In this paper, the heading control of an Autonomous Underwater Vehicle is improved in order to counteract the undesirable effect of the waves in the actuators system. Wave filter suggested is a linear passive observer and includes features like estimation of both the low frequency heading and heading rate of the vehicle from noisy measurement of an Inertial Measurement Unit, removing the oscillatory component. Matlab/Simulink tool is used to show the proposed solution into the control loop, its performance and the simulation with real data. The experimental results confirm the suitable filtering, the estimating properties of the observer and the navigation response expected, reducing control action and thus vibrations of the rudder.

**Keywords**: Passive observer, Wave filter, Heading control, Wave induced motion, Underwater vehicle

Introduction

The Group of Automation, Robotic and Perception (GARP) of the Central University of Las Villas (UCLV) and the Hydrographic Research Center (HRC) has developed an Autonomous Underwater Vehicle (AUV) based on low costsensors. The vehicle is built by the HRC and GARP is the one in charge of designing the Dynamic Positioning System (DPS). The DPS has great importance for AUV’s moving through an unknown environment and is a field of control engineering that has received the attraction of many Researchers Centers, Universities and Companies around the world.

For marine applications the total motion of the vehicle-waves system is the sum of a low frequency motion (LF) representing the motion of the vehicle and a high frequency (HF) wave induced motion. Therefore, one of the most important issues to take into account when designing DPS for these applications is wave filtering, in order to cancel out the oscillatory behavior of the wave induced motion component.

A large variety of solutions has been proposed to improve the performance of the vehicle autopilot and offer wave filtering. The first DPS’s were designed using dead band techniques, conventional low pass and/or notch filters but have the inconvenient to limit the control action and to introduce significant phase lag, and thus performance degradation when a high control gain is required. Later, more advanced techniques were implemented on vehicle model, it means, a wave induced motion model and an observer in order to separate the high frequency wave induced motion from the low frequency vehicle motion. The Kalman Filter (KF) approach is also used but is computationally more intensive and the tuning procedure is difficult because apriori information of the process and measurement noise covariance is required.

This paper aims at improving the performance of the heading control of an AUV, used by the HRC who develop AUV’s for research purposes. The solution proposed is based on the first order Nomo to model for heading response of ships, a second order waves transfer function and direct measurements of an inertial sensor. The heading control considers a single loop with a PI-D controller with heading angle feedback. The wave filter, that uses linear models and an observer is quite advantageous and it has been tested by others researchers in different marine applications.

To illustrate the robustness of the proposed wave filter, the effects on the measurements and the

Wave filtering for heading control of an AUV based on passive observer

Delvis Garcia-Garcia, Yunier Valeriano-Medina, Luis Hernández & Alain Martínez-Laguardia
Departamento de Automática y Sistemas Computacionales, Facultad de Ingeniería Eléctrica, Universidad Central “Marta Abreu” de Las Villas. Carretera a Camajuaní km 5.5, Santa Clara (54830), Villa Clara, Cuba.
[E-mail:dggarcia@uclv.edu.cu, yunierv@uclv.edu.cu, luishs@uclv.edu.cu, amguardia@uclv.edu.cu]

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actuators system and its performance, simulation results via MATLAB/Simulink, as well as experimental results with real data obtained during a sea trial are presented. These experimental results confirm the expected behavior of the observer, separating the LF and HF motion components from noisy measurements.

The paper is organized as follows: Introduction, following by the principal specifications of the HRC-AUV and also the description of the coordinate systems and specific nomenclature adopted. The next part is related firstly with the mathematical models used to represent Underwater Vehicles (UV’s) dynamics and the first order heading response, and secondly with the models used to represent the wave forces and the waves induced motion. Then, the fixed gain observer is proposed where the heading angle of vehicle is measured by an inertial sensor. Finally, experimental results from different amplitudes of steps input to the heading control loop are shown, demonstrating the good performance of the system with wave filter included in the control loop.

**Materials and Methods**

**A. Description of the System**

As shown in Figure 1, the system considered consists of two segments: the onboard and remote segments. The onboard segment hardware architecture is composed of two computational units\(^2\); an industrial PC-103 and an embedded system based on a Microchip DSPIC-30F4013. These two units share the tasks of data acquisition from the sensors and the control/navigation tasks. The remote segment is a laptop running the high level supervision software and provided with a wireless link. Embedded systems are the most hardware architecture used in underwater vehicles\(^20-21-22\).

The sensors installed in the HRC-AUV are:

1. **Inertial Measurement Unit (IMU):** MTi from XSens Corporation. For accurate real-time attitude and orientation of the vehicle.
2. **Depth:** Cerabar T PMP 131 from Endress+Hauser, analog sensor. Used to determine the operation depth of the AUV.
3. **Battery Level:** Analog sensor. Estimate the status of the battery based on the voltage and current levels.
4. **Leak:** Digital sensor. In order to detect any water leakage.
5. **Rudders angle:** MLO-POT-225-TLF from Festo, analog sensor. Provide the true position of the rudders.
6. **Thruster rpm:** Digital sensor. Provide the revolutions of the main propulsion thruster.
7. **GPS:** XL12 from Garmin, digital sensor. Provides accurate information on the status of the vehicle, given in latitude, longitude, speed and height. (It is used only to surface navigation).

![Fig. 1—System structure](image-url)
B. Coordinate systems and nomenclature

The motion of a submarine at sea is described with respect to an inertial reference system. It is usually assumed that the acceleration of a point on planet surface produced by the rotation of the Earth does not affect the motion of a low speed marine vehicle\textsuperscript{15-19}. HRC-AUV moves at speed of 1.9 m/s thus the rotation can be neglected and the Earth-fixed reference system can be considered as an inertial frame and a North, East, Down (N.E.D.) navigation frame. Figure 2 depicts the coordinate systems and the definition of translation and rotation variables of the vehicle.

Table 1 summarizes the nomenclature used to describe the movement of mobile forces and moments. This is the recommended standard notation to use on applications maneuver and control of submarines\textsuperscript{18}.

C. Mathematical Models for Wave Filter Design

Dynamic model of the HRC-AUV

The equations that describe the vehicle motion can be obtained from the conservation laws of linear and angular moments referred to an inertial reference system. The general dynamic model of UV’s can be expressed as\textsuperscript{1-19,20}:

\[
\dot{\eta} = R(\eta)v
\]  \hspace{1cm} \text{(1)}

\[
M \cdot \ddot{v} + C(v)\dot{v} + D(v)v + g(\eta) = \tau
\]  \hspace{1cm} \text{(2)}

Where:

\[
M = M_{RB} + M_A
\]  \hspace{1cm} \text{(3)}

\[
C(v) = C_{RB}(v) + C_A(v)
\]  \hspace{1cm} \text{(4)}

\[
\begin{align*}
&\text{M} = \text{inertia matrix (including added mass } M_A) \\
&\text{C}(v) = \text{matrix of Coriolis and centripetal terms (including added mass } C_A(v)) \\
&\text{D}(v) = \text{damping matrix.}
\end{align*}
\]

\[
\begin{align*}
&\text{g(}\eta) = \text{vector of gravitational forces and moments} \\
&\tau = \text{vector of control inputs} \\
&v = \text{vector of velocities} \\
&\eta = \text{vector of position (N. E.D.)} \\
&R(\eta) = \text{transformation matrix from body to navigation frame}
\end{align*}
\]

The first order Nomoto model for heading response

The UV’s general model contains nonlinear terms\textsuperscript{1}, however the heading control is used to correct deviations from a desired equilibrium heading and therefore a linear model is sufficient for control and observer design. The response in yaw rate due to a small deviation in the angle of rudder can be derived from equations (1) and (2) by isolating the yaw motion, which is given by:

\[
N_\delta \dot{\delta} = (I_{zz} - N_r)\dot{r} - N_r r
\]  \hspace{1cm} \text{(5)}

Where \( I_{zz} \) is the moment of inertia around the z-axis, \( N_r \), \( N_\delta \) and \( N_r \) are hydrodynamic coefficients, \( \dot{r} \) is the yaw rate and \( \delta \) is the actuator or rudder angle. This model is known as the first order Nomoto model\textsuperscript{20} and can be written in transfer function as:

\[
\frac{r(s)}{\delta(s)} = \frac{K}{Ts+1}
\]  \hspace{1cm} \text{(6)}
Where the time constant and gain are given by:

\[
K = \frac{-N_\delta}{N_r} \quad \ldots (7)
\]

\[
T = \frac{1}{s^2 - N_r} \quad \ldots (8)
\]

The transfer function needed for observer design is the response in yaw angle versus the rudder angle. The real experiments performed demonstrate that the heading of our vehicle in open loop exhibit an unstable behavior due to small deviations in the rudder angle, because of the integrator in the transfer function. Hence, the identification of the parameters \(K\) and \(T\) was made by experiments on the sea using an open loop scheme, some step variations in the rudder position are manually introduced and the rate of yaw output is registered. Finally, the input signal \(\delta\) and output yaw rater, are processed in the System Identification Toolbox of MATLAB, obtaining \(K = 0.14\) and \(T = 4s\). Then, the transfer function of the yaw angle due to a small deviation in the rudder angle is:

\[
\psi(s) = \frac{K}{s(T+1)} \quad \ldots (9)
\]

Equation (9) represents the LF vehicle dynamics and is used to obtain the useful signal to the heading control loop.

**Model for wave forces and wave induced motion**

The main environmental disturbances affecting marine vehicles during navigation are the waves generated by wind and ocean currents\(^{15-16}\). Taking into account the effects of the waves, equation (1) can be rearranged as:

\[
M \ddot{\psi} + C(\psi)\psi + D(\psi)\psi + g(\eta) = \tau_t \quad \ldots (10)
\]

Where \(\tau_t = \tau + \tau_{waves}\) and \(\tau_{waves}\) represent the moment and forces caused by waves. Wave forces are usually modeled as the sum of a linear and a nonlinear component\(^9\), as:

\[
\tau_{waves} = \tau_{wlin} + \tau_{wnlin} \quad \ldots (11)
\]

The second term on the right hand side of the expression (11) corresponds to the low frequency component and is commonly treated as an input disturbance and modeled by a bias term\(^8\), hence in the rest of the paper it will be dismissed. On the other hand the linear high frequency component is usually modeled by the wave elevation transfer function approximation of the wave spectrum selected\(^{13}\), in this case the Jonswap spectrum is chosen\(^{1-10}\). For simplicity a 2\(^{nd}\) order of the wave transfer function approximation is considered in this article, in the form as shown in expression (12). However, higher order wave transfer function approximations can also be used, such as 4\(^{th}\) and 6\(^{th}\) order\(^{13}\), with greater order a more precise approximation to the wave spectrum can be obtained but this also increase the number of model parameters to be determined and the dimension of the observer gains to be tuned\(^3\).

\[
\psi_H(s) = \frac{K_w s}{s^2 + 2\zeta \omega_n s + \omega_n^2} w(s) \quad \ldots (12)
\]

Where:

\[
K_w = 2\zeta \omega_n \sigma \quad \ldots (13)
\]

In the expressions (12) and (13), \(\omega_n\) is the dominating wave frequency, \(\zeta\) is the relative damping ratio, \(\psi_H\) is the yaw angle induced by the waves, \(w\) is a zero mean Gaussian white noise and \(\sigma\) is a parameter related to the wave intensity that is adjusted on the sea trials depending on the level of affection of the waves on the vehicle.

In addition, the wave frequency response of the ship is generated by using the principle of linear superposition due to the total motion can be separated in LF and HF components as shown in Fig. 3, obtaining the expression:

\[
\psi = \psi_L + \psi_H \quad \ldots (14)
\]

Taken this into a consideration, we can write the LF yaw dynamics and the HF motion as:

\[
\psi_L = r_L \quad \ldots (15)
\]

\[
\dot{r}_L = -\frac{1}{T} r_L + \frac{K}{T} \delta \quad \ldots (16)
\]

\[
\dot{\psi}_H = \psi_H \quad \ldots (17)
\]

Fig. 3—Total motion of the vehicle as the sum of LF and HF components.
\[ \psi_H = -2\zeta \omega_n \psi_H - \omega_n^2 \xi_H + K_w w \] \quad \ldots (18)

Where \( \psi_L \) and \( r_L \) are the LF states, \( \psi_H \) is the HF yaw and \( \xi_H \) is a HF state introduced to represent in state space form the HF wave induced motion equations.

For AUV’s heading measurement is an essential requisite. To obtain this measurement the HRC-AUV relies on the MTi sensor. The accuracy of this sensor in the yaw angle measurement is in the magnitude of 0.1 (deg.) and is degraded considerably in presence of vibrations. Taking into account the sensor noise, equations (14) is modified as (19), resulting a model shown in Figure 4:

\[ \psi = \psi_L + \psi_H + v \] \quad \ldots (19)

Where \( v \) is zero mean Gaussian white measurement noise. The observer must be capable to neglect the differences in the noise levels of the measured signals and perform proper filtering of all high frequency signals. In case of being affected the yaw measurement by a period of time, the system only depends on the estimations of the observer, hence the equation (19) takes the form:

\[ \hat{\psi} = \hat{\psi}_L + \hat{\psi}_H \] \quad \ldots (20)

### D. Observer Structure

The main purpose of the observer or state estimator is to reconstruct the unmeasured LF motion components from the noisy measurement\(^{14-18}\), since the measurements consist of both a LF and a HF component. This is crucial in AUV’ heading control systems because the oscillatory motion due to 1st order wave induced disturbances will, if it enters in the feedback loop, cause wear and tear of the actuators and will increase the energy consumption. Therefore the filtering must be accomplished before the signals are used in a feedback control system.

In general, it is possible to counteract the 1st order wave induced motion of a vessel when applying a reasonable propulsion and thruster system\(^9\). Hence, no improvement in heading autopilot performance should be expected by feeding back the HF signal to the controller due to the controller output maintains the oscillatory behavior and excessive vibration will be presented.

#### Observer equations

To obtain the observer equations, an injection terms have to be added to the dynamics equations (15) ~ (18):

\[ \dot{\hat{\psi}}_L = \hat{\dot{r}}_L + K_1 \hat{\psi} \] \quad \ldots (21)

\[ \dot{\hat{r}}_L = -\frac{1}{T} \hat{r}_L + \frac{K}{T} \delta + K_2 \hat{\psi} \] \quad \ldots (22)

\[ \dot{\hat{\xi}}_H = \hat{\psi}_H + K_3 \hat{\psi} \] \quad \ldots (23)

\[ \dot{\hat{\psi}}_H = -2\zeta \omega_n \hat{\psi}_H - \omega_n^2 \xi_H + K_w w + K_4 \hat{\psi} \] \quad \ldots (24)

Where \( \hat{\psi} = \psi - \hat{\psi}_L - \hat{\psi}_H \) is the estimation error, \( \psi \) is the yaw angle measurement, \( \hat{\psi}_L \) and \( \hat{\psi}_H \) is the LF yaw and yaw rate estimates respectively, \( \hat{\psi}_H \) is the HF yaw estimated and \( K_1, K_2, K_3 \) and \( K_4 \) are the observer gains to be found later. Making use of the notation \( \Delta x = x - \hat{x} \), the estimation error dynamics can be written in state-space form as:

\[
\begin{bmatrix}
\Delta \dot{\psi}_L \\
\Delta \dot{r}_L \\
\Delta \dot{\xi}_H \\
\Delta \dot{\psi}_H
\end{bmatrix} =
\begin{bmatrix}
-K_1 & 1 & 0 & -K_1 \\
-K_2 & -\frac{1}{T} & 0 & -K_2 \\
-K_3 & 0 & 0 & 1 - K_3 \\
-K_4 & 0 & -\omega_n^2 & -2\zeta \omega_n - K_4
\end{bmatrix}
\begin{bmatrix}
\Delta \psi_L \\
\Delta r_L \\
\Delta \xi_H \\
\Delta \psi_H
\end{bmatrix}
\]

\quad \ldots (25)

The characteristic equation of the error dynamic presented in (25) can be found by \( \text{det}[sI - M] \) and take the form:

\[ \pi(s) = s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0 \] \quad \ldots (26)

Where the coefficients are:

\[ a_0 = \omega_n^2 (K_1/T + K_2) \] \quad \ldots (27)

\[ a_1 = K_1 (2\zeta \omega_n/T + \omega_n^2) + 2K_2 \zeta \omega_n - (K_3 + 1) \omega_n^2/T \] \quad \ldots (28)

\[ a_2 = K_1 (1/T + 2\zeta \omega_n) + K_2 + (1 - K_3) \omega_n^2 + K_4/T + 2\zeta \omega_n/T \] \quad \ldots (29)

\[ a_3 = K_1 + K_4 + 2\zeta \omega_n + 1/T \] \quad \ldots (30)
In order to obtain the gains for the observer design, the error dynamic must be satisfied:
\[ \prod_{i=1}^{4}(s - p_{i}) = \pi(s) \]  \hspace{1cm} (31)

Where \( p_{i} \) (\( i = 1 \ldots 4 \)) are the four designed parameters specifying the values of the desired location of the error dynamic poles. The resulting gains of the observer are represented by the vector \( \mathbf{k} = [K_1 K_2 K_3 K_4] \) and it is computed as:

\[ \mathbf{k} = \mathbf{P}^{-1}\mathbf{Q} \]  \hspace{1cm} (32)

Where

\[
\mathbf{P} = \begin{bmatrix}
\omega_n^2/T & \omega_n^2 & 0 & 0 \\
\omega_n^2 + 2\zeta \omega_n/T & 2\zeta \omega_n - \omega_n^2/T & 0 \\
2\zeta \omega_n + 1/T & 1 & -\omega_n^2 & 1/T \\
1 & 0 & 0 & 1
\end{bmatrix} \]  \hspace{1cm} (33)

\[
\mathbf{Q} = \begin{bmatrix}
p_{1234} & \omega_n^2/T \\
-p_{12+4+12+3+4+13+34} + \omega_n^2/T & -p_{12+4+12+3+4+13+34} - (\omega_n^2 + 2\zeta \omega_n/T) \\
-p_{12+4+12+3+4+13+34} - (\omega_n^2 + 2\zeta \omega_n/T) & -p_{12+4+12+3+4+13+34}
\end{bmatrix} \]  \hspace{1cm} (34)

The subscript numbers in matrix (34) indicate sum or multiplication of the corresponding poles. The vector \( \mathbf{k} \) can be computed through \( \mathbf{P} \) and \( \mathbf{Q} \) depending at the same time on the Nomoto model for heading response time constant \( T \), the gain \( K \) and the waves model parameters \( \zeta \) and \( \omega_n \).

\textit{Tuning procedure}

To minimize the estimation error and to satisfy faster convergence of the error dynamics that corresponds to the LF states. The real component of the two poles associated with this states of the observer (\( p_1, p_2 \)), are chosen slightly to the left of the open loop poles of the low frequency model (poles of the linear 1st order Nomoto model. The other two poles (\( p_3, p_4 \)) of the observer are chosen equals and to the left of the first two poles selected. This is to guarantee that the HF estimation error corresponding to the 1st order wave disturbances should converge much faster than the LF states. Also, in order to avoid an oscillatory convergence of the HF state’s estimations errors, the poles \( p_3 \) and \( p_4 \) must be contained real part only. Furthermore, due to the difference between \( p_3 = p_4 \) of the observer and the complex conjugate poles of the wave model, the convergence of the HF state estimation error is not affected by these two poles of the wave model\(^{20}\). Taken this into account, the fixed gain observer will be simulated or implemented using the equations (35) and (36) and following the scheme of Figure 5.

\[
\dot{\mathbf{x}} = A\mathbf{x} + Bu + E_ww + k(y - \hat{y}) \]  \hspace{1cm} (35)

\[
\hat{y} = C\hat{\mathbf{x}} \]  \hspace{1cm} (36)

The state vector in this case is \( \hat{\mathbf{x}} = [\hat{\psi}_L \ \dot{\hat{\psi}}_L \ \hat{\xi}_H \ \dot{\hat{\psi}}_H]^T \), \( u \) is the control input.
(thruster angle), the measurement matrix is $C = [1 \ 0 \ 0 \ 1]$, the gain matrix to be multiplied by the injection term $\hat{y} = y - \hat{y}$ have to be the form previously indicated and $A, B$ and $E_w$ take the forms (37) and (38):

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -1/T & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\omega_n^2 & -2\zeta\omega_n \end{bmatrix} \quad \ldots (37)$$

$$B = \begin{bmatrix} K/T \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad E_w = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad \ldots (38)$$

\section*{Results and Discussion}

\subsection*{Simulations results}

There was a prior 6 DOF model obtained in previous research, later the weaves effect model were attached to it. All of this is shown in Figure 5, particularly in block 2. Only is analyzed the heading control loop, which is controlled by a PI-D (block 1) with $K_p = 1.5$, $K_t = 0.12$ and $K_d = 1$ and with yaw angle feedback. The observer implementation can be seen in blocks 3 and 4. The first represents the LF states estimation, which could be obtained from the first order Nomoto model according to equations (21) and (22) and they will be the smoothed signals to be used in the control loop. The first order Nomoto model is identified with the parameters $K = 0.14$ and $T = 4$s. Block 4 is representing the oscillatory states caused by the ocean weaves and it is in accordance with the equations (23) and (24).

In order to obtain a proper simulation of the measurement signal, a component of noise is added to the 6DOF model output in addition to the wave’s effect, like it is shown in equation (19). This highly disturbed measurement is used to achieve the estimation error that is multiplied by the observer gains obtained with the equation (32). Finally, to verify the suitable operation of the observer and the heading control loop, it is made a change in the heading set-point. Then it is computed the error between this set-point and the LF estimation of the observer; signal that is used by the PI-D controller to offer the actual control action needed to the rudder.

The aim of the observer is to smooth the control action, with a reduction of the HF components and therefore minimize the positioning error and the vibrations of the actuator system. This methodology is applied in the following sections to verify the awaited results.

\subsection*{A. Observer performance in bad weather conditions}

This simulation was performed with parameters of the wave model corresponding of a moderate weather situation. The amplitudes of the 1st order wave induced motions in yaw were selected between 1.0 and 2.0 degrees, this interval corresponds to sea state codes 2 and 4 (smooth and moderate sea)\textsuperscript{19-20}. The wave model damping ratio is fixed to $\zeta = 0.1$ according to the sea operation states\textsuperscript{1} and $\sigma$ was chosen equal to 0.5. Moreover the dominating wave frequency is estimated to approximately $\omega_0 = 6 \text{ rad/sec}$ according to the conditions in which the experiment is carried out, equivalent to a linear frequency of impact of the waves of approximately 1 second. The poles location are chosen $\tilde{\zeta}_1 = -1.5/T$, $\tilde{\zeta}_2 = -0.01/4$, $\tilde{\zeta}_3 = p_4 = -12\zeta\omega_n$ resulting the observer gains $k = [0.183 - 0.040 - 0.48813.151]$.

The LF observer output of yaw is represented in Figure 6 when the system receives step variation of 30° in $\psi_d$ and the $\psi_e$ output is returned to the controller. Note that the measured angle is affected by the ocean waves in addition to high frequency noise intrinsic from the sensor.

Moreover in Figure 7 is shown the estimation errors for both yaw and yaw rate, discern that the estimation errors corresponding to LF states are small. The main reason to use the observer into a control loop is to reduce tear and wear of the rudder and thruster system and to increase the life time of the mechanical structure. This idea can be confirmed if the controller output (desired rudder angle) is checked when the observer is connected and disconnected to

![Fig. 6—Measurement and LF observer output of yaw.](image-url)
the feedback signal. During the first 31 seconds of the simulation shown in Figure 8, the wave filter is switched off and the wave induced motion produces significant control action. Once the wave filter is switched on and the control action at wave frequencies is reduced considerably.

Also, the observer possesses the capability of produces estimates of the LF states despite the absence of heading measurement or when the measurement is extremely noised. Figure 9 exhibits the behavior of the LF yaw observer output with measurement unavailable by different time intervals.

It is seen from the plots that most of the 1st order waves disturbances are filtered out resulting in smooth estimates of the heading and heading rate. Hence, the feedback controller should not be too much affected by the rough sea condition.

B. Observer performance with experimental data

To investigate the performance and robustness of the observer in the real submarine, the algorithm was tested with data obtained from a sea trial. The heading controller implemented in the Onboard Station of the HRC-AUV was a PI-D with identical parameters mentioned in the previous simulations. Again is considered $\zeta = 0.1$, $\sigma = 0.5$, $\omega_n = 6 \text{ rad/second}$ equal pole locations. In Figure 10 is shown the wave induced motion between -1 and 1 degree.

In Figure 11 is shown the same experiment of Figure 4, but using the step input (in green) of 50
degrees, the real yaw angle (in blue) and the LF yaw observer estimated (in red). An important reduction of the wave induced motion and high frequency sensor noise is obtained.

Hence, Figure 12 exhibits the control signal to the rudder. A better performance of the heading control loop is evident; the HF motion caused by the ocean waves is removed and the actuator system receives only the desired control action. The transient response obtained with observer included is similar as the real response and similar as the simulation of Figure 6.

A similar procedure based on linear models and a passive observer is been implemented by GARP for the filtering of the rest components of the attitude vector (roll and pitch) and vehicle depth. The results of these investigations will be shown in future publications.

C. Robustness evaluation

The robustness of the observer should be analyzed in different conditions like: miss of measurement signal, changes in sea conditions, and uncertainties in the vehicle model. The first two cases have been already evaluated in previous subsections in which the good performance of this algorithm is expressed. Finally, the design is completely robust only if the filter adjustment is capable to support some variations in the 6 DOF model parameters.

To test this last possible event, model parameters: \(N_\theta, N_r\) are varied 20% over mean valued. These parameters are selected as center of the variation due the structure of the model used for the observer and the complexity in its determination (through experimental sea test\(^2\)). In table 2 and Figure 13 are presented the different combinations of these parameters and the results achieved by the heading control.

As is possible to discern the results are quite similar to the one presented on Figure 6, experiment in with we assume a total knowledge of the model. So is possible to conclude that the filter is capable of assuming these changes and maintaining the desired performance.

![Fig. 12—Control signal.](image1)

![Fig. 13—Behavior of the observer due the variation of the parameters of the 6 DOF vehicle model.](image2)

Conclusions

Application of a passive wave filter algorithm for AUV heading control is presented. The vehicle performance is increased allowing the system to accommodate changes in parameters and environmental conditions. Simulations results are given to support the results.

The observer has been simulated in different conditions to demonstrate the performance and robustness of it. Experimental results from sea trials performed in the Cuban coast have also been reported. It has been shown that both the low frequency heading and heading rate of the HRC-AUV can be computed from noisy heading measurements. In addition, filtering of 1st order wave induced disturbances has been done. The observer algorithmis
relatively simple and consequently feasible to implement in the embedded hardware for real-time operation.
As future work GARP researchers will implement the same algorithm for the longitudinal subsystem, with the purpose of depth/pitch filtering.

References
12 SNAME, Nomenclature for treating the motion of a submerged body through a fluid, Technical and research bulletin No. 1-5, New York, 1950.
14 Fossen, T. I., Handbook of Marine Craft Hydrodynamics and Motion Control, (John Wiley and Sons Ltd.) 2011, pp. 575.