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U-model based controller design for an unmanned free swimming submersible (UFSS) vehicle under hydrodynamic disturbances

I. Abbasi[1], S. S. A. Ali[1*], M. Ovinis[2] & W. Naeem[3]

[1]Department of Electrical & Electronic Engineering, [2]Department of Mechanical Engineering,
Universiti Teknologi PETRONAS, Bandar Seri Iskandar 32610, Malaysia

[3]School of Electronics, Electrical Engineering and Computer Science,
Queen's University Belfast BT7 INN UK

[Email: msc.isra@gmail.com, saad.azhar@utp.edu.my*, mark_ovinis@utp.edu.my, w.naeem@qub.ac.uk]

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This paper presents design and implementation of the U-model based controller for controlling pitch angle and heading of an unmanned free swimming submersible vehicle. It is shown that the U-model can adaptively model dynamics of unmanned free swimming submersible and since the U-model is a control oriented scheme, a simple law based on internal model control is used to synthesize the control input. Performance of designed controller is evaluated under hydrodynamic disturbances caused by water current. Further, the performance of proposed scheme is compared with the traditional PID. Both controllers give satisfactorily performance with the U-model performing better in terms of settling time and steady state error.

[**Keywords:** Adaptive Internal Model Control, Pitch Control, Heading Control, U-model, Underwater Robotics]

Introduction

The unmanned underwater vehicle (UUV) has revolutionized the way underwater tasks are performed. With no human operator on board, the UUV navigates in ocean and performs tasks that were either hard or impractical for human to undertake. These vehicles are equipped with internal sensors that monitors the vehicle's heading, depth and attitude and external sensors that are constantly scanning the ocean to determine environmental properties. UUVs are broadly classified into two types, remotely operated vehicle (ROV) and autonomous underwater vehicle (AUV). The AUV has gained wider popularity as compared to the ROV due to its autonomous nature and intelligent decision making capability. Whereas, the ROV needs a tether connection or human operator on ship platform to control and supervise the vehicle.

The smooth operation of the AUV depends largely on its control structure. Multivariable and highly dynamic nature of the AUV combined with hydrodynamic disturbances of ocean intensify the burden on effective design of controller. Variety of control schemes have been studied and implemented in terms of controlling the AUV. Most existing AUVs use the traditional PID control structure to control various parameters of vehicle. A number of researchers used sliding mode control (SMC) in order to tackle the variations in hydrodynamic behavior[1-4]. Further, the linear quadratic regulator (LQR) has widely been researched to control the AUV with LQR showing better performance than the PID[5] and the state feedback[6]. However, LQR being a model based control structure needs an accurate mathematical model of the AUV to tune Q and R matrices. This limits the application of the LQR as obtaining accurate dynamic model based on physical laws is complicated and intricate. In this regard, intelligent modeling techniques like the fuzzy logic[7-9]and the neural network[10-11] (NN) offers an advantage as they don't explicitly need to derive the mathematical model based on laws of physics and yet can approximate the system with high accuracy. However, these intelligent techniques demand substantial computational power as controller based on the NN has to deal with computation involved in each node and that based on the fuzzy logic has to execute complex decision making processes. With limited on-board computational power embedded on the AUV, use of controller based on artificial techniques becomes impractical and unfeasible. Moreover, the presence of hydrodynamic disturbances caused by water wave has far been neglected in most of control schemes studied and implemented in literature.

Hence, there is a need of controller that can control adaptively in presence of hydrodynamic disturbances without requiring to model equations for dynamics and kinematics of the vehicle. In this regard, a recently developed control-oriented model for multivariable systems called the U-model can be beneficial[12]. U-model has the ability of adaptively identifying the dynamics of the system along with the external disturbances. The controller design based on the U-model methodology is simply the root solving. Hence, the design of controller is quite simple even for a highly dynamic varying system under disturbances.

This paper implements the U-model based control scheme for controlling pitch and heading of an unmanned free swimming submersible (UFSS) vehicle designed in Naval research laboratory (NRL) by Johnson[13]. Further, in this work, the performance of the U-model based controller is evaluated in the presence of simulated hydrodynamic disturbances and is compared with the conventional PID.

Materials and Methods

UFSS is an autonomous underwater vehicle embedded with real-time software that provides the vehicle with an autonomous guidance and control capability. There are two pairs of elevator surfaces at the empennage of the vehicle. The depth of the vehicle is controlled using the pair of pitch elevator surface. This deflection causes the vehicle to rotate about the pitch axis to create a vertical force for the vehicle to submerge or rise. The vehicle incorporates a variable ballast system to vary the vehicle ballast as required by environmental and operational conditions[14]. The dynamics for pitch and heading control system is given in Fig.1.

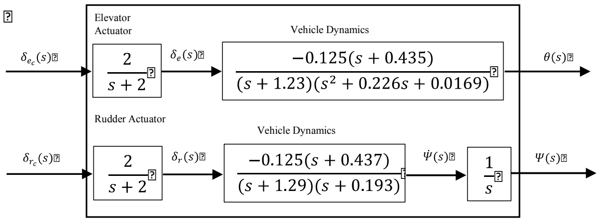


Fig. 1. Dynamics of UFSS for pitch and heading control[15]

In Fig. 1, $\delta_{e_c}(s)$ is commanded elevator deflection, $\delta_e(s)$ is deflection of elevator, $\theta(s)$ is the pitch angle of the vehicle, $\delta_{r_c}(s)$ is commanded rudder deflection, $\delta_r(s)$ is deflection of rudder and $\Psi(s)$ is the heading of vehicle.

The transfer function for pitch control system and heading control system is given in equation 1 and equation 2 respectively.

$$\frac{\theta(s)}{\delta_{e_c}(s)} = \frac{-0.25s-0.10875}{s^4+3.456s^3+3.2068s^2+0.610547s+0.041574} \quad (1)$$

$$\frac{\Psi(s)}{\delta_{r_c}(s)} = \frac{-0.25s-0.10925}{s^4+3.483s^3+3.21497s^2+0.49794s} \quad (2)$$

The internal model control (IMC) structure, where the controller implementation includes an explicit model of the plant has shown to be very effective for the control of stable plants, typically encountered in process control[16]. However, implementation of the IMC scheme requires the availability of reasonably accurate mathematical model of the plant to be used as part of the controller. This limits application of the IMC as accurate model of system is not always provided.

In cases when plant is not accurately known, additional techniques like adaptive parameter estimation can be used to model the plant without understanding physical laws associated with it. One such control oriented model called the U-model is recently developed that has the ability of adaptively identifying the dynamics of the system along with external disturbances[17]. It is more general compared to other parameterizing system identification approaches and exhibits a polynomial structure in terms of the control term. The uniqueness and simplicity of this newly parameterized model lies in the fact that the system is modeled based only on single parameter that is current control input. The nonlinear algebraic equation obtained from the U-model exhibits a polynomial structure based on single variable as given by equation 1, hence it becomes easier to solve those equations to obtain the controller output.

$$y_m(t) = \alpha_0(t) + \alpha_1(t)u(t-1) + \alpha_2 u^2(t-1) + \dots + \alpha_M(t)u^M(t-1) \tag{3}$$

$$\alpha_j(t) = [\alpha_1, \alpha_2, \dots, \alpha_M] \tag{4}$$

Now the model can be treated as a pure power series of the input $u(t-1)$ with associated time varying parameters $\alpha_j(t)$. As compared with other modelling techniques, U-model has benefit of representing a system in a polynomial structure in current control term. This implies to design a controller that is inverse of polynomial expression based on $u(t-1)$. The inverse of polynomial expression can be computed using various nonlinear methods such as Newton Raphson, Bisection method etc. This is a clear advantage as many other methods leads to complex nonlinear equations. To assist system identification and achieve higher modelling accuracy especially in case of additional disturbances and noises, RBF is incorporated with U-model[18-19] to compute $\alpha_o(t)$.

$$\alpha_0(t) = \widehat{w}_0(t)\Phi\big(u(t-1)\big) + \widehat{w}_1(t)\Phi\big(u(t-1)\big) + \dots + w\mathrm{n}(t)\Phi(u(t-1) \tag{5}$$

$$W(t) = [\widehat{w}_0, \widehat{w}_1, \dots, \widehat{w}_n\ ] \tag{6}$$

U-model time varying parameters $\alpha_j(t)$ and weights of RBFNN $W(t)$ are updated online using Normalized Leaky Least Mean Square (nLLMS) as given by equation 7 and equation 8.

$$\alpha_j(t+1) = \alpha_j(t)\big(1 - \mu(t)\gamma(t)\big) + \left(\frac{\mu(t)}{\gamma(t) + U(t)U'(t)}\right)Error(t)U(t) \tag{7}$$

$$W(t+1) = W(t)\big(1 - \mu(t)\gamma(t)\big) + \left(\frac{\mu(t)}{\gamma(t) + \Phi(t)\Phi'(t)}\right)Error(t)\Phi(t) \tag{8}$$

Here μ(t) and $\gamma(t)$ represents learning rate anc leakage factor respectively ranging from 0 to 1 $Error$(t) is the mismatch error between actual anc modeled output.

$$Error(t) = y(t) - y_m(t) \tag{9}$$

The control law is synthesized based on Interna Model Control (IMC) structure, where controller is designed to be inverse of the U-model. The complete structure of U-model based adaptive IMC is given in Fig. 2. As U-model is in a polynomial structure, the controller output is synthesized using Newton-Rapson method recursively using equation 10 with the feedback error $E(t)$ as a root solver (as defined by equation 11).

$$u_{i+1}(t-1) = u_i(t-1) - \frac{\sum_{j=0}^{k} \alpha_j(t)u_i^j(t-1) - E(t)}{d\left[\sum_{j=0}^{k} \alpha_j(t)u^j(t-1)\right]/du(t-1)} \tag{10}$$

$$E(t) = r(t) - y(t) + y_m(t) \tag{11}$$

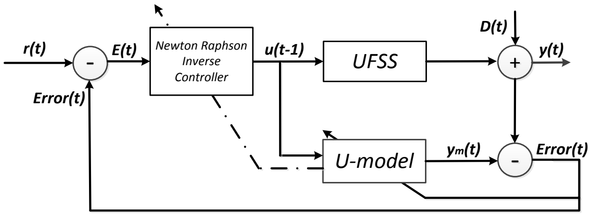
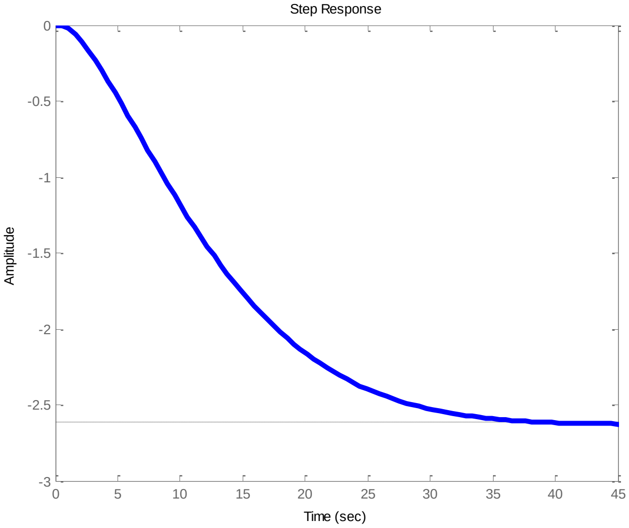


Fig. 2 U-model based Adaptive IMC Structure

It must be notified that stability is one of the critical requirement of IMC structure. If the system to be controlled is stable, true model of system will also be stable and as a result controller being a solution of polynomial will be stable as well. An unstable system will lead the whole structure of IMC to be unstable. Hence if the system is inherently unstable, it must be stabilized using robust techniques prior to applying proposed control scheme. In general, stability of U-model is discussed separately in [20].

Fig. 3 and Fig. 4 show the step response for



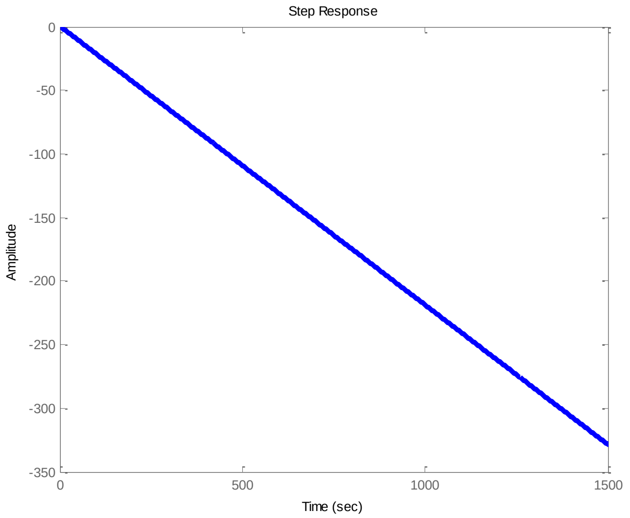


Fig. 4. Heading

From the step response as given in Fig. 3 and 4, it can be inferred that vehicle dynamics for both pitching angle and heading are unstable, hence it is stabilized using compensator before applying the U-model based adaptive IMC scheme. The structure of proposed control scheme (as shown in Fig. 2) is modified to add an inner stability loop as shown in Fig. 5.

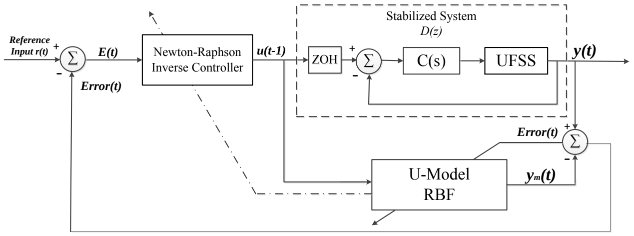


Fig. 5. Proposed Controller Structure

The PID compensator for pitching angle is given in equation 12 and corresponding stabilized system in discrete form is as given in equation 13. The discrete form is achieved by using zero order hold (ZOH) method with sampling time of 0.5 seconds.

$$C_1(s) = \frac{-20.68s^3 - 41.36s^2 - 41.36s - 20.68}{s} \tag{12}$$

$$D_1(z) = \frac{0.8553z^4 - 2.427z^3 + 2.663z^2 - 1.334z + 0.2556}{z^5 - 3.007z^4 + 3.522z^3 - 1.91z^2 + 0.4197z - 0.01339} \tag{13}$$

The PID compensator for heading is given in equation 14 and corresponding stabilized system in discrete form is as given in equation 15. The discrete form is achieved by using zero order hold (ZOH) method with sampling time of 0.5 seconds.

$$C_2(s) = \frac{-141.6s^2 - 21.53s - 0.7244}{s} \tag{14}$$

$$D_2(z) = \frac{1.398z^4 - 3.112z^3 + 1.538z^2 + 0.701z - 0.5246}{-1.787z^4 + 0.126z^3 + 0.9685z^2 - 0.1313z - 0.1753} \tag{15}$$

Results & Discussion

In this section proposed control scheme is implemented in simulation environment to control pitch angle and heading of UFSS with consideration of hydrodynamic disturbance caused by water wave. The hydrodynamic disturbances considered in this work are simulated using signal builder block function in MATLAB as shown in Fig. 6. Hence, it's an approximation of the water current wave.

In this work, optimal values for U-model order, learning rate[20], leakage factor and initial values of $\alpha j(t)$ and $W(t)$ are selected by trial and error method. There are seventeen RBFNN centers chosen ranging between -2 and 2 with a constant width of 0.25 to cover input space of reference signal for both control variables. After few trial runs, order to control pitch angle and heading is selected to be 3 and 5, respectively. The learning factor and leakage factor for controlling both variables is 0.13 and 0.2 respectively. The performance of proposed scheme is compared with the most commonly used Proportional Integral Derivative (PID) controller. The parameters for PID controller are auto-tuned using MATLAB and the gain values that gives optimal performance are listed in Table 1.

Table 1—PID Tuning Parameters

	Pitch Angle	Heading
K_p	-0.731	-0.721
K_i	0.0730	-0.00083
K_d	0	0.389

Fig. 7 compares performance between the U-model and the PID to control pitching angle of UFSS. It is clear that the U-model performs better in terms of rise time, settling time and steady state error as compared to PID. Though in terms of overshoot, U-model results in higher overshoot as compared to PID yet considerable decrease in overshoot is noticed in the second step change and onwards. Similar behavior is observed in case of controlling heading of UFSS as given in Fig. 8. The U-model based controller overshoots at first few iterations mainly due to its training and adaptive learning at the first step change. However, once the U-model algorithm has captured the behavior of system, performance of controller improves and overshoot decreases significantly as can be noticed from second step change and onwards.

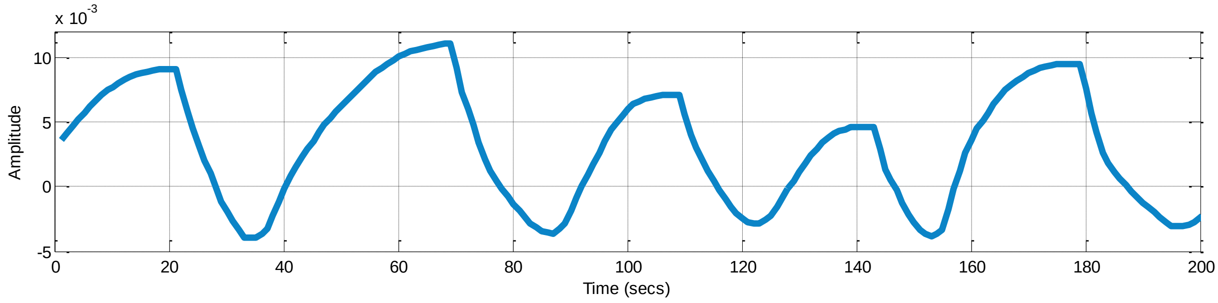


Fig. 6. Water Wave Current

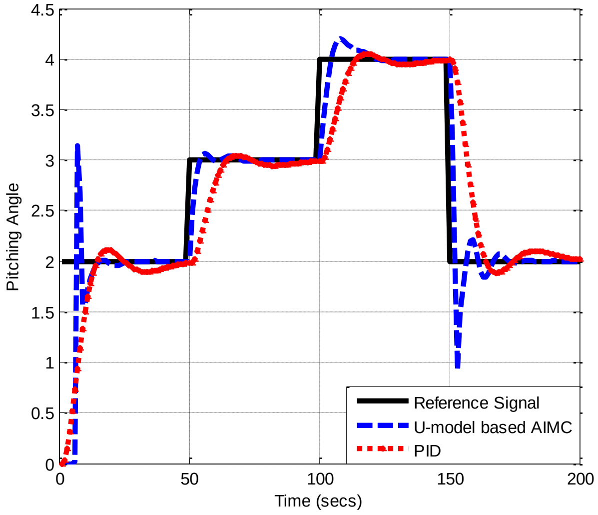


Fig. 7. Pitching Angle Control

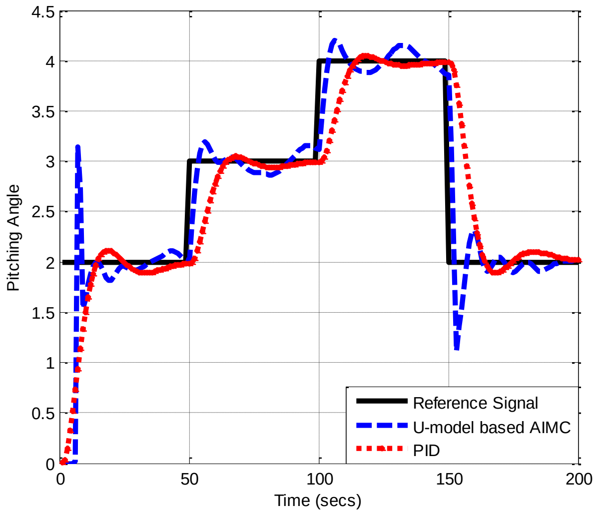


Fig. 9. Pitching Angle Control with hydrodynamic disturbances

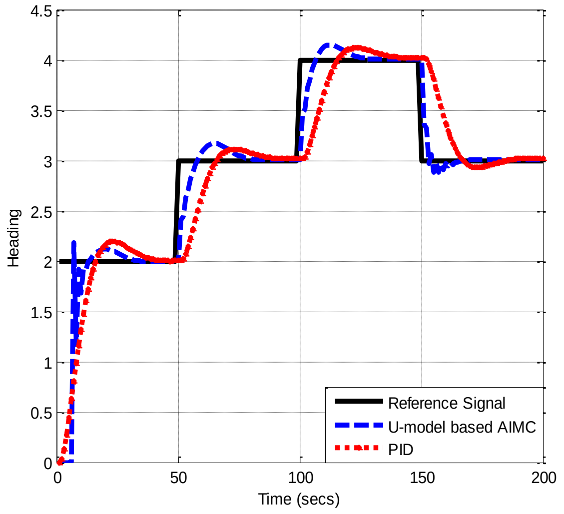


Fig. 8. Heading Control

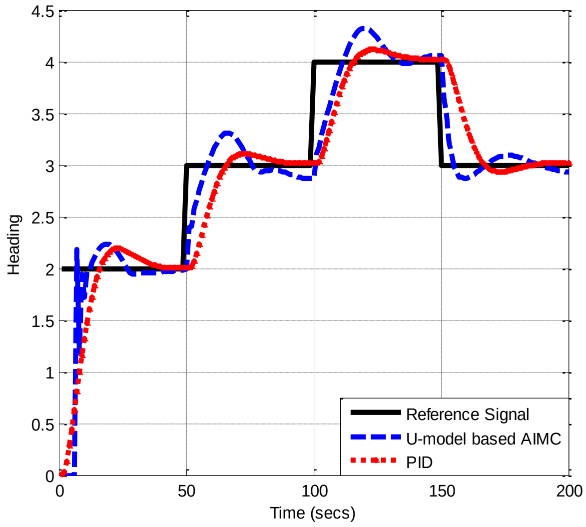


Fig. 10. Heading Control with hydrodynamic disturbances

Fig 9 and 10 compares performance between the U-model and the PID to control pitching angle and heading, respectively, in the presence of simulated hydrodynamic disturbances. As shown, slight turbulence is observed in performance of U-model based controller as hydrodynamic disturbances are taken into account. Nonetheless U-model still converges back to reference signal as desired. Moreover, it must be noticed that PID parameters are already pre-tuned to give the optimal performance from the very first iteration, hence less oscillation is observed in performance of PID. Generally, PID requires regular tuning of the gains to maintain the performance according to parameter changes and disturbances. In contrast, U-model adapts to the parameter changes and disturbances yet keeping the controller structure simple.

A brief comparison in terms of maximum overshoot, rise time, settling time and steady state error for controlling pitching angle and heading is presented in Table 2. The control signal for U-model are as shown in Fig. 11 and 12. It can be seen that U-model control signal are bounded and reflects actual tracking of reference signal. In terms of limitations, the performance of U-model depends heavily on adaptive algorithm. Further, application of U-model is also limited to system varying slowly with time.

Table 2−Performance Comparison

	Pitching Angle		**Heading**	
	U-model	**PID**	**U-model**	**PID**
Maximum Overshoot (%)*	8.5	5.61	18	15
Rise Time	2	13.5	7.365	15
Settling Time	20	60	30	50
Steady State Error	0	0.0012	0.0028	0.0233

Conclusion

In this work, U-model based control scheme has shown satisfactory performance for controlling pitch angle and heading of highly dynamic UFSS under hydrodynamic disturbances. Comparison with the PID has further advocated effectivity of proposed scheme. Without requiring to mathematically model dynamics and kinematics of vehicle, U-model offers a simplistic controller design with the ability to adaptively control the vehicle under hydrodynamic disturbances. This makes the U-model based control structure attractive to be used in underwater robotics.

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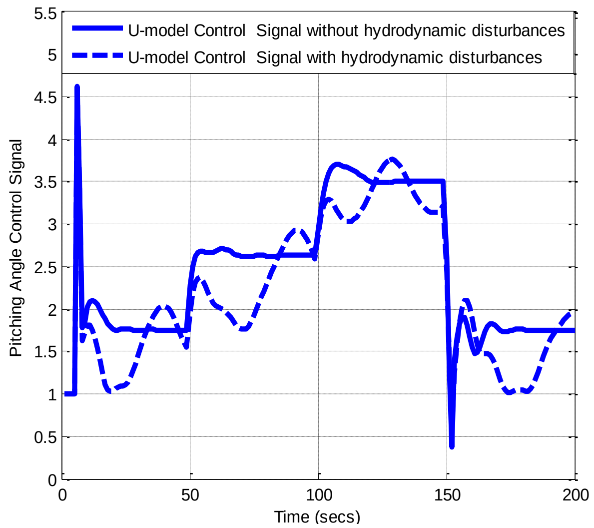

Fig. 11. U-model Control Signal for Pitching Angle

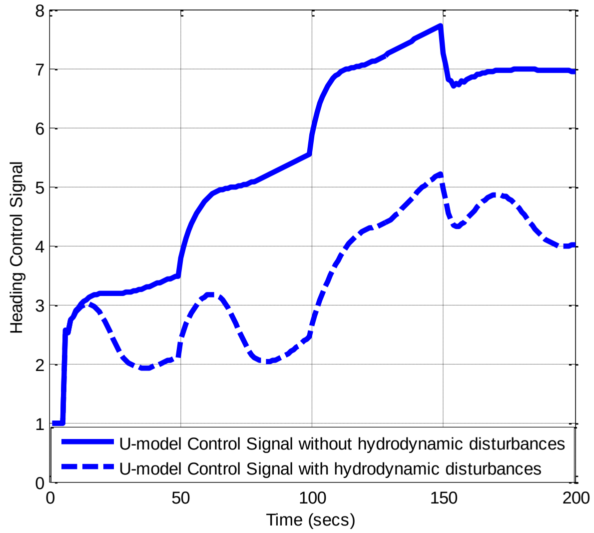

Fig. 12. U-model Control Signal for Heading

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