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## **RESPONSE AMPLITUDE OPERATORS OF A WIGLEY SHIP MODEL VIA COMPUTATIONAL FLUID DYNAMICS**

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**Abstract.** *This work aims to predict numerically the vertical motions (heave and pitch) of a Wigley ship model heading over regular waves. The flow is assumed to be incompressible and viscous with mass and momentum fluxes being conserved. The Computational Fluid Dynamics (CFD) software ANSYS Fluent is employed to solve continuity and the unsteady Reynolds Averaged Navier-Stokes (RANS) equations with a Shear-Stress Transport (SST)  $\kappa$ - $\omega$  turbulence model. Air-water interface is modeled via the Volume of Fluid (VOF) method. Different sea conditions are simulated with Response Amplitude Operators (RAOs) being compared to experiments, with a good agreement being found.*

**Keywords:** *Ship motions, water waves, RAO, CFD.*

### **1. INTRODUCTION**

The prediction of ship performances, resistance and propulsion at different sea conditions affect the hull stability and is an important concern to naval and offshore industries. The relationship between ship motion and the ocean wave characteristics is commonly measured by using the Response Amplitude Operators (RAO).

A floating structure in the ocean surface with no mooring system is a dynamic system with six possible degrees of freedom (6DOF) to move: three translational movements (surge, sway and heave) and three rotational movements (roll, pitch and yaw). However, it is extremely complicated and difficult to predict and evaluate all 6DOF at the same analysis.

Since the 60's several researchers have investigated experimentally ship motions and wave-induced loads for different hulls and wave conditions. Vossers *et al.* (1960) tested series 60 models with five different wave lengths and one wave height. Nakamura and Naito (1977) tested resistance and self-propulsion for a container ship in regular and irregular waves. Journée (1992) developed experimental data of vertical motions for 4 Wigley hull forms and various wave lengths and wave amplitudes.

With the advances of numerical methods and computer technology, CFD (Computational Fluid Dynamics) analysis have become an important tool to predict ship motions and sea loads (see e.g. Yan *et al.* 2015 and Chen *et al.* 2015). One of the most consolidated hull form in CFD works is the Wigley series. Weymouth *et al.* (2005) performed simulations with an unsteady RANS computational code to predict heave and pitch motions for a Wigley hull form for a range of Froude numbers, wavelengths, and wave amplitudes. Ghassemi *et al.* (2015) investigated RAOs heave and pitch motions for a Wigley ship and two other hulls forms (S60 and DDG) by modifying the strip theory using the Maxsurf software.

In this work, the vertical motions of a Wigley ship model are estimated numerically for various Froude numbers ( $0.2 \leq Fr \leq 0.4$ ) and wave steepnesses ( $0.021 \leq ak \leq 0.084$ , where  $k$  and  $a$  are the wave number and amplitude). The reference frame is changed such that water flows with the velocity of the ship. Two degrees of freedom are allowed for the ship motion: heave and pitch. The Wigley III hull model has 3m of length, 0.3m of breadth and 0.1875m of draught. The fluid domain has 15m of length, 6m of width and 4.5m of height, with a water depth of 2.75m below the free surface level. The flow is assumed to be incompressible and viscous. Continuity and the unsteady RANS equations with a SST  $\kappa$ - $\omega$  turbulence model is solved via the finite volume method. Air-water interface is modeled via the Volume of Fluid (VOF) method.

The initial value problem is solved by the CFD package ANSYS Fluent release 15.0, which makes use of the finite volume method. The mesh was refined near the hull in order to better predict the dynamics of the fluid motion. All the computations were carried out on a 64 bit, 3.40 GHz Intel Core i7-2600 processor with 16 Gb of RAM.

## 2. INITIAL VALUE PROBLEM AND CFD MODEL

The unsteady incompressible and viscous flow with a free surface is modeled in three-dimensions with momentum and mass being conserved in the fluid domain. Continuity and the unsteady RANS equations are satisfied,

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial (\bar{u}_i \bar{u}_j)}{\partial x_j} = f_i - \frac{1}{\rho} \frac{\partial \bar{P}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j^2} - \frac{\partial}{\partial x_j} \overline{u_i' u_j'} \quad (2)$$

where the subscript  $i$  indicates the direction of an orthogonal axes system;  $t$  is time;  $x_i$  is the position;  $u_i = \bar{u}_i + u_i'$  is the fluid velocity decomposed, respectively, in mean and fluctuating velocities;  $f_i = (0, 0, -g)$  is the acceleration due to gravity;  $\rho$  is the fluid density;  $\bar{P}$  is the mean dynamic pressure;  $\nu$  is the kinematic viscosity. The shear stress transport  $\kappa$ - $\omega$  turbulence model, proposed by Menter (1994), is used to solve the closure problem.

$$\frac{\partial (\rho \kappa)}{\partial t} + \frac{\partial (\rho \kappa u_i)}{\partial x_i} = P_\kappa - \beta^* \rho \omega \kappa + \frac{\partial}{\partial x_i} \left[ (\mu + \sigma_\kappa \mu_t) \frac{\partial \kappa}{\partial x_i} \right] \quad (3)$$

$$\frac{\partial (\rho \omega)}{\partial t} + \frac{\partial (\rho \omega u_i)}{\partial x_i} = \rho \alpha S^2 - \rho \beta \omega^2 + \frac{\partial}{\partial x_i} \left[ (\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_i} \right] + 2(1 - F_1) \sigma_d \frac{\rho}{\omega} \frac{\partial \kappa}{\partial x_i} \frac{\partial \omega}{\partial x_i} \quad (4)$$

where  $\kappa$  is the turbulent kinetic energy;  $\omega$  is the rate of dissipation of the eddies;  $\mu$  is the molecular viscosity;  $\mu_t$  is the turbulent viscosity. The term  $S$  and  $S_{ij}$  are defined by

$$S = \sqrt{2 S_{ij} S_{ij}} \quad (5)$$

$$S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (6)$$

The term  $P_\kappa$  is defined by

$$P_\kappa = \min \left( \mu_t \frac{\partial u_i}{\partial x_j} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right); 10 \beta^* \omega \kappa \right) \quad (7)$$

and the term  $F_1$  is defined by

$$F_1 = \tanh \left\{ \left[ \min \left( \max \left( \frac{\sqrt{\kappa}}{\beta^* \omega y}, \frac{500 \nu}{y^2 \omega} \right); \frac{4 \rho \sigma_{\omega 2} \kappa}{CD_{\kappa \omega} y^2} \right) \right]^4 \right\} \quad (8)$$

where  $y$  is the non-slipping distance, and  $CD_{\kappa \omega}$  is defined by

$$CD_{\kappa \omega} = \max \left( 2 \rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial \kappa}{\partial x_i} \frac{\partial \omega}{\partial x_i}; 10^{-10} \right) \quad (9)$$

The other constants are:  $\beta = 0.075$ ;  $\beta^* = 0.09$ ;  $\sigma_\kappa = 0.5$ ;  $\sigma_\omega = 0.5$ ;  $\sigma_d = 0.856$ ;  $\alpha = 5/9$ .

Air-water interface is modeled via the VOF (Volume of Fluid) method, proposed by Hirt and Nichols (1981),

$$\frac{\partial \Phi}{\partial t} + u_i \cdot \nabla \Phi = 0 \quad (10)$$

where  $\Phi$  represent the volume fraction of liquid phase,  $0 \leq \Phi \leq 1$ .

The initial value problem is solved by the CFD package ANSYS Fluent, release 15.0, which makes use of the finite volume method. Cartesian coordinates are defined by setting, respectively, the  $x$  and  $y$ -axis in the longitudinal and transverse directions of the air-water interface and the  $z$ -axis in the vertical direction. The fluid domain has 13.2m of length, 7m of width and 3.25m of height, with a water depth of 2.75m below the free surface level. The Wigley III hull model has 2.36m of length, 0.236m of breadth and 0.1475m of draught, and its center of gravity is positioned at the origin. The mesh was refined near the hull in order to better predict the dynamics of the fluid motion. Figure 1 illustrates the computational grid employed. Long run computations were adopted aiming to achieve a “quasi steady-state” regime. All the computations were carried out on a 64 bit, 3.40 GHz Intel Core i7-2600 processor with 16 Gb of RAM.

The reference frame is changed such that water flows with the velocity of the ship. An UDF (User Defined Function) is set to allow only two degrees of freedom for the ship motion: heave and pitch. The vertical motions are simulated during 15 seconds for two Froude numbers ( $Fr = 0.23$  and  $Fr = 0.34$ ) and various wave steepnesses ( $0.021 \leq ak \leq 0.084$ ), where  $k$  and  $a$  are the wave number and wave amplitude. The Froude number  $Fr$  and wave number  $k$  are defined as,

$$Fr = \frac{U}{\sqrt{gL}}, \quad k = \frac{2\pi}{\lambda} \quad (11)$$

where  $U$  and  $L$  are the hull's velocity and length whereas  $\lambda$  is the wavelength. The wave height is constant and equal to 0.04m; wavelengths range from 1.5 to 6.0m.

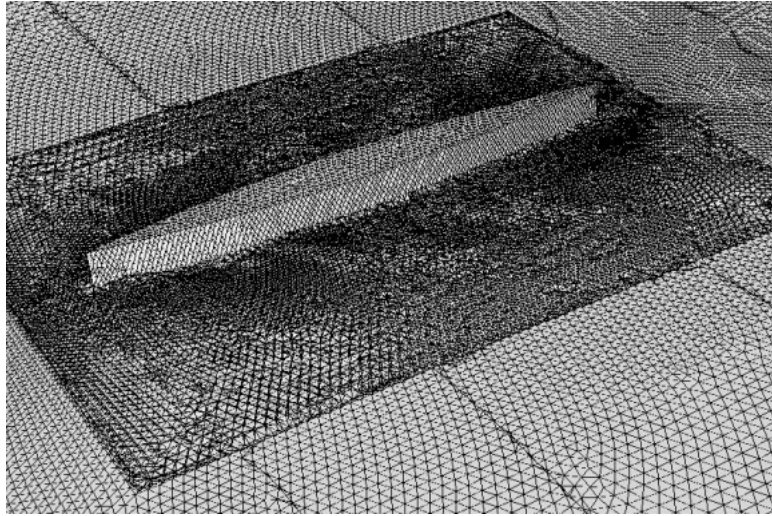


Figure 1. Snapshot of the free-surface grid.

### 3. RESULTS

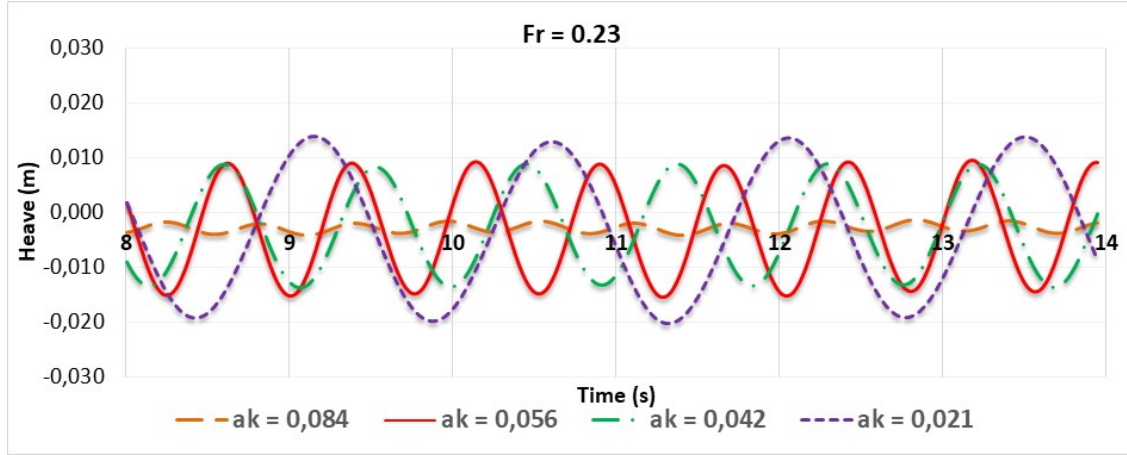
Results for the RAOs are validated with the experimental data of Journée (1992). Heave  $z_a$  (in m) and pitch  $\theta_a$  (in degrees) are non-dimensionalised such that,

$$z_a'' = \frac{z_a}{a}, \quad \theta_a'' = \frac{\theta_a}{360} \frac{L}{a} \quad (12)$$

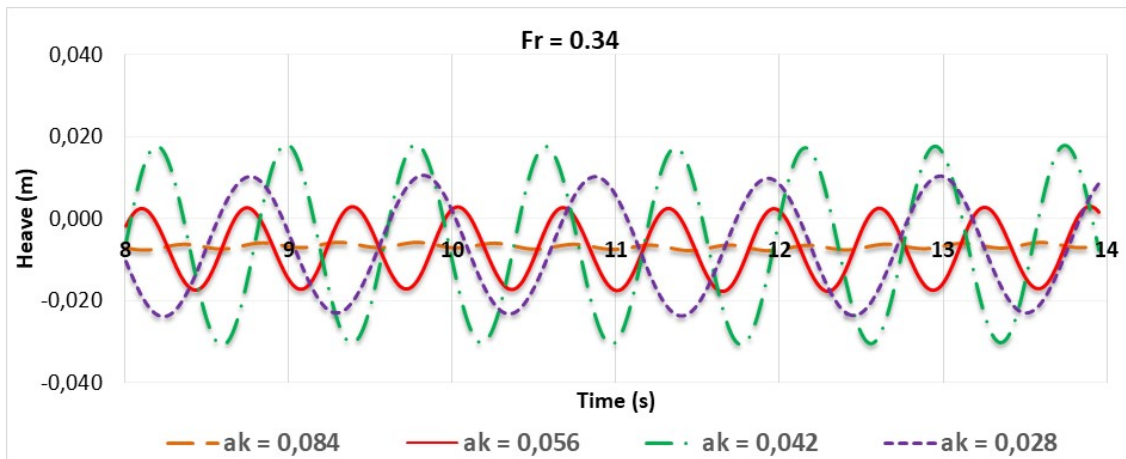
where  $a = 0.02\text{m}$  and  $L = 2.36\text{m}$ .

### 3.1 Heave

Figure 2 shows the evolution of heave  $z_a$  (in m) for various Froude numbers ( $Fr = 0.23$ ;  $0.34$ ) and wave steepnesses ( $ak = 0.021$ ;  $0.028$ ;  $0.042$ ;  $0.056$ ;  $0.084$ ). As expected steep waves cause high frequency disturbances to the hull whereas longer waves augment the magnitude of heave.



(a)



(b)

Figure 2. Evolution of heave for various wave steepnesses: (a)  $Fr = 0.23$ ; (b)  $Fr = 0.34$ .

Figure 3 compares the non-dimensional heave  $z_a''$  with experiments carried out by Journée (1992). A good agreement is found for  $Fr = 0.23$ ;  $0.34$ . Heave amplitudes are quite small for wavelengths less than  $0.5L$  and approximate wave amplitude for  $\lambda \geq 1.5L$ . As shows Fig. 2, high frequency waves have a minor effect on heave since  $L > \lambda$ . At low frequencies, the vessel moves up and down with the wave, augmenting heave amplitudes. Furthermore, a local maximum of heave is expected when  $L \approx \lambda$ , as shows Fig. 3. As the Froude number increases, heave amplitudes also augment.

### 3.2 Pitch

Figure 4 shows the evolution of pitch  $\theta_a$  (in degrees) for fixed Froude numbers ( $Fr = 0.23$  and  $Fr = 0.34$ ) and various wave steepnesses ( $ak = 0.021$ ;  $0.028$ ;  $0.042$ ;  $0.056$ ;  $0.084$ ), with the following wavelengths: 6.00; 4.50; 3.00; 2.25; 1.50m. Waves with intermediary  $ak$  cause high modifications to the hull vertical orientation, while great steepnesses tend to low pitch values.

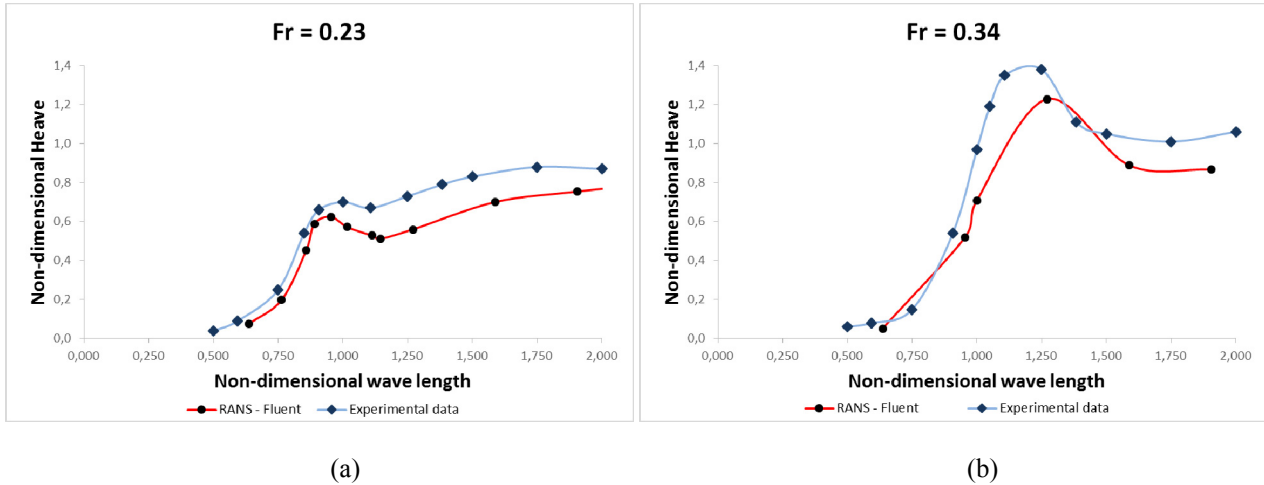


Figure 3. Non-dimensional heave  $z_a''$  for various wavelengths  $\lambda/L$ : (a)  $Fr = 0.23$ ; (b)  $Fr = 0.34$ .

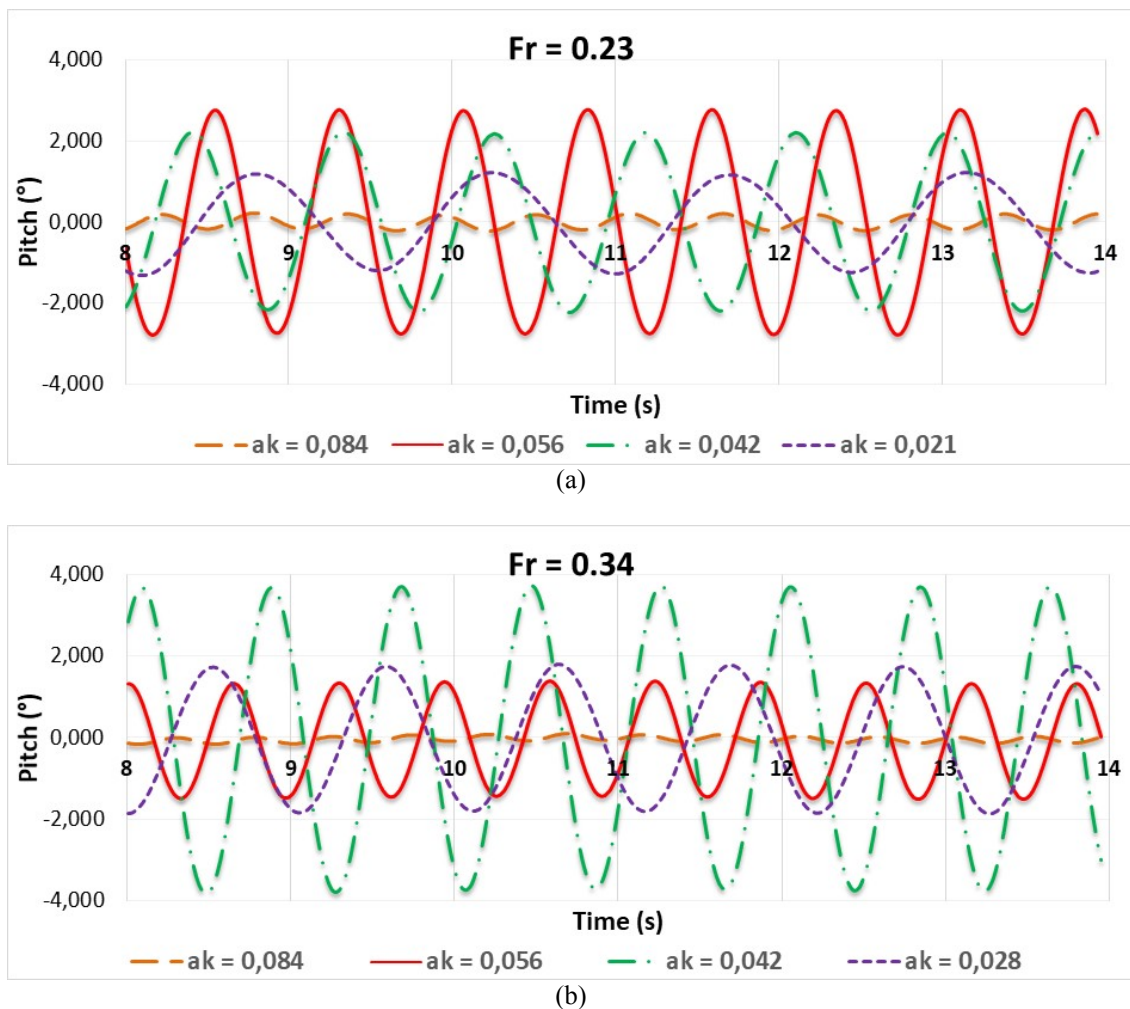


Figure 4. Evolution of pitch for various wave steepnesses: (a)  $Fr = 0.23$ ; (b)  $Fr = 0.34$ .

Figure 5 compares our RAO of pitch calculations with experimental data. A good agreement is found between experimental and numerical results except for  $1.0 \leq \lambda/L \leq 1.25$  for  $Fr = 0.23$  and  $\lambda/L \approx 1.25$  for  $Fr = 0.34$ . Sea conditions with wave lengths similar to the size of the hull cause high changes in the vertical orientation of the ship model. Furthermore, high Froude numbers increase pitch magnitudes, with numerical results approaching experimental data.

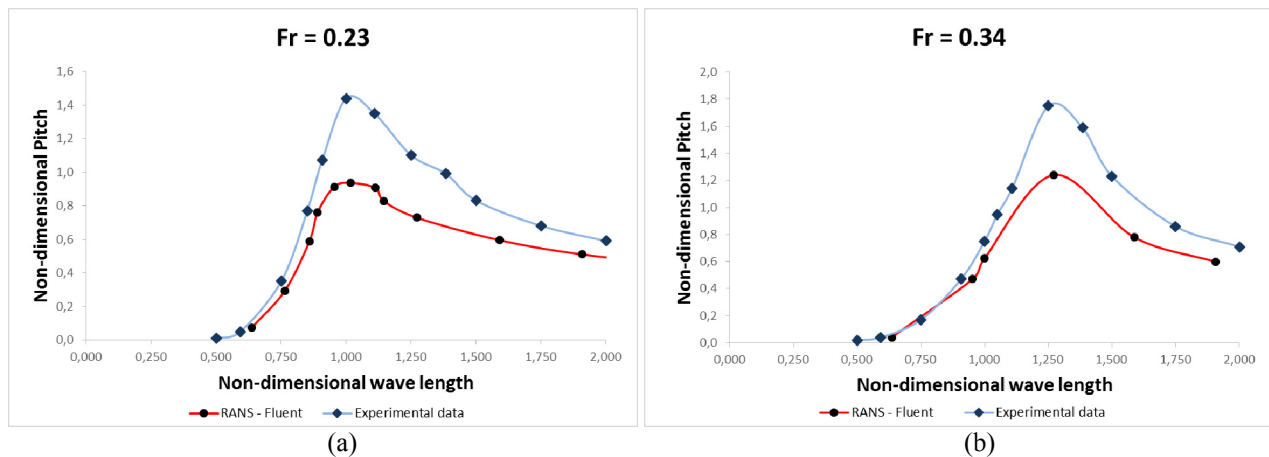


Figure 5. Non-dimensional pitch  $\theta''$  for various wavelengths  $\lambda/L$ : (a)  $Fr = 0.23$ ; (b)  $Fr = 0.34$ .

#### 4. CONCLUSIONS

The ship motions heave and pitch for a Wigley-III model could be reproduced numerically and validated with experiments carried out by Journée (1992). Results show CFD simulations can preview with good precision the RAOs far from  $\lambda/L \approx 1.0$  (cases that incident waves have length next to ship hull size), and the dynamic profile of both vertical degrees of freedom could be evaluated. Furthermore, Froude number increase rises both heave and pitch motions for long waves. The present analysis of verticals motions for a ship hull can be used to investigate vessel stability and the prediction of RAOs via computational methods represents an input to develop models more adapted to a large range of sea conditions.

#### 5. ACKNOWLEDGEMENTS

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