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Virtual bottom for ships sailing in restricted waterways (unsteady squat)

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ABSTRACT

The focus of this paper is to update the classic criterion for the determination of the safe keel clearance for ships sailing in restricted waterways. Ship's dynamics is taken into account by integrating the notion of the unsteady squat. This paper shows the existence of unstable equilibrium position of the ship during heave motion. Furthermore, it proposes a new mathematical expression to evaluate it as a function of canal and ship parameters. It is shown that this unstable equilibrium position can be considered as a virtual bottom for ship. It should not be reached during ship motion in order to avoid grounding. The importance of this result, confirmed both by an analytical model as well as by a numerical model with Finite Elements Method, lies in the reduction of the safety margin actually allowed for pilots. So this result points out the knowledge of a virtual bottom that could lie above the real nautical bottom.
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1. Introduction

The under keel clearance (UKC) is considered as one of the most important factor which governs the navigation safety in restricted waters (Gucma and Schoeneich, 2009). Safe value of UKC should be maintained by Masters and pilots to ensure secure marine navigation. In other words, vessel's minimum UKC should be determined for areas with restricted available water depth. To define the UKC, static and dynamic values should be distinguished as follows (see Fig. 1): Static UKC means the minimum clearance available between the vessel's keel and the bottom in still water.

Dynamic UKC describes the clearance left from the static UKC after substraction of squat caused by the forward motion of the ship (Wieslaw, 2008).

The principal goal of this paper is to update the definition of the safe under keel clearance (the safe navigation condition) by taking into account ship's dynamic. However, the notion of safe under keel clearance is directly related to squat phenomena. In the literature, several formulas for the determination of squat and trim of ships sailing in restricted or open water exist. According to the used method, three main approaches can be distinguished:

- Theoretical approach (Schijf, 1949; Constantine, 1960; Tothil, 1966; Gates and Herbich, 1977; Tuck, 1966; Gourlay, 2008).
- Empirical approach (Eryuzlu and Hausser, 1978; Barrass and Derrett, 2006).
- Numerical approach based on finite differences (Gourlay, 2000) or finite elements (Debaillon, 2010).

This work is based on the numerical model given by Alderf et al. (2010) to simulate ship squat. The last one has shown the existence of a stable equilibrium position (which is equivalent to water level depression (steady squat) and an unstable equilibrium position). The transition effects are integrated in this model to simulate the behavior of a vessel during and after an acceleration phase (Alderf et al., 2010). It has been shown that although the vessel speed is lower than Schijf Limiting Speed (Schijf, 1949), grounding due to the oscillations generated at the end of the acceleration phase will occur when the unstable equilibrium position is reached. The application of this model has been limited in highly restricted waterways where a 2D model has been considered. In this paper, a new mathematical expression has been established to evaluate the unstable equilibrium position as a function of ship and canal parameters, the validity of this expression has been confirmed by a 3D numerical model using finite elements method. The principal result highlights the existence of a virtual bottom for a ship in the dynamic clearance. This virtual bottom is located at the unstable equilibrium position.

The structure of the paper is as follows: Section 2 presents the analytical model. The last one is based on the model of Alderf

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Nomenclature

Subscripts

A_b	area amidship section (m^2)
A_c	wetted area of canal cross-section (without the ship) (m^2)
b	ship's breadth (m)
B	canal width (m)
C_B	block coefficient
C_b	blockage factor
$DUCK$	dynamic under keel clearance
Fr	depth Froud number
H	depth of area after taking into account the error in its determination
Lpp	length between perpendiculars (m)
m	mass of ship per unit beam (kg/m)
$\vec{n}$	unit normal vector (oriented outside)
$SUKC$	static under keel clearance when ship at rest
T	ship draft at rest
$\mathcal{T}_{ship}$	natural frequency of ship's heave
$UKC(safe)$	safe under keel clearance
V_∞	vessel speed
V_{cr}	critical speed
$\vec{V}$	flow velocity
$\delta\Phi$	test function
ω	transient vertical motion of the ship (function of time)
$-\omega_1$	squat
ω_3	critical value of omega at which point the ship becomes vertically unstable
Ω	calculation domain
ρ	water density
Φ	potential velocity

et al. (2010). It will be extended to give a mathematical expression for the unstable equilibrium position for a ship in highly restricted waterways (2D model). In Section 3, the 3D fluid–structure model is presented, this model enables to generalize the results obtained in Section 2 to wide canal. Section 4 presents results and analysis: ship responses as a function of vessel speed, analysis of the sum of acting forces over the hull, confirmation of the presence of the unstable equilibrium position and thus the virtual bottom. Finally, a conclusion and some prospects close this paper.

2. Analytical model

This model is based upon a Newton's second law limited to one degree of freedom in heave motion. The reference frame is fixed to the canal bottom. The equation governing the dynamic equilibrium of the ship is given by

$$m\frac{d^2\omega}{dt^2} = -mg + \int_{hull} P\vec{n}\,\vec{e}_z\, ds \tag{1}$$

with $m=\rho.Lpp.T$ The continuity equation gives the velocity under the keel:

$$V(x) = \frac{V_\infty H}{z(x)}$$

with $z(x) = H - T + \omega$. Bernoulli's equation gives

$$P = \rho g(H - z(x)) + \frac{\rho}{2}V_\infty^2\left(1 - \frac{H^2}{z(x)^2}\right).$$

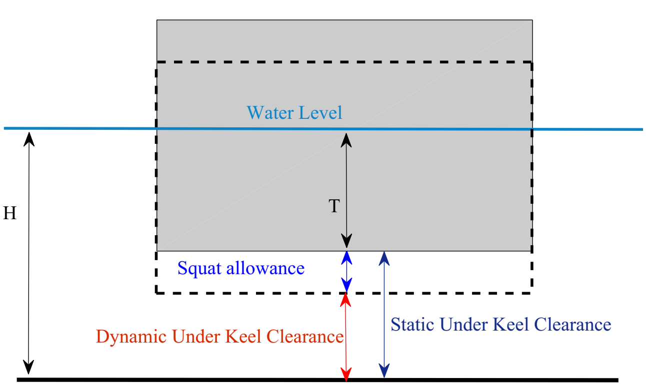

Fig. 1. Canal cross-section.

Injecting the continuity equation and Bernoulli's equation in the Eq. (1) leads to

$$m\frac{d^2\omega}{dt^2} = \frac{g\rho Lpp}{(H-T+\omega)^2}f(\omega) \tag{2}$$

with

$$f(\omega) = -\omega^3 + \left(-2(H-T) + \frac{1}{2g}V_\infty^2\right)\omega^2 + \left(-(H-T)^2 + \frac{V_\infty^2}{g}(H-T)\right)\omega + \frac{1}{2g}V_\infty^2\left((H-T)^2 - H^2\right) \Longrightarrow f(\omega) = -(\omega-\omega_1)(\omega-\omega_2)(\omega-\omega_3) \tag{3}$$

$f(\omega)$ given by the Eq. (3) can be rewritten in polynomial form (d'Alembert's theorem) admitting three roots each one corresponding to an equilibrium position of the ship; two stable positions (ω_1 and ω_2) and an unstable position (ω_3), that means in heave motion, vessel displacement can reach position in UKC, according to ship and canal parameters this position may be stable or unstable.

$$f(\omega) = (\omega-\omega_1)(\omega-\omega_2)(\omega-\omega_3)$$

Multiplying the Eq. (2) by $d\omega/dt$ enables after integration, to define the kinetic and potential energies of the ship

$$E_c = \frac{1}{2}m\left(\frac{d\omega}{dt}\right)^2 \tag{4}$$

$$E_p = -\int\left(\frac{g\rho\, Lpp}{(H-T+\omega)^2}\right)\times f(\omega)d\omega \Longrightarrow$$

$$E_p = -\rho\, g\, Lpp\left(T\,\omega - \frac{\omega^2}{2}\right) - 0.5\rho\, Lpp\, V_\infty^2\left(\omega + \frac{H^2}{H-T+\omega} - \frac{H^2}{H-T}\right) + \rho\, g\, Lpp\, T\,\omega \tag{5}$$

The stability equilibrium positions are determined by the sign of the second derivative of the potential energy.

Fig. 2 shows the displacement of the vessel in heave motion as a function of the potential energy for a given value of Froude number. That means for a given value of vessel speed the potential energy has been calculated as a function of a range of vessel displacement ω.

The blue arrows refer to the direction of the curve of potential energy form positive value of ω corresponding to initial vessel displacement to the negative ones.

The stable position (ω_1) is the steady squat given by most researchers in this domain. ω_3 is the unstable equilibrium position, and the unsafety margin is measured from canal bottom to

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