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Air Cushion Adaptive Disturbance Cancellation for the Reduction of Wave Induced Motion of Ramp-Connected Ships

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ABSTRACT

We consider the problem of cargo transfer in high sea states over a ramp from an LMSR (large, medium-speed, roll-on/roll-off) vessel to a smaller connector vessel, the T-Craft. Due to the complexity of the wave and ship interactions, this problem represents significant challenges for ship and control system designers and requires the use of computational tools to simulate the system. We utilize Matlab, AEGIR, and Rhino to model and simulate the system in two configurations: 1) the ships are oriented side by side, and 2) the ships are in a bow-to-stern configuration. To reduce the oscillations in the ramp connecting the vessels, we design and employ adaptive wave cancellation algorithm with air flow rate as actuator. When the ships are oriented side by side, the wave disturbance in heave of the T-Craft is estimated and cancelled by using fans to control the pressure in an air cushion positioned underneath the vessel. For the bow-to-stern configuration, a two-chamber air cushion is considered, where wave disturbance in pitch is estimated and cancelled by inducing a moment through a pressure difference between the chambers. We present simulation results.

KEYWORDS

wave cancellation, adaptive control, backstepping, ACV

1.0 INTRODUCTION

The T-Craft is a vessel being developed that has combined characteristics of both a surface effect ship (SES) and an air cushion vehicle (ACV). One of its main operational requirements is the transfer of cargo from a large vessel, LMSR, to nearby land targets. The T-Craft has two modes of operation: It is either supported entirely by twin hulls resembling a catamaran, or by an air cushion that uses a bag system and fans to fill a pocket of air to lift the craft towards the surface of the water. Currently, there is great effort being placed into the modelling of such ships. There are a number of highly complex and coupled interactions that increase the task difficulty. In addition to the synthesis of equations of motion, there is also an effort to simulate these ships with an effective software package.

T-Craft operation presents unique challenges that have not been addressed from a control standpoint. We exploit the capabilities of this type of ship to stabilize a ramp during cargo transfers with the LMSR. Two transfer methods considered a side by side configuration and a bow to stern configuration. We use existing software to model the system and simulate it with and without control. Though the used software doesn't contain the air cushion dynamics, we model the effect separately and add it during simulation. Adaptive backstepping method is used to regulate the pressure in the air cushion. With this method, we estimate the unknown wave disturbance and cancel its effect to the system. Simulation results demonstrate significant reduction in heave for the side by side configuration, and in pitch in a bow to stern configuration, both of which reduce ramp oscillation.

2.0 SYSTEM MODELING

2.1 Wave Modelling using AEGIR

The modelling of the ocean waves and contributing forces is done through a proprietary wave sea keeping program called AEGIR. This greatly simplifies the difficult aspect of approximating the wave forces while also providing accurate solutions in a short time scale.

AEGIR uses a series of sine inputs provided by the user to represent a typical wave pattern. While many models exist to produce these sine waves, we use the Pierson-Moskowitz spectrum for fully developed wave conditions. The power for a given wave frequency is

$$S(\omega) = \left(\frac{\alpha g^2}{(2\pi)^2 \omega^4} \right)^{\frac{-1.25\omega_p{}^4}{\omega^4}} \tag{1}$$

with α = 8.1 × 10^{-3} and $\omega_p = g / U_{19.5}$, where $U_{19.5}$ is the wind speed 19.5 meters above the water. A random phase between 0 and 2π is assigned to each frequency.

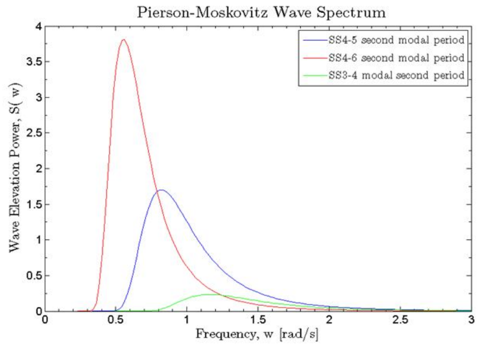

Fig. 1. Pierson-Moskowitz spectrum of SS 3 and SS 4 wave.

In addition to amplitude, extracted from the power spectrum, the important characteristics of the waves are the modal period and wave heading. Fig. 1 shows the spectrum for waves in sea state 3 and 4 with modal periods of four, five, and six seconds. During simulations, different wave patterns are used to compare system behaviours in varying conditions and headings.

2.2 Configurations and Parameters

The vessel parameters are shown in Table 1.

Table 1. System parameters

	LMSR	T-Craft	Ramp
Length (ft)	990	250	90
Beam (ft)	100	75	
Weight (tons)	81,700	820	
Roll Gyradius (ft)	40	15	
Pitch Gyradius (ft)	200	50	
Yaw Gyradius (ft)	200	50	

The ramp has two hinges that only allow pitch at each pivot point. The ramp is assumed to be massless and rigid. We test multiple setups to determine the effectiveness of each controller while also determining optimal transfer conditions. Fig. 2 shows the ships in a bow to stern configuration. Conversely, Fig. 3 shows the ships in a side by side configuration. Each configuration produces different motions while also altering the approach to the control of the system. In the side by side setup, roll of the T-Craft is nearly uncontrollable. As a result, the heave is the main degree of freedom that we control. In the bow to stern setup, a two chamber air cushion controls pitch and heave of the vessel. This in turn reduces ramp oscillation.

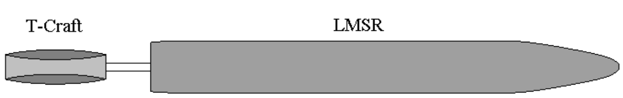

Fig. 2. Bow to stern configuration.

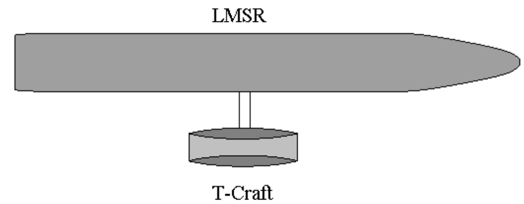

Fig. 3. Side by side configuration.

2.3 Lagrangian Equations of Motion

The most accurate way to implement the T-craft model into AEGIR, is the treatment of its two hulls as two separate bodies and consideration of the rigid connection between the two hulls in the systems equations of motion, which accordingly have to be derived for a three-body case. We use Lagrangian framework to derive the equations of motions. Lagrange's equations are given by

$$L = T - U$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\zeta}_j}\right) - \frac{\partial L}{\partial \zeta_j} = \Xi_j \quad \text{for} \quad j = 1, \ldots, 12$$

with kinetic energy T, potential energy V, and the generalized forces Ξ_j for each of the independent generalized coordinates ζ_j.

The kinetic energy of the 3-body system can be expressed as a sum of kinetic energies of each of the three bodies as $T = T_1 + T_2 + T_3$. Similarly, for the potential energy with g as gravity the combined potential energy is expressed as $U = m_1 g z_1 + m_2 g z_2 + m_3 g z_3$. The focus of the primary work mainly lies in the stabilization of the ramp between the two vessels, control and reduction of heave, pitch and roll motions are of prime interest in this time. Thus the surge, sway and yaw of the combined, two-vessel system can be disregarded without loss of generality for the simulation and control development.

The heave motion of the whole system along the z-axis of main frame of reference follows,

$$\begin{aligned} F_{z_1} + F_{z_2} + F_{z_3} - (m_1 + m_2 + m_3)\, g = {} & (m_1 + m_2 + m_3)\, \ddot{\zeta}_3 \\ & + \left(m_1 y_{c_1}^0 + m_2 y_{c_2}^0 + m_3 y_{c_3}^0\right) \ddot{\zeta}_4 \\ & - \left(m_1 x_{c_1}^0 + m_2 x_{c_2}^0 + m_3 x_{c_3}^0\right) \ddot{\zeta}_5 \\ & + \left[m_1 \left(y_{c_1}^0 - y_{p_1}\right)\right] \ddot{\zeta}_7 \\ & + \left[m_2 \left(y_{c_2}^0 - y_{p_2}\right) \right. \\ & \left. + m_3 \left(y_{c_3}^0 - y_{p3}\right)\right] \ddot{\zeta}_{10}. \end{aligned} \tag{2}$$

Similar expressions can be derived for roll and pitch of the whole system as well as roll and pitch of each of the vessels around the pivot points. The considered and ignored degrees of freedom for the bow-to-stern configuration are shown in. For the side-by-side (respectively, bow-to-stern) configuration, pitch (resp., roll) of LMSR and T-Craft is constrained and roll (resp., pitch) is considered. The considered, ignored and dependent degrees of freedom for bow to stern configuration are summarized in Table 2.

Table 2. Degrees of freedom for bow-to-stern configuration

DoF Considered	Ignored DoF	Dependent DoF
1. Total Heave	6. Total Surge	9. Surge of T-Craft
2. Total Roll	7. Total Sway	10. Surge of LMSR
3. Total Pitch	8. Total Yaw	11. Sway of T-Craft
4. Pitch of T-Craft		12. Sway of LMSR
5. Pitch of LMSR		13. Heave of T-Craft
		14. Heave of LMSR
		15. Roll of T-Craft
		16. Roll of LMSR
		17. Yaw of T-Craft
		18. Yaw of LMSR

2.4 Air-Cushion Dynamics

Reynold's Transport Theorem and mass conservation are used to find the equation for pressure change in the air cushion. The control volume is deformable and shown in Fig. 4. The cross-sectional area of the control volume only varies in height. The free surface is considered as being flat and the pressure distribution to be uniform in the control volume.

The air leakage depends on physical properties of the skirt and finger and also the pressure inside of the cushion. We assume the leakage has a linear relationship with air pressure and define a resistance term to represent the physical properties of the air cushion, R_L, and assume it remains constant. The final expression for change in air pressure is

$$\dot{P}_c = -\frac{\rho_0 A_c}{C_c}\dot{h} - \frac{1}{C_c R_L}P_c + \frac{1}{C_c}q \qquad (3)$$

where ρ_0, V_0, and P_0 are initial values, q is the mass flow rate, A_c is the cross sectional area of *x,y* plane and $C_c = \rho_0 V_0 / P_0$.

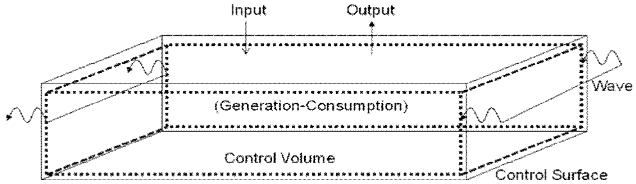

Fig. 4. The representation of the air cushion model.

3.0 SYSTEM CONTROL

Controller design for air-cushion vehicles poses significant challenges. The difficulty arises from the unmeasured wave disturbance, the inaccurate system parameters such as mass and hydrodynamic terms, the indirect actuation of the air cushion pressure. We present several algorithms that tackle some combinations of the said challenges.

3.1 Heave and Pitch Dynamics

Although dynamics of ocean vehicles are coupled and have complex hydrodynamic effects (presented in detail in Fossen, 1994), AEGIR provides a reliable simulation environment to test our controllers. It is common to consider a linear decoupled model of the ship dynamics to design the controller. Following (Sorensen and Egeland, 1995) and (Fossen, 1994), we consider the following models for design purpose. The heave dynamics (decoupled from pitch) are given by

$$(m + A_{33})\ddot{\zeta}_{33}(t) + B_{33}\dot{\zeta}_{33}(t) + C_{33}\zeta_{33}(t) - A_c P_c = F_3^e(t), \quad (4)$$

whereas the pitch dynamics (decoupled from heave) are given by

$$(I_{55} + A_{55})\ddot{\zeta}_{55}(t) + B_{55}\dot{\zeta}_{55}(t) + C_{55}\zeta_{55}(t) - A_c P_d \frac{L_c}{8} = F_5^e(t), \quad (5)$$

where ζ_{33}, ζ_{55} represent the heave and pitch of ship respectively, P_c is the current pressure in the air cushion and P_d is the current pressure difference between two chambers. A_c, L_c are area and length of the air cushion respectively. m is the mass of ship and I_{55} is moment of inertia around y-axis. Hydrodynamic (added-mass), radiation damping coefficient and hydrostatic (restoring) terms for heave and pitch are represented as A_{ii}, B_{ii} and C_{ii} respectively. $F_3^e(t), F_5^e(t)$ are hydrodynamic excitation force and moment, which affect heave and pitch.

3.2 Wave Modelling for Control Design

While the actual wave consists of many sinusoids, for the purpose of wave cancellation by control we adopt a single-sinusoid (*N*=1) model, where the wave frequency, amplitude, and phase are tracked by a parameter estimator. As discussed in (Faltisen, 1990), the single-sinusoid hydrodynamic excitation force F_3^e is written as

$$F_3^e(t) = 2\sqrt{S(\omega_1)}e^{k_1 d}\frac{\sin\frac{k_1 L}{2}}{\frac{k_1 L}{2}}\left(C_{33} - \omega_1\omega_e A_{33}\right)\sin\omega_e t \qquad (6)$$

where d and L represent draft and length of the side-hulls respectively, ω_e is called encounter frequency which is equal to $\omega_1 + k_1 U$.

For the purpose of control design, we assume that draft of the side hulls, hydrodynamics and hydrostatics terms do not change with time. Then, F_3^e is expressed as

$$F_3^e(t) = K_3^e \sin \omega_e t \tag{7}$$

which can be treated as the output of an autonomous (second-order, mass-spring) exosystem with unknown parameters. The hydrodynamic excitation moment F_5^e can be expressed in the same way.

3.3 Wave Disturbance Representation

In this section, we represent the unknown wave disturbance (7) as the product of an unknown constant vector and the known regressor by using the result in (Nikiforov, 2004a and 2004b).

3.3.1 Known System Parameters

As it is shown and proved in (Nikiforov, 2004a), it is possible to represent (7) as the output of a linear system whose input is itself, whose state and input matrices are known , and whose output matrix is unknown. Dividing F_3^e by constant $(m + A_{33})$ affects only the amplitude. Therefore, we can write the scaled unknown disturbance as follows,

$$\nu = \frac{F_3^e}{(m + A_{33})} = \theta^T z, \tag{8}$$

where

$$\dot{z} = Gz + l\nu \tag{9}$$

where G is a 2×2 Hurwitz matrix and constitutes a controllable pair with a chosen vector $l \in \mathbb{R}^2$.

In this representation, z is not accessible, since the unknown disturbance F_3^e cannot be measured. However, it is possible to estimate z by using the measurements of heave, heave rate and pressure which are assumed to be available for measurement. Decoupled heave dynamics (4) can be represented in the state-space form as follows

$$\dot{x} = Ax + BP_c + b_0 \nu, \tag{10}$$

where

$$x = \begin{bmatrix} \zeta_{33} \\ \dot{\zeta}_{33} \end{bmatrix},$$

$$A = \begin{bmatrix} 0 & 1 \\ -\dfrac{C_{33}}{(m + A_{33})} & -\dfrac{B_{33}}{(m + A_{33})} \end{bmatrix},$$

$$B = \begin{bmatrix} 0 \\ \dfrac{A_c}{(m + A_{33})} \end{bmatrix},$$

$$b_0 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}.$$

By applying the proposed filter in (Nikiforov, 2004a) to x, P_c and using the system parameters in (10), z is given as,

$$\begin{aligned} \dot{\eta} &= G(\eta + Nx) - N(Ax - BP_c) \\ \hat{z} &= \eta + Nx, \\ z &= \hat{z} + \delta \end{aligned} \tag{11}$$

where

$$\begin{aligned} N &= \frac{1}{B^T B} l B^T, \\ \dot{\delta} &= G\delta. \end{aligned} \tag{12}$$

Since G is Hurwitz, the estimation error δ decays to zero exponentially. Using (8) and (11), we obtain

$$\nu = \theta^T \hat{z} + \theta^T \delta. \tag{13}$$

3.3.2 Unknown System Parameters

The system matrix A and the vector B can be represented as

$$A = A_0 + b_0 \tau^T, \quad B = \frac{1}{\beta} b_0 \tag{14}$$

where

$$A_0 = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix},$$

$$\tau = \begin{bmatrix} -\dfrac{C_{33}}{(m + A_{33})} \\ -\dfrac{B_{33}}{(m + A_{33})} \end{bmatrix},$$

$$\frac{1}{\beta} = \frac{A_c}{(m + A_{33})}.$$

The proposed filter in (Nikiforov, 2004b) to estimate the unknown signal ν is given as,

$$\begin{aligned} \dot{\eta}_0 &= G(\eta_0 + N_u x) - N_u A_0 x, \\ \dot{\eta}_1 &= G\eta_1 - N_u b_0 x_1, \\ \dot{\eta}_2 &= G\eta_2 - N_u b_0 x_2, \\ \dot{\eta}_u &= G\eta_u - N_u b_0 P_c, \end{aligned} \tag{15}$$

where

$$N_u = \frac{1}{b_0^T b_0} l b_0^T. \tag{16}$$

By using (8) and (15) , ν is represented as follows

$$\nu = \kappa^T w + \theta^T \delta, \tag{17}$$

where

$$\begin{aligned} w^T &= \left[\left(\eta_0 + N_u x \right)^T \quad \eta_1 \quad \eta_2 \quad \eta_u \right], \\ \kappa^T &= \left[\theta^T \quad \tau_1 \theta^T \quad \tau_2 \theta^T \quad \beta \theta^T \right]. \end{aligned} \tag{18}$$

3.4 Heave Control

We apply adaptive backstepping method to design a control law, which cancels the unknown wave disturbance by actuation of air flow rate. The structure of the control problem is illustrated in Fig. 5. We consider two different cases; known and unknown system parameters.

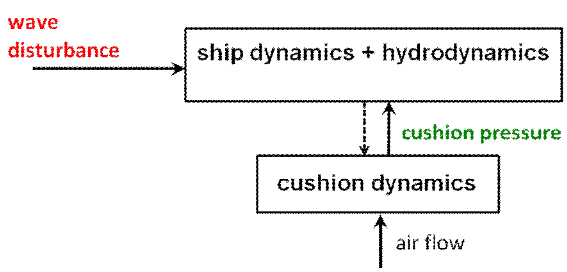

Fig. 5. The structure of the control problem.

3.4.1 Known System Parameters

We consider the following Lyapunov/energy function to design an air-cushion pressure controller, which cancels wave disturbance in heave,

$$V = x^T P x + \frac{1}{\gamma} \tilde{\theta}^T \tilde{\theta} + \mu \delta^T P_\delta \delta \tag{19}$$

where $\gamma > 0$, $\tilde{\theta}$ represents the wave estimation error, the positive definite matrix $P \in \mathbb{R}^{2\times 2}$ is a solution of the matrix equation

$$\left(A + BK\right)^T P + P\left(A + BK\right) = -2I, \tag{20}$$

with the control gain $K \in \mathbb{R}^{1\times 2}$, the positive definite matrix $P_\delta \in \mathbb{R}^{2\times 2}$ is a solution of the matrix equation

$$G^T P_\delta + P_\delta G = -\theta \theta^T, \tag{21}$$

and

$$\mu = b_0^T P P b_0. \tag{22}$$

We choose the air-cushion controller as follows,

$$P_c = \frac{\left(m + A_{33}\right)}{A_c} \left(Kx - \hat{\theta}^T \hat{z} \right), \tag{23}$$

where $\hat{\theta}$ is the estimate of θ. Taking derivative of V and using (20), (21) and (23), we obtain

$$\begin{aligned} \dot{V} = &-2x^T x + 2x^T P b_0 \theta^T \delta + 2\tilde{\theta}^T z b_0^T P x - \frac{2}{\gamma} \tilde{\theta}^T \dot{\hat{\theta}} \\ &-\mu\left(\theta^T \delta\right)^2. \end{aligned} \tag{24}$$

Choosing the update law as follows

$$\dot{\hat{\theta}} = -\gamma z b_0^T P x, \tag{25}$$

and using Young's inequality, we obtain

$$\dot{V} \le -x^T x. \tag{26}$$

By LaSalle's theorem, it is concluded that all signals are bounded and heave and heave rate go to zero in time. However the air-cushion pressure cannot be actuated directly. To find the implementable control and update law by the actuation of air-flow rate, we apply adaptive backstepping design.

The deviation of P_c from its desired value is written as

$$e = P_c - \left(Kx - \hat{\theta}^T \hat{z} \right). \tag{27}$$

The Lyapunov function for (x, e) system is chosen as

$$V_a(x, e) = V(x, e) + \frac{1}{2} e^2. \tag{28}$$

We design control and update law for air-flow rate actuation to make

$$\dot{V}_a \le -x^T x - ce^2, \quad c > 0, \tag{29}$$

with

$$\begin{aligned} q = \frac{\rho_0 V_0}{P_0} \Big[&-B^T P x + K\left(Ax + BP_c + B\hat{\theta}^T \hat{z} \right) \\ &-\left(\dot{\hat{\theta}}^T z + \hat{\theta}^T \dot{\hat{z}} \right) + \frac{P_0 A_c}{V_0} \dot{\zeta}_{33} + \frac{P_0}{\rho_0 V_0 R_L} P \\ &-c\left(P_c - \left(Kx - \hat{\theta}^T \hat{z} \right) \right) \Big], \end{aligned} \tag{30}$$

$$\begin{aligned} \dot{\hat{\theta}} = &\, z B^T P x \\ &-z B^T \left(K^T - N^T \hat{\theta} \right) \left(P_c - \left(Kx - \hat{\theta}^T \hat{z} \right) \right). \end{aligned} \tag{31}$$

3.4.2 Unknown System Parameters

We consider the following Lyapunov function to design an air-cushion pressure controller which cancels wave disturbance in heave for uncertain system parameters,

$$V = x^T P_u x + \frac{1}{\gamma_\tau} \tilde{\tau}^T \tilde{\tau} + \frac{1}{\gamma_\kappa} \tilde{\kappa}^T \tilde{\kappa} + \frac{1}{\gamma_\beta \beta} \tilde{\beta}^2 + \mu \delta^T P_\delta \delta \tag{32}$$

where $\gamma_\tau, \gamma_\kappa, \gamma_\beta > 0$ and $\tilde{\tau}$, $\tilde{\kappa}$, $\tilde{\beta}$ represents the estimation error of the system parameters, wave and high frequency gain, respectively. The positive definite matrix P_u is a solution of the matrix equation

$$\left(A_0+b_0K\right)^T P_u + P_u\left(A_0+b_0K\right) = -2I. \tag{33}$$

We choose the adaptive air-cushion controller as follow,

$$P_c = \hat{\beta}\left(-\hat{\tau}x - \hat{\kappa}w + Kx\right), \tag{34}$$

and update laws are given as

$$\begin{aligned}\dot{\hat{\tau}} &= \gamma_\tau x b_0^T P x,\\ \dot{\hat{\kappa}} &= \gamma_\kappa w b_0^T P x,\\ \dot{\hat{\beta}} &= -\gamma_\beta\left(-\hat{\tau}x - \hat{\kappa}w + Kx\right) b_0^T P x.\end{aligned} \tag{35}$$

We apply adaptive backstepping design to reach the real actuation. The control law is given as

$$\begin{aligned}q = \hat{C}_c\Big(&-x^T P b_0 e - \hat{c}_1 x_2 - \hat{c}_2 P_c\\ &+\Big(\dot{\hat{\beta}}\left(-\hat{\tau}^T x - \hat{\kappa}^T w + Kx\right) - \hat{\beta}\left(\dot{\hat{\tau}}^T x - \dot{\hat{\kappa}}^T w\right.\\ &\left.-\hat{\kappa}^T\left[\dot{\eta}_0^T \;\; \dot{\eta}_1^T \;\; \dot{\eta}_2^T \;\; \dot{\eta}_u^T\right]^T\right) + S\bar{A} - de\Big)\end{aligned} \tag{36}$$

where $d>0$, $\hat{C}_c$, $\hat{c}_1$ and $\hat{c}_2$ are the estimates of C_c, $-\dfrac{\rho_0 A_c}{C_c}$ and $-\dfrac{1}{C_c R_L}$ respectively, and

$$e = P_c - \hat{\beta}\left(-\hat{\tau}x - \hat{\kappa}w + Kx\right), \tag{37}$$

$$S = \hat{\beta}\left(-\hat{\tau}^T + K - \hat{\theta}^T N_u\right), \tag{38}$$

$$\bar{A} = \left(A_0 + b_0K\right) + b_0 e. \tag{39}$$

The update laws are given as

$$\begin{aligned}\dot{\hat{c}}_1 &= \gamma_{c_1} x_2 e,\\ \dot{\hat{c}}_2 &= \gamma_{c_2} P_c e,\\ \dot{\hat{C}}_c &= \gamma_{c_c}\frac{1}{\hat{C}_c} q e,\\ \dot{\hat{\tau}} &= \gamma_\tau x b_0^T\left(Px + Se\right),\\ \dot{\hat{\kappa}} &= \gamma_\kappa w b_0^T\left(Px + Se\right),\\ \dot{\hat{\beta}} &= -\gamma_\beta\left(-\hat{\tau}x - \hat{\kappa}w + Kx\right) b_0^T\left(Px + Se\right).\end{aligned} \tag{40}$$

where $\gamma_{c_1}, \gamma_{c_2}, \gamma_{c_c} > 0$.

3.5 Pitch Control

Two chambers air-cushion model enables us to control pitch by using pressure difference between two chambers. The pressure changes for each chamber are given as

$$\begin{aligned}\dot{P}_1 &= -\frac{P_0A_c}{2V_0}\dot{\zeta}_{33} + \frac{P_0A_0L}{4V_0}\dot{\zeta}_{55} - \frac{P_0}{\rho_0V_0R_L}P_1 + \frac{P_0}{\rho_0V_0}q_1,\\ \dot{P}_2 &= -\frac{P_0A_c}{2V_0}\dot{\zeta}_{33} - \frac{P_0A_0L}{4V_0}\dot{\zeta}_{55} - \frac{P_0}{\rho_0V_0R_L}P_2 + \frac{P_0}{\rho_0V_0}q_2.\end{aligned} \tag{41}$$

These equations are used for simulations. However, the pressure difference is needed for control design. By subtracting P_1 and P_2, we obtain

$$\dot{P}_d = -\frac{P_0A_cL}{2V_0}\dot{\zeta}_{55} - \frac{P_0}{\rho_0V_0R_L}P_d + \frac{P_0}{\rho_0V_0}q_d \tag{42}$$

where $P_d = P_2 - P_1$ and $q_d = q_2 - q_1$.

By following the same procedure in Section 3.3, $\nu_p = \dfrac{F_5^e}{\left(I_{55}+A_{55}\right)}$ is represented as follows

$$\nu_p = \theta_p^T\hat{z}_p + \theta_p^T\delta. \tag{43}$$

where

$$\begin{aligned}\dot{\eta}_p &= G\left(\eta_p + N_px_p\right) - N_p\left(A_px_p - B_pP_d\right)\\ \hat{z}_p &= \eta_p + N_px_p,\end{aligned} \tag{44}$$

with

$$x_p = \begin{bmatrix}\zeta_{55}\\ \dot{\zeta}_{55}\end{bmatrix},$$

$$A_p = \begin{bmatrix}0 & 1\\ -\dfrac{C_{55}}{\left(I_{55}+A_{55}\right)} & -\dfrac{B_{55}}{\left(I_{55}+A_{55}\right)}\end{bmatrix},$$

$$B_p = \begin{bmatrix}0\\ \dfrac{A_cL}{8\left(I_{55}+A_{55}\right)}\end{bmatrix},$$

$$N_p = \frac{1}{B_p^TB_p}lB_p^T.$$

By using (5), (42), (43) and following the same procedure in Section 3.4.1, we obtain

$$\begin{aligned}q_d = \frac{\rho_0V_0}{P_0}\Big[&-B_p^TP_px_p + K_p\left(A_px_p + B_pP_d + B_p\hat{\theta}_p^T\hat{z}_p\right)\\ &-\left(\dot{\hat{\theta}}_p^Tz_p + \hat{\theta}_p^T\dot{z}_p\right) + \frac{P_0A_cL}{2V_0}\dot{\zeta}_{55} + \frac{P_0}{\rho_0V_0R_L}P_d\\ &-c\left(P_d - \left(K_px_p - \hat{\theta}_p^T\hat{z}_p\right)\right)\Big],\end{aligned} \tag{45}$$

$$\dot{\hat{\theta}}_p = z_p B_p^T P_p x_p \\ - z_p B_p^T \left(K_p^T - N_p^T \hat{\theta}_p\right)\left(P_d - \left(K_p x_p - \hat{\theta}_p^T \hat{z}_p\right)\right), \tag{46}$$

where the positive definite matrix $P_p \in \mathbb{R}^{2\times 2}$ is a solution of the matrix equation

$$\left(A_p + B_p K_p\right)^T P_p + P_p\left(A_p + B_p K_p\right) = -2I. \tag{47}$$

4.0 SIMULATIONS AND RESULTS

4.1 Overall Structure of Simulation System

We use time-domain sea-keeping code AEGIR provided by Navatek/APS, to solve hydrodynamic forcing imparted to vessels. Though the current software doesn't contain the air cushion dynamics and ramp connection between T-Craft and LMSR, we add them with the designed controller during simulation by using MATLAB interface code. AEGIR and MATLAB interface is illustrated in Fig. 6.

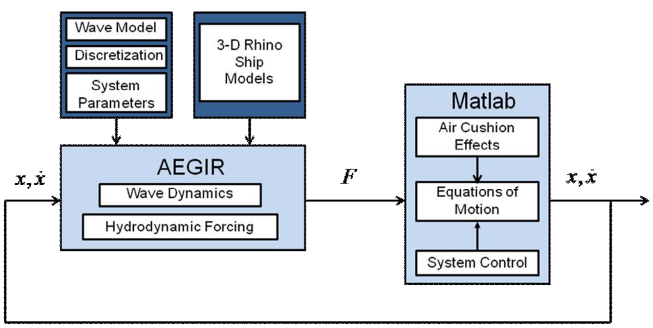

Fig. 6. AEGIR and MATLAB interface.

The rigid body motions and control laws are implemented in MATLAB. The resulting generalized coordinates of the vessels are provided as inputs to AEGIR, which in turn simulates the wave motions and generates the hydrodynamic forces on the vessels, which are provided as inputs to MATLAB. The Rhino CAD program is used to model LMSR and T-Craft hulls. CAD models are given in Fig. 7 and Fig. 8.

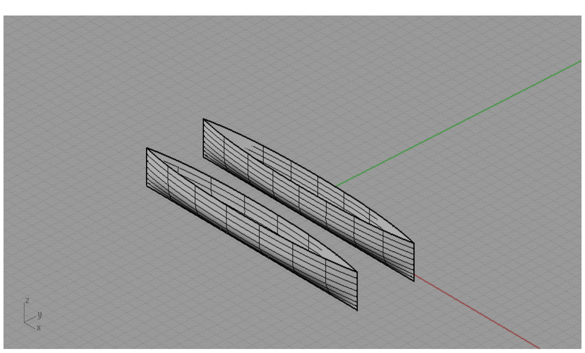

Fig. 7. 3D Rhino model of T-Craft hulls.

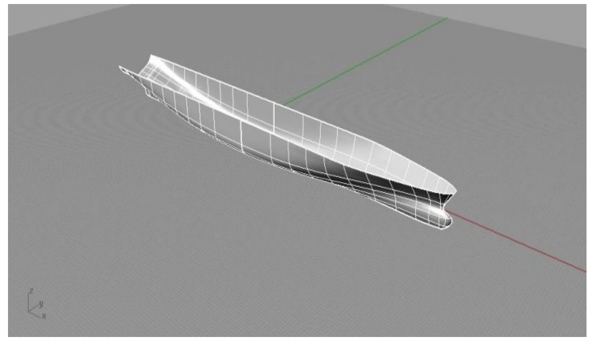

Fig. 8. 3D Rhino model of LMSR.

4.2 Results

The estimation of wave disturbance and heave of T-Craft for heading angle 20 in SS4 in side by side configuration for known system parameters are given in Fig. 9 and Fig. 10.

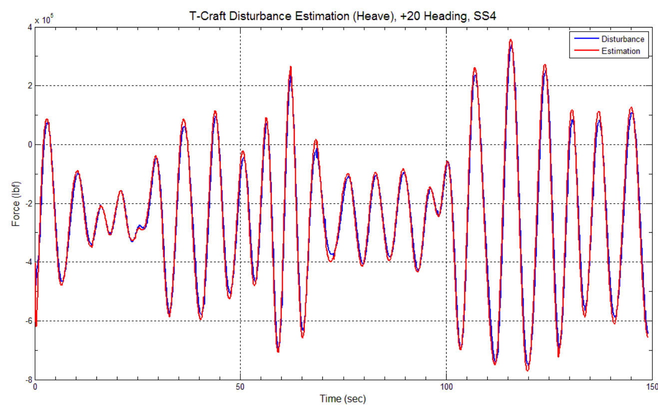

Fig. 9. Disturbance estimation in heave of T-Craft for 20 heading angle in side by side configuration.

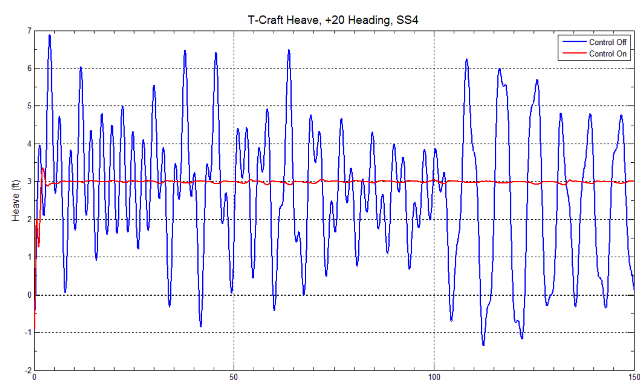

Fig. 10. The simulation result of control algorithm for known system parameters.

The simulation result of heave of T-Craft for unknown system parameters in bow to stern configuration is given in Fig. 11.

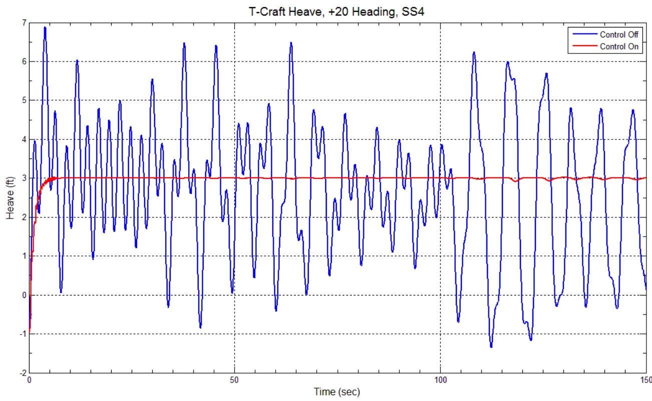

Fig. 11. The simulation result of control algorithm for unknown system parameters in bow to stern configuration.

The result of simultaneous application of heave and pitch control is given in Fig. 12.

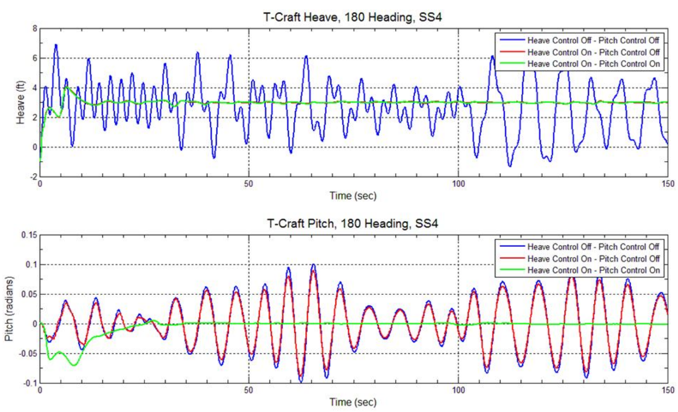

Fig. 12. The simulation result of heave and pitch controller simultaneously for known system parameters in bow to stern configuration.

5.0 CONCLUSION

In this paper we present the details of the modelling of a Sea Base consisting of an LMSR and T-Craft and design of an adaptive wave cancellation algorithm for T-Craft. Lagrangian equations of motion are derived for a pitch hinged ramp connecting the two vessels. The vessels are modeled in Rhino with dimensions and parameters used from experimental data. A wave sea-keeping program, AEGIR, is used to calculate wave forcing. Finally, an air cushion model is derived and incorporated through added forcing.

We develop an adaptive wave cancellation algorithm utilizing backstepping for known and unknown system parameters to regulate pressure in an air cushion underneath the vessel. This leads to perfect estimation of wave disturbance and significant reduction of heave in a side by side configuration and pitch in a bow to stern configuration. As actuators, this method conveniently uses the fans in the air cushion, which are already present in the vessel.

REFERENCES

M. Krstic, I. Kanellakopoulos, and P. V. Kokotovic, 1995 Nonlinear and Adaptive Control Design, Wiley.

T. I. Fossen, 1994. Guidance and Control of Ocean Vehicles, John Wiley & Sons, New York.

O. M. Faltinsen, 2005 Hydrodynamics of High Speed Marine Vehicles, Cambridge.

A. J. Sorensen and O. Egeland, 1995. “Design of Ride Control System for Surface Effect Ships using Dissipative Control,” Automatica, **31**.

V. O. Nikiforov, 2004a “Observers of External Deterministic Disturbances. I. Objects with Known Parameters,” Automation and Remote Control, **65.**

V. O. Nikiforov, 2004b “Observers of External Deterministic Disturbances. II. Objects with Unknown Parameters,” Automation and Remote Control, **65**.

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