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A seakeeping analysis method for T-Craft

Zhiqun Guo[a], Qingwei Ma[b,a,*], Hanbing Sun[a]

[a]*College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China*
[b]*School of Engineering and Mathematical Sciences, City University London, London EC1V 0HB, United Kingdom*

Abstract

The Transformable-Craft (T-Craft) is an innovative vessel serving as a connector between sea base and beachheads. When operatingat seas, the T-Craft is a surface effect ship (SES) with compartmented air cushions. To analysis the seakeeping performance of the T-Craft SES, a high efficient 2D/2.5D analytical model has been developed by combining the one dimensional waveequation for solving aerodynamics of pressurized cushion air with the STF/2.5D method for solving hydrodynamics of demihulls at low/high speeds. To enhance the computational efficiency, the entire model is linearized except the dynamics of air leakage, which is strongly nonlinear and inappropriate for linearization. Results obtained from the proposed seakeeping analysis model show reasonable agreement with experimental data, while the proposed model hascompetitiveness in the computational efficiency as compared with some 3D models from public works.

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*Keywords:*T-Craft; Seakeeping; STF; 2.5D method; Wave equation; Nonlinear

1. Introduction

The Transformable-Craft (T-Craft) is a novel marine vehicle for the purposes of transporting cargo from ships at sea to beach at high speeds. According to the operation conditions, the T-Craft can operate in modes of full displacement, partial air cushion support and full air cushion support, which correspond to catamaran, surface effect ship (SES) and air cushion vehicle (ACV), respectively. With partial air cushion support, the T-Craft will be able to navigate at rough seas at high speeds. Inversely, when operating at ACV mode, the T-Craft could land on the shores for loading/off-loading operations [1]. Another advantage of the T-Craft concept is that, the craft is designed to

* Corresponding author. Tel.: +44 (0)20 7040 5060.
E-mail address: q.ma@city.ac.uk

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achieve higher seaworthiness capabilitythan conventional ACV or SES — could navigate at 40 knots through Sea State 4, 20 knots through Sea State 5, and be survivable in Sea State 8 [2].

To demonstrate the capability of the T-Craft design, a series of scale model tests have been carried out [3], including seakeeping tests at zero and high forward speeds at SES mode. Moreover, some numerical efforts [1, 4-6] were made to study the dynamics of the T-Craft SES system. Connell *et al* [1] extended an ACV dynamic simulation tool ACVSIM [7] to including the displacing hulls of SES for investigating the seakeeping of the T-Craft SES. In the ACVSIM a zero/forward speed 3D time-domain spline-based boundary element method AEGIR is employed to perform the hydrodynamic solution and craft motions, while the Immersed Boundary Method is adopted to solve the 3D wave equation for the dynamics of the compressible air in the cushion. Donnelly [4] utilized RANS equation based air – water two-phase flow model in the solver Star CCM+ to perform the T-Craft seakeeping simulation. The seals in the model are rigid but empirically shortened to make them slightly above the free surface to prevent craft plowing in waves. Bhushan *et al* [5] used RANS equation based water phase flow model in the solver CFD Ship-Iowa V4 to study the motions of the T-Craft in waves, while the air dynamics in the cushion was modeled by potential method, including the spatial averaged air pressure in each cushion, linear fan characteristic curve and so on.

The above methods [1,4,5] showed effectiveness on the T-Craft seakeeping motion prediction. However, they are all based on 3D potential or viscous flow theory or the mixture of two theories, which require much computational effort and thus they are not viable for engineering practices. On the other side, the validity of traditional high efficient STF and 2.5D methods for catamaran displacing hulls has already been proved [6,8], and Guo *et al* [6] demonstrated the possibility of using STF to predict the motions of low speed T-Craft. Nevertheless, the method proposed by Guo *et al* [6] only applies to low speed case and the model is fully linear, which overlooks the nonlinearity of air leakage and its accuracy may not be sufficient.

In this work, for the purpose of improving the accuracy and expanding the application range of the previously developed low speed model [6], a partially nonlinear model is presented, which considers the nonlinearity of air leakage, and attempts to incorporate the 2.5D method into the model for the high speed case. The 2.5D method has been successfully used in a seakeeping analysis method for a high speed mono-cushion SES — partial air cushion supported catamaran [11], but the analytical model in that work is linear and only applies to mono-cushion case.

2. Analytical model for seakeeping analysis

Let *o-xyz* be a T-Craft-fixed coordinate systemthat moves together with the craft. The origin *o* locates on the mean free surface. The *x*-axis points forward parallel to the longitudinal plane of the craft, while the *z*-axis is vertically upward through the centre of gravity (COG) of the craft, respectively. The COG and transverse skirt (splitter of fore and aft cushion) approximately locates at the midship [4]. Fig. 1 shows the 3D model of the T-Craft.

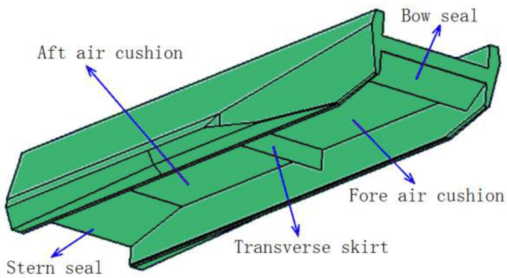

Fig. 1. The T-Craft model

Longitudinal motions in head waves are considered in this work. The equations of heave and pitch of the T-Craft could be expressed as

$$M\ddot{\eta}_3 = \underbrace{\int_{-\frac{b}{2}}^{\frac{b}{2}}\left(\int_{-\frac{l}{2}}^{0}(p_1 - p_1^0)|_{z=h}dx + \int_0^{\frac{l}{2}}(p_2 - p_2^0)|_{z=h}dx\right)dy}_{aerodynamics} + \underbrace{F_3^R + F_3^W}_{hydrodynamics}\ , \tag{1}$$

$$I_{55}\ddot{\eta}_5 = \underbrace{-\int_{-\frac{b}{2}}^{\frac{b}{2}}\left(\int_{-\frac{l}{2}}^{0} x(p_1 - p_1^0)|_{z=h}dx + \int_0^{\frac{l}{2}} x(p_2 - p_2^0)|_{z=h}dx\right)dy}_{aerodynamics} + \underbrace{F_5^R + F_5^W}_{hydrodynamics}, \tag{2}$$

where $l, b, h, p_1, p_1^0, p_2, p_2^0, \eta_3, \eta_5, F_3^R, F_3^W, F_5^R, F_5^W, M, I_{55}$ are length, breadth, height of air cushion, transient aft air cushion pressure, aft air cushion pressure at equilibrium condition, transient fore air cushion pressure, fore air cushion pressure at equilibrium condition, heave, pitch, radiation force due to heave, scattering force in heave direction, radiation moment due to pitch, scattering moment in pitch direction, mass of the T-Craft, moment of inertia for pitch, respectively. The integrals on Eq. (1) and Eq. (2) are performed over the wet deck ($z = h$), in which the thickness of the splitter of air cushion is ignored.

The seakeeping motion is determined by solving the above equations. For this purpose, one needs to evaluate the pressure in air cushions and hydrodynamics of sidehulls, which will be performed in the following two sub-sections.

2.1. Aerodynamics of air cushion

The air pressure in the cushion satisfies the wave-equation and adiabatic conditions below [6]:

$$\nabla^2 p_i - \frac{1}{c^2}\frac{\partial^2 p_i}{\partial t^2} = 0, \quad i = 1,2, \tag{3}$$

$$\rho_i^0 c^2 = \gamma(p_i^0 + p_a), \quad i = 1,2, \tag{4}$$

where t is time, c is acoustic speed in air cushion, $\gamma = 1.4$ is the ratio of specific heats for air, p_a is atmosphere pressure, ρ_i^0 is average air density in i th cushion, $i = 1,2$ refer to aft, fore air cushion, respectively.

Assuming that the variation in pressure in the y and z directions are much smaller than in the x direction, and defining the sectional averaged pressure

$$\overline{p_i}(x,t) = \frac{1}{bh}\int_{-\frac{b}{2}}^{\frac{b}{2}} dy \int_0^h p_i(x,y,z,t)dz, \quad i = 1,2. \tag{5}$$

Using Eq.(5), one can rewrite Eq.(3)as a one dimensional wave equation below

$$\left(\frac{\partial^2}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\overline{p_i}(x,t) = -\frac{1}{bh}\int_{-\frac{b}{2}}^{\frac{b}{2}}\left(\frac{\partial p_i}{\partial z}\Big|_{z=0}^{z=h}\right)dy, \quad i = 1,2. \tag{6}$$

To the first order, the sectional averaged pressure $\overline{p_i}$ can be assumed to have the following form [6]

$$\overline{p_i}(x,t) = p_i^0 + p_i^0\alpha_i e^{j\omega t}, \quad i = 1,2, \tag{7}$$

where j is the imaginary number, ω is the wave encountered frequency, α_i is a complex unknown, the first term p_i^0 supports a part of the T-Craft weight, independent on time. Substituting the pressure p_i of Eq. (1) and Eq. (2) with $\overline{p_i}$ follows that

$$M\ddot{\eta}_3 - F_3^R - F_3^W = \frac{A}{2}(p_1^0\alpha_1 + p_2^0\alpha_2)e^{j\omega t}, \tag{8}$$

$$I_{55}\ddot{\eta}_5 - F_5^R - F_5^W = \frac{Al}{8}(p_1^0\alpha_1 - p_2^0\alpha_2)e^{j\omega t}, \tag{9}$$

where $A = bl$ is the sum of horizontal projected area of two air cushions.

Under vehicle-fixed coordinate system *o-xyz* the incident wave in air cushion could be written as

$$\zeta(x,t) = \zeta_a\, e^{j\cdot(\omega t + kx)}, \tag{10}$$

where ζ_a, k are wave amplitude, wave number, respectively.

Substituting the pressure $\overline{p_i}(x,t)$ of Eq. (6) with Eq. (7), integrating Eq.(6) with respect to x, then integrating the resulting equation with respect to t, taking Eq.(4), Eq.(8) and Eq.(10) into account, one obtains

$$\frac{j\omega h(M\ddot{\eta}_3 - F_3^R - F_3^W)}{\gamma(p_0+p_a)} + A\dot{\eta}_3 + \left(\sum_{i=1}^2 q_i^{out} - \sum_{i=1}^2 q_i^{in}\right) - \frac{2j\omega b\zeta_a \sin\frac{kl}{2}}{k} e^{j\omega t} = 0, \tag{11}$$

where $p_0 = (p_1^0 + p_2^0)/2$ is the average time-independent pressure of fore and aft air cushion, q_i^{in} is the air inflow from inlet holes distributed in the middle of aft and fore wet deck, i.e. longitudinal positions of inlet holes are $\pm l/4$; q_i^{out} is air outflow via gaps between free surface and underneath of bow seal and stern seal.

Multiplying Eq. (6) by x, then taking the integration as for Eq.(11), one obtains

$$\frac{j\omega h(I_{55}\ddot{\eta}_5 - F_5^R - F_5^W)}{\gamma(p_0+p_a)} + \frac{Al^2}{12}\dot{\eta}_5 - \left(\sum_{i=1}^2 x_i^{out} q_i^{out} - \sum_{i=1}^2 x_i^{in} q_i^{in}\right) + \frac{kl\cos\frac{kl}{2} - 2\sin\frac{kl}{2}}{k^2}\omega b\zeta_a e^{j\omega t} = 0, \tag{12}$$

where $x_1^{\text{in}} = -l/4, x_2^{\text{in}} = l/4, x_1^{\text{out}} = -l/2, x_2^{\text{out}} = l/2$ are longitudinal position of aft, fore cushion air inlet, outlet hole, respectively.The inflow and outflow could be written as

$$q_i^{in} = q_{0i}^{in} + \left(\frac{\partial q_i^{in}}{\partial p_i}\right)_0 p_i \alpha_i e^{j\omega t}, \tag{13}$$

$$q_i^{out} = C_s\big(h_i + \eta_3 - x_i\eta_5 - \zeta(x_i,t)\big) b \sqrt{\frac{2\overline{p_i}(x_i,t)}{\rho_i^0}}, \tag{14}$$

where$\left(\partial q_i^{\mathrm{in}} / \partial p_i\right)_0$ is i-th inlet hole discharge by fan per unit pressure, $C_s = 0.61$ is coefficient of flow shrinkage, h_i is the air leakage height, i.e. gaps between free surface and underneath of bow fingers and stern bag. The outflow in Eq. (14) is strongly nonlinear, in which the variable $h_i, \eta_3, x_i\eta_5, \zeta(x_i,t)$ are in the same order and $\overline{p_i}(x_i,t)$ depends on η_3, η_5 (see Eq.(8) and Eq. (9)).

Combining Eq. (8), Eq. (9) and Eq. (13), Eq. (14) gives the expressions of the inflow and outflow without pressure unknown α_i, then putting them into Eq. (11) and Eq. (12), the motion equations will be solvable.

2.2. Hydrodynamics of sidehulls

In Eq. (8) and Eq.(9), the hydrodynamics of the T-Craft sidehulls should be taken into account. In previous work [6], the problem is solved by the STF method [9]. However, the STF only apply to low speed case [10]. In this work, the high speed theory—2.5D method [8] is employed for solving hydrodynamics of the T-Craft advancing with high Froude numbers, while the STF is kept for lowFroude numbers. The computational setup for 2.5D method is the same as STF, details of which could be found inwork [6].

The numerical model discussed in the above two sub-sections is nonlinear, which is different from the linear one [6, 11]. The fourth order Ronge-Kutta method is adopted to solve the nonlinear motion equations.Nevertheless, the present method has more computational efficient than Rankine panel or CFD methods. In practice, the algorithm of present method only takes a few seconds to run, while the Rankine panel or CFD methods requires several hours for simulation.

3. Numerical results

The main parameters and experimental setup of the T-Craft can be found in reference [3]. Fig.2-3 show the comparison of EFD data, numerical results of present method and that from public papers (the references are marked in labels of figures).At zero speed, all results agree well with the EFD data, while the present nonlinear method performs better than the linear one. At the higher speed, the agreement between three numerical results from different methods and EFD data is found not to be very good. The discrepancies might be due to the fact that the model setup in the numerical calculation may not the exact the same as that in experiments, as the available details for the experiments are limited. Nonetheless, the results of the present method follow the same trend as that of Rankine panel or CFD methods. More investigation is underway to improve the prediction for the higher speed case.

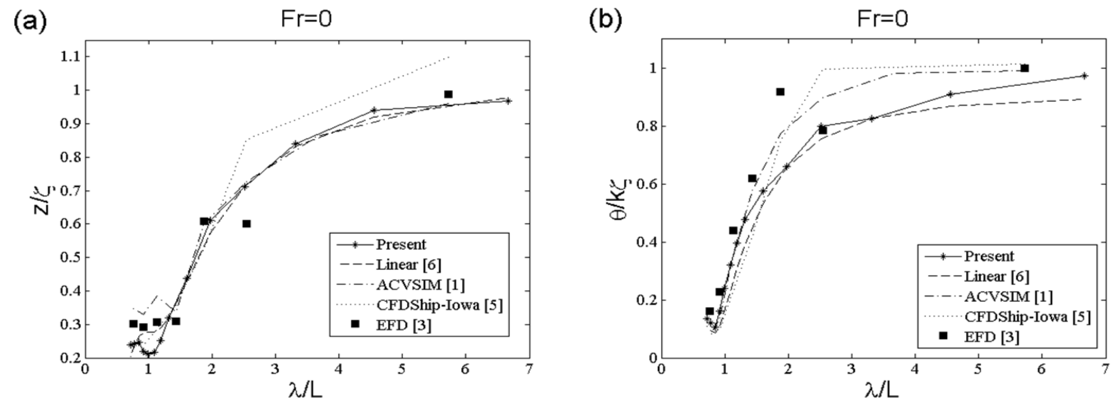

Fig. 2. (a) Heave response of the zero speed T-Craft in head waves; (b) Pitch response of thezero speed T-Craft in head waves.

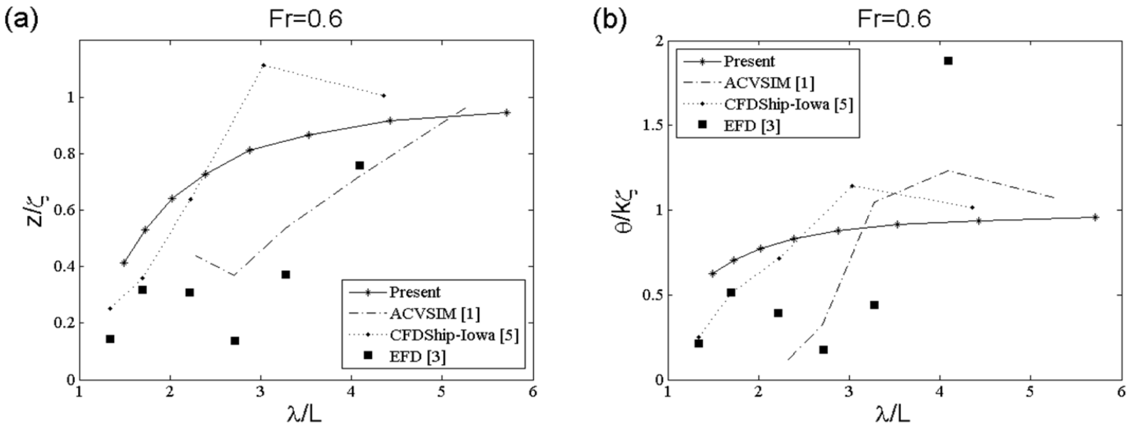

Fig. 3. (a) Heave response of the high speed T-Craft in head waves; (b) Pitch response of the high speed T-Craft in head waves.

4. Conclusions

In this work, an efficient nonlinear seakeeping analysis method is proposed for a T-Craft with compartmented air cushions, which combines the one dimensional wave equation for aerodynamics of air cushion and the STF/2.5D method for the hydrodynamics of sidehulls at low/high speeds. The numerical results of the present method are compared with EFD data and that of other numerical methods, and the agreement between them at zero or lower speed is acceptable. The cases at high speeds need more investigations. Moreover, the computational efficiency of the method presented here outperforms the Rankine panel or CFD methods.

Acknowledgements

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