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Head-wave parametric rolling of a surface combatant

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ABSTRACT

Complementary CFD, towing tank EFD, and nonlinear dynamics approach study of parametric roll for the ONR Tumblehome surface combatant both with and without bilge keels is presented. The investigations without bilge keels include a wide range of conditions. CFD closely agrees with EFD for resistance, sinkage, and trim except for $Fr>0.5$ which may be due to free surface and/or turbulence modeling. CFD shows fairly close agreement with EFD for forward-speed roll decay in calm water, although damping is over/under predicted for largest/smaller GM. Most importantly CFD shows remarkably close agreement with EFD for forward-speed parametric roll in head waves for $GM=0.038$ and 0.033 m, although CFD predicts larger instability zones at high and low Fr, respectively. The CFD and EFD results are analyzed with consideration ship motion theory and compared with Mathieu equation and nonlinear dynamics approaches. Nonlinear dynamics approaches are in qualitative agreement with CFD and EFD. The CFD and nonlinear dynamics approach results were blind in that the actual EFD radius of gyration k_{xx} was not known a priori.

1. Introduction

Ships with pronounced bow flare, flat transom sterns, and wall-sided/wide-beam mid-ship sections are vulnerable to large amplitude roll limit-cycle oscillations suddenly occurring especially in head or stern seas, which is referred to as parametric roll. Causes in order of importance include periodic changes of transverse stability (restoring moment) from increased/decreased stability when ship encounters wave trough/crest, nonlinear restoring moment, and nonlinear roll–pitch–heave resonance. Large roll motions are major sources of discomfort and limiting factors in the operability of ships and can lead to loss of life, damage, and capsize. The probability of occurrence is exacerbated by the traditional maritime practice of steering into heavy-weather head seas at reduced speed, although recent international guidelines provide alternative recommendations. Different approaches have been used to evaluate and understand parametric rolling.

Model experiments were first step to find correlation between parametric roll and ship and wave properties. In the experiments, wave period, wave height, load condition, and speed of the model were varied and their effects on the threshold for the occurrence of parametric rolling and the resultant rolling amplitude were investigated. Model experiments on head-sea parametric rolling are divided into two categories. The first uses a model towed by a carriage or other device in a towing tank and the second uses a free-running model with autopilot in a wide rectangular basin. For head-sea parametric rolling the variation of the roll restoring moment in waves plays an important role in addition to the coupling between roll and vertical motions (Skomedal, 1982). Therefore, if a towed model is used, special attention should be paid to the towing arrangements to ensure that there is no interference with the vertical motions. Burcher (1990), Neves et al. (2002), Francescutto (2001), and Olivieri et al. (2006b, 2008) described this kind of towing arrangement. Neves et al. (2002) used two auxiliary lines, respectively, fixed to the bow and stern of the model at calm water level and tied to the towing wire. The resulting elasticity of the set was found in all cases to be appropriate in order to secure free evolution of the different symmetric and anti-symmetric modes of motion at a controlled speed. Neves et al. (2002) conducted a series of experiments on parametric rolling undertaken for two fishing vessels with different stern shape in head waves. One was a typical round stern vessel while the other one was a transom stern fishing vessel. Several parameters such as wave steepness, metacentric heights, and Fr number effects were studied. It was concluded that effect of speed on parametric resonance is strongly dependent on stern shape. A transom stern, incorporating longitudinal

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Nomenclature

A	wave amplitude
Ak	wave steepness ($=A\times k$)
A_{wp}	water-plane area
$E\%D$	comparison error ($=100(D-S)/D$)
Fr	Froude number
g	gravity
GM	transverse metacentric height
GM_a	amplitude of GM variation in waves
GM_L	longitudinal metacentric height
GM_m	mean value of GM variation in waves
GZ	roll restoring moment arm
I_x, I_y, I_z	moment of inertia
I_{xy}, I_{yz}, I_{xz}	product of inertia
k	wave number ($=2\pi/\lambda$)
KG	vertical position of center of gravity respect to the keel
k_{xx}, k_{yy}, k_{zz}	radii of gyration based on dry mass values
L	ship length
l_n	restoring moment coefficient in calm water
m	mass
Q_{pm}, Q_{pa}	restoring moment mean value and harmonic amplitude in waves
t	time
T	draft
u, v, w, p, q, r	perturbation velocities
U_0	ship speed
u_T, v_T, w_T, p_T, q_T, r_T	total velocities (perturbation+steady)
x, y, z, ϕ, θ, ψ	perturbation motions
x_{CF}	flotation center
X_h, Y_h, Z_h, K_h, M_h, N_h	hydrostatic forces and moments
x_T, y_T, z_T, ϕ_T, θ_T, ψ_T	total motions (perturbation+steady)
X_T, Y_T, Z_T, K_T, M_T, N_T	total forces and moments
ΔGZ_w	change of GZ due to waves
α	linear damping coefficient
α_e	equivalent damping coefficient
β	drift angle
δ	logarithmic decrement
ϕ_0	initial roll angle
ϕ_m	mean roll angle
γ	cubic damping coefficient
λ	wave length
ρ	density of water
σ	sinkage
τ	trim
ω_a	amplitude of parametric excitation in waves in form of frequency ($=2\pi f_a$)
ω_e	wave encounter frequency ($=2\pi f_e=\omega_w+2\pi U_0/\lambda$ in head waves)
ω_w	wave frequency ($=2\pi f_w=\sqrt{2\pi g/\lambda}$)
ω_ϕ	roll natural frequency in waves ($=2\pi f_\phi$)
$\omega_{\phi d}$	damped roll frequency ($=2\pi f_{\phi d}$)
$\omega_{\phi h}$	hydrostatic roll frequency ($=2\pi f_{\phi h}$)

asymmetry in flare, may exert a significant influence in establishing the tendency of a fishing vessel hull to display strong parametric amplification in head-seas particularly in a condition of low metacentric height. Francescutto (2001) conducted experiment for a destroyer model using a tethering system based on pairs of elastic mooring lines symmetric about the center line of the model, to attach the model to the towing carriage while the model is free to roll, pitch and heave. This system ensures the model remains on a straight course, while it is sufficiently loose to avoid significant interference with the roll and vertical motions. The results clearly indicated that there is a speed window where the roll motion can be sustained in head waves. The width of the window and the amplitude of steady rolling depend on wave steepness. In particular, the roll amplitude increases with the wave steepness, and in some cases leads to ship capsize. Olivieri et al. (2006b, 2008) conducted the experiment where the model was connected to the carriage by means of a joint specifically designed for 3DOF parametric roll. Model motions are measured using both an optical motion tracker (Krypton) and gyroscopic (MOTAN) platform. Bulian et al. (2004) used the tethering system in irregular waves. However, even with the elastic mooring line towing arrangement it is difficult to reproduce speed variation in irregular waves. Therefore, free model tests are used by Hashimoto et al. (2006) and France et al. (2003) to improve test results in irregular waves. It is noted that comparative studies between free-running and towed model experiments have shown acceptable agreement (IMO, 2006).

Theoretical/analytical dynamics provides a mathematical framework and qualitative understanding. The roll motion neglecting nonlinear damping and restoring moment and considering wave effects and pitch–heave coupling only through a time varying restoring coefficient is modeled as a 1D mass–damper–spring linear system with small damping and periodic restoring coefficient, which can be transformed into the Mathieu equation (Paulling and Rosenberg, 1959). Bounded/unbounded solutions to the Mathieu equation are delineated in the Ince–Strutt diagram as $q=\omega_a{}^2/\omega_e{}^2$ versus $p=(\omega_\phi{}^2-\alpha^2)/\omega_e{}^2$ curves. Linear and higher order theories for the first instability zone provide instability estimates for small q. For $q=0.0$, instability occurs at $p=n^2/4$, $n=1, 2, 3,\ldots$. The first parametric resonance region occurs for $n=1$ meaning $p=0.25$ or, equivalently, for zero damping $\omega_e=2\omega_\phi$: in other words for small excitation and damping the roll period equals twice the wave encounter/pitch motion period for first parametric resonance region. For $q>0.0$ instability occurs for increasing ranges of p for increasing q, which can be equivalently expressed as a Froude number (Fr) range. Typically roll excitation in head waves occurs for wavelengths about $0.5<\lambda/L<2$ where L is ship length (Shigunov et al., 2009). Unbounded solutions to the Mathieu equation may not lead to unbounded roll unless the damping α is less than a threshold value $\alpha_T=\alpha_T(p, q)$ (Shin et al., 2004). In order to be able to assess the magnitude of roll, more advanced theories include nonlinear damping and restoring, nonlinear time-dependent restoring, and nonlinear roll–pitch–heave coupling mathematical models. Generally, the damping consists of contributions from linear and quadratic/cubic terms of roll velocity estimated from roll decay towing tank test as described in Francescutto et al. (2004) and Umeda et al. (2004). The restoring term can be described by cubic or higher order functions of roll angle. Bulian (2004, 2005) considered a ninth order restoring function estimated from hydrostatic computation to account for the calm water righting arm and Hashimoto and Umeda (2004) chose fifth order restoring function derived from hydrostatic computation. The time-dependent restoring term due to waves can be expressed by first or higher order polynomial function of roll angle with time-dependent coefficients expressed as Fourier series.