Advances in Engineering Research (AER), volume 105
3rd Annual International Conference on Mechanics and Mechanical Engineering (MME 2016)

On Coupling Effect of Ship's Transverse / Longitudinal Motions Based on CFD

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Keywords: CFD, Ship, Sea-keeping, Coupling effect.

Abstract. Aiming to break through the assumption that ship's transverse (mainly roll) and longitudinal (mainly pitch and heave) motion are not coupled in traditional sea-keeping study, the mathematical model to study coupling coefficients of transverse / longitudinal motion was proposed, and ship's roll, pitch / heave and roll / pitch / heave coupling motions in oblique regular wave were numerical simulated by CFD method. Based on the simulation results, the coupling effect of transverse and longitudinal motions was analyzed. The results show that: the coupling effect exists between ship's transverse and longitudinal motions, which varies with the ratio of wave length and ship length, and compared to uncoupling data, the change of ship's hydrodynamics, amplitudes of motion and Respond Amplitude Operators (RAO) is up to 10% at maximum.

Preface

Among ship's six degree of freedom motions in waves, roll, pitch and heave affect the ship's performance most, and roll belongs to transverse motion while pitch and heave belong to longitudinal motion. To simplify the question's complexity, the traditional study is based on the assumption that the transverse and longitudinal motion are not coupled, which are studied separately. But this assumption is not in consonance with the actual situation at sea, and lots of studies show that the two types motions have coupling effect [1], which even may result in ship's nonlinear motions in some cases [2-3]. In recent years, with the development of computer hardware and viscous fluid theory, the Computational Fluid Dynamics (CFD) method has been becoming a new effect method in ship's hydrodynamic study, and many studies were applied on numerical simulations of ship's motions in waves [4-8]. However, the coupling effects of transverse and longitudinal motions are seldom studied because of the question's complexity.

The coupling effects between transverse and longitudinal motions were studied in this paper. The numerical model of ship' multi-DOF motions in regular waves was established based on CFD method. The DTMB 5512 model's heave and pitch motions were numerical simulated, and the results show good agreement with the experimental data, which verify the numerical model's effectiveness and precision; the DTMB 5512 model's transverse motion (roll), longitudinal motion (pitch and heave) and coupled motion (roll, pitch and heave) in oblique regular wave were simulated, and the coupling effect were studied based on the simulation results. The method in this paper provides a new way to forecast ship's precise motions in waves and extends the traditional sea-keeping research fields.

Mathematical Model

Governing Equations

As for ship motions, water can be seen as incompressible viscous fluid, so the governing equations is consistent of equations of continuity and Novier-Stokes equations:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t}+\frac{\partial}{\partial x_j}\left(u_i u_j\right)=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu\frac{\partial u_i}{\partial x_j}\right) \tag{2}$$

In which, xi, xj is the coordinate direction, I , j=1, 2, 3; ui is the velocity of xi direction; P is pressure; t is time; μ is coefficient of kinematic viscosity.

Turbulence Model

The RNG k-ε model was adopted to simulate turbulence flow, and the equations of turbulence energy k and dissipation rating ε are:

$$\begin{cases}\dfrac{\partial k}{\partial t}+\dfrac{\partial k u_i}{\partial x_i}=\dfrac{\partial}{\partial x_j}\left(\alpha_\kappa \mu_{eff}\dfrac{\partial k}{\partial x_j}\right)+G_K+\varepsilon \\ \dfrac{\partial \varepsilon}{\partial t}+\dfrac{\partial \varepsilon u_i}{\partial x_i}=\dfrac{\partial}{\partial x_j}\left(\alpha_\varepsilon \mu_{eff}\dfrac{\partial \varepsilon}{\partial x_j}\right)+\dfrac{C_{1\varepsilon}^{*}\varepsilon}{\kappa}G_K+C_{2\varepsilon}\dfrac{\varepsilon^2}{\kappa}\end{cases} \tag{3}$$

in which:

$$\mu_{eff}=\mu+\mu_t\ ;\quad \mu_t=\rho C_\mu k^2/\varepsilon\ ;\quad C_\mu=0.0845\ ;\quad \alpha_k=\alpha_\varepsilon=1.39\ ;$$

$$C_{1\varepsilon}^{*}=C_{1\varepsilon}-\eta\left(1-\eta/\eta_0\right)/(1+\beta\eta^3)\ ;\ C_{1\varepsilon}=1.42\ ,\ C_{2\varepsilon}=1.68\ ;$$

$$\eta=\left(2E_{ij}\cdot E_{ji}\right)^{1/2}k/\varepsilon\ ;\quad E_{ij}=\left(\partial u_i/\partial x_j+\partial u_j/\partial x_i\right)/2\ .$$

Free Surface Model

The Volume of Fluid (VOF) is adopted to capture free surface, and the governing equations of volume factor is:

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}(C_q\rho_q)+\frac{\partial}{\partial x_i}\left(C_q\rho_q u_i\right)\right]=\sum_{p=1}^{2}(m_{pq}-m_{qp}) \tag{4}$$

In which:

mpq is the mass transferred from phase q to phase p; ρq is the density of phase q; t is time.

Numerical Computation Scheme

Ship Model

DTMB 5512 is proposed by ITTC as a standard model to verify CFD computation's precision, and Table 1 shows the main parameters of the model. IIHR Center of University of Iowa has studied DTMB 5512 model's coupled pitch and heave motions in regular waves, the results of which can be used to verify the effectiveness and precision of this article's numerical method [4][5].

Table 1 Parameters of ship model

Length(m)	Width(m)	draft(m)	Displacement(t)	block coefficient C_b
3.048	0.410	0.132	0.083	0.506

Computational Domain and Mesh Generation

The computational domain was set to be a cuboid, the scale of which was 3L×5L×1.2L (L is the length of the ship model), and in which the depth of water was 1L, and the wave absorbing area was at the back and starboard side of the ship model (assuming the wave coming from port side). The detailed scale is shown in Figure 1.

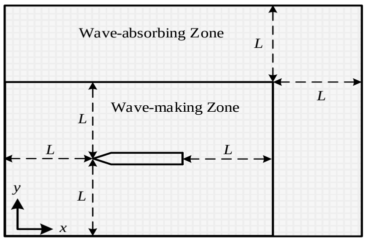

Fig.1. Scale of computational domain (top view)

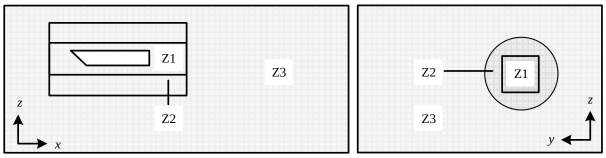

Fig.2 Multi-partitions of computational domain

The computational domain was divided into several partitions, as shown in Figure 2. And each partition was meshed as follows:

(1) Near-hull partition (Z1): a cuboid around the hull. The scale is 1.5L×1.5B×1.5B (L is ship model length; B is ship model width). The hull surface was set 20 boundary layers, and the maximum face grid scale is 0.01m. And this partition was meshed by non-structured grid, and the maximum volume grid scale is 0.02m.

(2) Cylinder partition (Z2): a cylinder around Z1. The height of the cylinder is equal to the cuboid, and the radius of the base is 2B. This partition was meshed by structured grid, and the maximum grid scale is 0.035m.

(3) Far-field partition(Z3): the computational domain apart from Z1 and Z2. This partition was meshed by structured grid, and the grid of Z direction at free surface level was intensified to A/2 (A is wave amplitude) to generate high-quality numerical wave, and the rest grid was loosed from free surface level to top and bottom.

The mesh is shown in Figure 3.

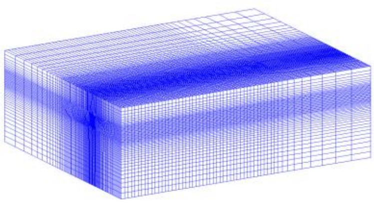

Fig.3. Grid of computational domain

Boundary Conditions

The name of each boundary is listed in Figure 4, and the conditions were set as follows (assuming the wave coming from port side):

(1) Flow-in boundary (in and port): velocity-inlet, at which the water particle velocities of 3 directions and the water phase was set.

(2) Flow-out boundary (out and stab): pressure-outlet, at which the calm water pressure was set.

(3) Outer-boundary (top and bot): velocity-inlet, at which the water particle velocities of 3 directions and the water phase (0) was set.

(4) Hull: no-slip wall.

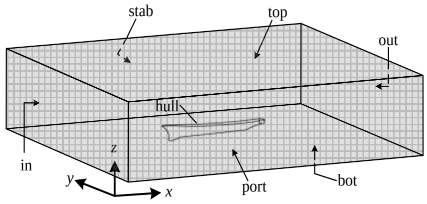

Fig.4 Boundary conditions

Experiment Parameters

Two types of experiments were simulated: one was the coupled pitch / heave motions in head waves, which was used to verify the precision and effectiveness of the simulation scheme; the other is the roll, coupled roll / heave and coupled roll / pitch / heave motions in oblique regular wave (the relative wave obliquity is 45°), which was used to study the coupling effect between transverse and longitudinal motion. The ship model is at medium speed (Fr=0.280), and the parameters of wave is listed in Table 2.

Table 2 Wave parameters

No.	length	amplitude	encounter frequency
1	4.56	0.054	0.82
2	3.48	0.042	0.98
3	3.04	0.036	1.07
4	2.59	0.031	1.20
5	2.16	0.026	1.35

Simulation Results and Analysis

Pitch / Heave Motions in Head Wave

No.1 and No.3 experiment listed in Table 2 were carried out in wave tank in reference [4][5]. And Ship model's heave force and pitch moment in No.1 experiment (Table 2) and time series of heave and pitch in No.3 experiment were processed and analyzed in detail. The comparison of this paper's simulation results and the experiment data is listed in Table 3 and Table 4, in which FZ, Mθ, Za and θa is the amplitude of heave force, pitch moment, heave and pitch respectively, and the same as follows.

It can be seen that, the relative error is around 5%, which proves that this paper's method is of high precision.

Table 3 Simulation results of force and moment

	F_Z (N)	M_θ (Nm)
simulation data	73.5	70.1
experiment data	78.3	68.4
error %	-6.13	2.5

Table 4 Simulation results of heave and pitch

	Z_a (m)	θ_a (deg)
simulation data	0.0154	1.375
experiment data	0.0161	1.397
error %	-4.52	-1.15

Coupled Motions in Oblique Wave

Hydrodynamic Force and Moment

The hydrodynamic force and moment of different working conditions is listed in Table 5.

Table 5 Simulation results of force and moment

No.	roll		pitch / heave		roll / pitch / heave		
	M_φ(Nm)	F_Z (N)	M_θ (Nm)	F_Z(N)	M_φ(Nm)	M_θ (Nm)	F_Z (N)
1	5.00	99.22	75.281	105.45	5.05	76.043	108.83
2	3.13	95.28	104.42	108.58	3.36	107.03	111.96
3	2.74	69.97	107.38	106.28	3.11	106.76	105.64
4	2.18	48.83	91.31	91.75	2.39	90.42	87.01
5	1.41	10.01	59.23	50.59	1.42	55.15	47.13

It can be seen from Table 5 that:

(1) The heave force of roll motion is much smaller than that of coupled heave / pitch and roll / heave / pitch motions, which indicates that the pitch and heave motions have more coupled effect, while the roll motion is less coupled with longitudinal motion.

(2) The roll moment increases with the wave amplitude in both roll and roll / heave / pitch motions, while the heave force and pitch moment do not change in the same way, but are associate with the encounter frequency, and the maximum values appear at fe=0.98 or 1.07, which is similar to the law of heave / pitch coupled motions in head wave.

(3) The time-history of heave force and pitch moment can become stable in less than 5 periods, while the roll moment need more than 20 periods, which indicate that the coupled effect between transverse and longitudinal motion is more complex.

Amplitude of Motions

The amplitudes of ship motions in different conditions is listed in Table 6, and it can be seen that:

(1) The time-history of heave and pitch can become stable in less than 5 periods, while roll need more than 20 periods, which is the same as the rules of force and moment.

(2) The impact of roll motion on amplitudes of longitudinal motions changes with wave length-ship length ratio (λ/L). Roll enlarges the amplitudes of longitudinal motions when λ/L<1, while diminishing the amplitudes when λ/L>1.

(3) The impact of longitudinal motions on amplitudes of roll also changes with wave length-ship length ratio (λ/L). The longitudinal motions enlarge the amplitudes of roll when λ/L<1, while diminishing the amplitudes when λ/L>1, and the impact increases with wave length.

Table 6 Simulation results of motion amplitude

No.	roll		pitch / heave		roll / pitch / heave		
	Φ(deg)	Z_a(m)	θ_a(deg)	Z_a(m)	M_φ(Nm)	θ_a(deg)	Z_a(m)
1	5.861	0.0451	2.977	0.0441	5.320	3.026	0.0475
2	2.490	0.0304	2.911	0.0348	2.273	3.016	0.0360
3	1.827	0.0159	2.508	0.0288	1.867	2.495	0.0287
4	1.190	0.0104	1.738	0.0196	1.229	1.672	0.0177
5	0.614	0.0037	0.898	0.0086	0.639	0.823	0.0079

Response Amplitude Operator

Response Amplitude Operator (RAO) is very important in ship's seakeeping calculation, and can be calculated by the method in Reference [12], the RAOs calculated from the simulation results is listed in Table 7, in which Kφ,Kθ,KZ is RAO of roll, pitch and heave respectively.

Table 7 Response Amplitude Operator

No.	roll	pitch / heave		roll / pitch / heave		
	K_φ	K_θ	K_Z	K_φ	K_θ	K_Z
1	5.752	0.693	0.817	5.320	0.704	0.880
2	2.490	0.677	0.829	2.273	0.702	0.857
3	1.827	0.584	0.797	1.867	0.581	0.800
4	1.190	0.404	0.632	1.229	0.389	0.571
5	0.614	0.209	0.331	0.621	0.192	0.304

It can be seen from Table 7 that:

(1) The impact of roll motion on RAOs of longitudinal motions changes with wave length-ship length ratio (λ/L). The roll motion diminishes the RAOs when λ/L<1, while enlarging the RAOs when λ/L>1.

(2) The impact of longitudinal motions on RAO of roll motion also changes with wave length-ship length ratio. The longitudinal motions enlarge the RAO of roll when λ/L<1, while diminishing the RAO when λ/L>1.

(3) The variation amplitude of RAO of coupled motions is up to 10%, which cannot be neglected in precise calculation of ship motions in waves.

Conclusions

Ship model's transverse (roll), longitudinal motions (pitch / heave) and coupled 3 DOF motions (roll / pitch / heave) were simulated, and the coupled effect between transverse and longitudinal motions were studied. It can be found that, the numerical method in this article can be used to simulate ship's coupled motions in waves precisely; compared with un-coupled motions, the variation amplitude of ship's hydrodynamics, amplitudes of motions and RAOs is up to 10% at maximum in coupled motions; and the coupling effect between transverse and longitudinal motions cannot be neglected in precise calculation of ship motions in waves. The following work will lie in the course and velocity's influence of the coupled effect between transverse and longitudinal motions.

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