)\{(v_w + jw_w)\rho_w S(x)\} \qquad (8)$$

Where the velocity components v_w, w_w along y and z-axes are given by

$$v_w + jw_w = \left(\frac{\partial}{\partial y} + j\frac{\partial}{\partial z} \right)\phi_w \qquad (9)$$

Using (9) in (8):

$$f_w(x) = be^{-kH} g(-1) \times E(-1;x)S(x)a\rho g + \frac{bu}{i\omega} e^{-kH} g(-1) \times E(-1;x)S'(x)a\rho g$$

Hence the total force exerted by the waves on the body is

$$f(x) = f_p(x) + f_w(x) \qquad (10)$$

B. INTERMEDIATE DEPTH $(0.05 < h_0/\lambda < 0.5)$

Intermediate depth waves are the waves for which the wavelength of the surface waves is comparable to the depth of the sea so the above equations can be written as under [1]:

$$\eta = a\cos(kx_0 - \omega t)$$
$$\left\{ \phi_w = \frac{ag}{\omega} \frac{\cosh[k(z_0 + h_0)]}{\cosh[k(h_0)]} \sin(kx_0 - \omega t) \right\}$$

where $\omega^2 = gk\tanh(kh_0)$

Following the procedure for deep water case we find forces due to pressure field of waves for intermediate depth for a unit cross-section as

$$f_p(x) = \frac{be^{k(h_0+H)}}{2\cosh(kh_0)} g(-1)E(x)S(x) + \frac{be^{-k(h_0+H)}}{2\cosh(kh_0)} g(-1)E(-1;x)S(x)$$

For velocity field of waves the force per unit length of the body is

$$f_w(x) = \frac{be^{k(h_0+H)}}{2\cosh(kh_0)} g(-1)E(1;x)S(x) + \frac{bue^{k(h_0+H)}}{2i\omega\cosh(kh_0)} g(-1)E(1;x)S'(x) + \frac{be^{-k(h_0+H)}}{2\cosh(kh_0)} g(-1)E(-1;x)S(x) + \frac{bue^{-k(h_0+H)}}{2i\omega\cosh(kh_0)} g(-1)E(-1;x)S'(x) \qquad (11)$$

Hence the total force exerted by the waves on the body is

$$f(x) = f_p(x) + f_w(x)$$

C. SHALLOW WATER WAVES $(0 < h_0/\lambda < 0.05)$

Shallow water waves are the waves for which the wavelength of the waves is very large and the waves travel to the depth and reflect back. The hyperbolic function in this case is approximated as follows:

$\sinh(kh_0) \cong \tanh(kh_0) \cong kh_0$, and $\cosh(kh_0) \cong 1$

such that $\quad \eta = a\cos(kx_0 - \omega t)$

$$\lambda = \frac{2\pi}{k} = (gT^2 h_0)^{1/2}$$
$$\phi_w = \frac{agT}{2\pi}\sin(kx_0 - \omega t)$$

Where $\quad \omega^2 = gk\tanh(kh_0) \cong gk^2 h_0$

$$\phi_w = -\frac{iagT}{2\pi} e^{i\{k(\bar{x} + T_{11}x + T_{12}y + T_{13}z) - \omega t\}}$$

So the expressions for the force due to pressure field of waves become

$$f_p(x) = b\omega T g(0)E(0;x)S(x)$$

and

$$f_w(x) = b\omega T u g(0)E(0;x)S(x) + \frac{b}{i}Tg(0)E(0;x)S'(x) \qquad (12)$$

Hence the total force exerted by the waves on the body is

$$f(x) = f_p(x) + f_w(x)$$

Total forces and moments along the total length of the body are given by

$$F_y = \int_{-l}^{l} Y dx, \; F_z = \int_{-l}^{l} Z dx$$
$$M_y = \int_{-l}^{l} (-Z)x dx, \; M_z = \int_{-l}^{l} Yx dx$$

Onward treatment is confined to right-running wave.

III. SIMULATION RESULTS AND DISCUSSION

Reference vehicle: For the illustration of our work in this paper, REMUS AUV [14] is chosen as a plate form. REMUS is developed for application in autonomous docking, long range oceanographic survey, and shallow water mine reconnaissance ref [2].

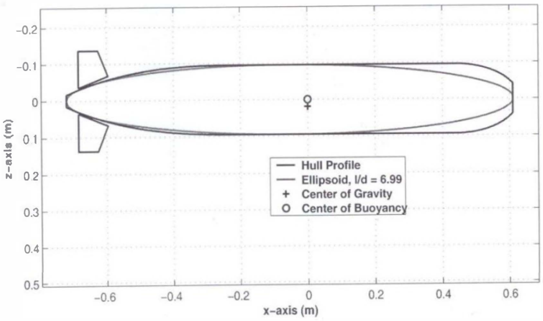

Fig. 2: Standard REMUS Profile

The REMUS vehicle is equipped with four identical control fins, mounted in a cruciform pattern near the aft end of the hull. The weight of the REMUS vehicle can change between missions and the typical values for the vehicle weight of 299N and buoyancy 306N. Buoyancy centre (x_{cb}, y_{cb}, z_{cb})=(-0.611, 0,0)m w.r.t. the nose and values of the centre of gravity w.r.t. the buoyancy centre are (x_{cg}, y_{cg}, z_{cg})=(0, 0, 0.0196)m. We assume that for a given REMUS vehicle during field operations, the centre of buoyancy stays roughly constant. The vehicle centre of gravity, on the other hand, can vary.

The average values of the centre of buoyancy (w.r.t. vehicle that effect of the changes in centre of gravity on the vehicle moments of inertia are small enough to be ignored. The estimated values are (I_{xx}, I_{yy}, I_{zz}) = (0.177,3.45,3.45) kg.m^2. Further a simpler model for the REMUS propulsion system is used which treats, the propeller as a source of constant thrust and torque which is good enough under small amplitude perturbations.

A simple PID control is taken for the pitch and yaw control. Roll remained to be bounded due to a suitable lowering of the CG. The hydrodynamics force and moment coefficients are taken from the [14].

The block diagram of the simulation scheme in the presence of see disturbance is shown in Fig3.

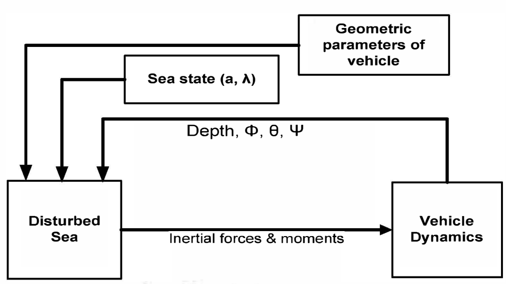

Fig 3: Simulation Block Sets

Simulation Results: We have chosen four different cases for the illustration. Case 1 & 2 use the sea state 4 (a wave height=2m, time period=5sec) and sea state 6 (a wave height=2m, time period=9sec), respectively, the vehicle is operating at a depth of 25m. In case 3, we have taken the sea state 7 (a wave height=11m, time period=11sec) while in case 4 the combined effects of all sea states from sea state 4 to sea state 8 is shown for vehicle operating at a depth of 100m. Time history of three cases is given in Fig 4-7. From the figures, the sinusoidal motion of the attitudes of the vehicle is correlated with the chosen sea state.

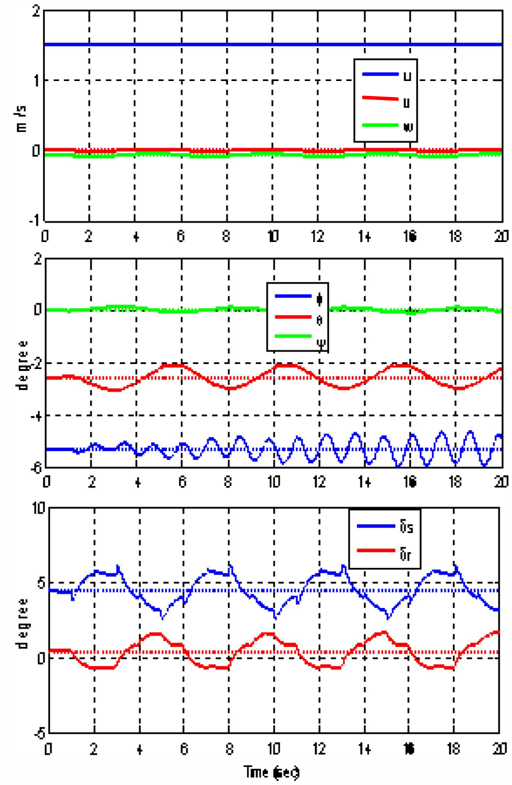

Fig. 4: REMUS motion under sea state 4 at a depth of 25m (a) velocity components; (b) attitude angles; and (c) elevator (δs) and rudder (δr). Dotted lines corresponds to nominal motion of the vehicle

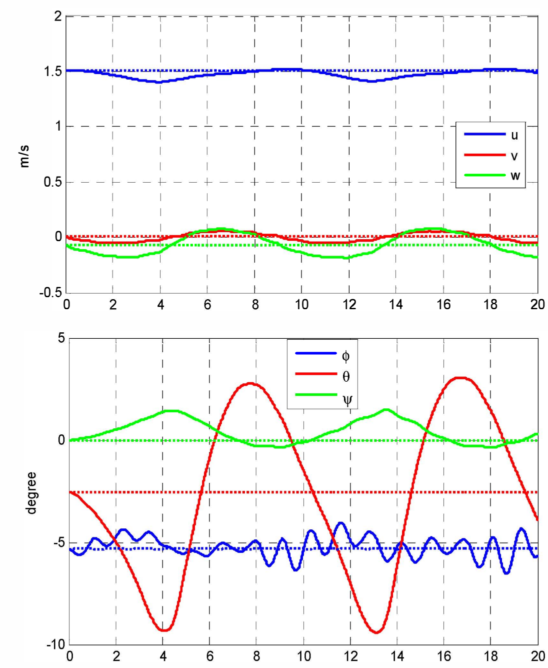

Fig. 5: REMUS motion under sea state 6 at a depth of 25m (a) velocity components; (b) attitude angles.

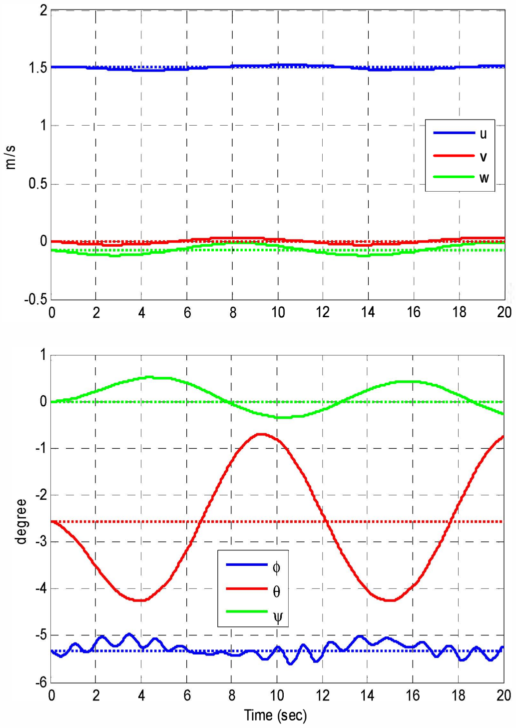

Fig. 6: REMUS motion under sea state 7 at a depth of 100m (a) velocity components; (b) attitude angles.

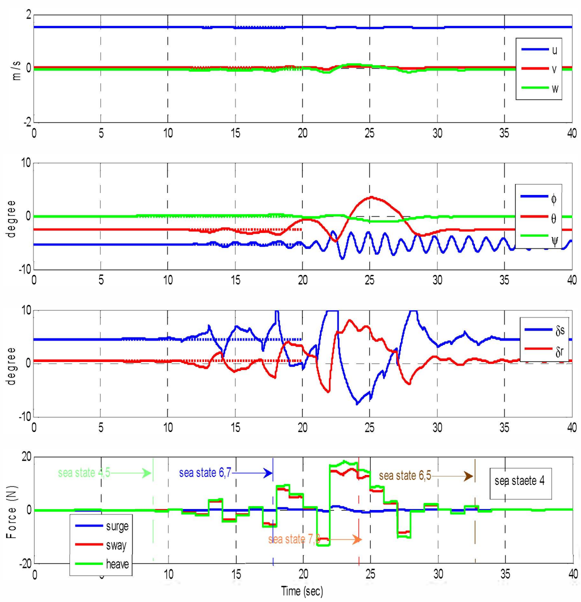

Fig. 7: REMUS motion under sea state 4 to 8 at a depth of 100m (a) velocity components; (b) attitude angles; (c) control surfaces deflections; (d) wave forces

IV. Conclusion

In this paper we have derived 3D surface waves model for different sea states and represented the effect the forces and moments on the underwater vehicle so that safety conditions for operating such vehicles may be determined by simulating its 6DOF motion under a disturbed sea.

Based on the velocity and pressure fields of the waves under linear wave theory we estimate the induced disturbance. An analytical formalism was derived for forces and moments integrated over the vehicle geometrical configuration arbitrarily oriented during the motion. For the sake of illustration REMUS was taken up as reference vehicle. In comparison of wavelength with the sea depth three limiting cases were analytically derived and simulated.

Numerical results showed that in case of deep water wave at lower sea states (up to 3) the disturbance no longer remains significant after certain depth. On the other hand in deep water at higher sea states and in the shallow water case, the disturbance was found significant at higher depths also, affecting the dynamics of the underwater vehicles. Deep water wave case is further taken up for study of vehicle motion in three dimensions. Two specific vehicle orientations (i) head sea and (ii) beam sea, were specifically simulated, analyzed and compared. And here we have shown the beam sea cases as they have the effects both for pitch as well as yaw motion of the vehicles.

To conclude, simulating the disturbances induced by higher sea states are of great significance with reference to control and stability analysis of underwater vehicle motion.

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