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Numerical study of forced roll oscillation of FPSO with bilge keel

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ABSTRACT

This work shows a study about the bilge keel and its influence, width and form, on the roll damping of FPSO sections. A computational code was developed to simulate forced roll oscillation of a middle section of FPSO with different bilge keels types. The computational code calculates the solution of the Navier-Stokes equations in 2D, using the finite volume method and the upwind TVD scheme of Roe-Sweby. The effect of wave radiation is neglected. This work shows how the generated vortices influence the pressure distribution around the middle section of FPSO. The numerical results are compared with experimental results to validate the computational code. New bilge keel configurations were studied to improve the roll damping of FPSO.

1. Introduction

In the field of hydrodynamics of ocean engineering, to predict the motion of ship and floating platforms is one of the most important goals. In general, all movements can be reproduced fairly accurately using known linear methodologies, except the strongly nonlinear roll motion. The roll motion is very sensitive to the effects of viscosity, especially in the presence of appendages such as bilge keels. This appendage is a prompter of flow separation around the body, generating vortices and viscous damping. It is the most traditional passive stability system used in ships. The vortices around the hull influence the pressure distribution on the body surface. These vortices depend directly on the body geometry and the appendages in the case of floating platforms as FPSOs (Floating Production Storage and Offloading).

FPSOs have cost advantages and cargo capacity, especially in regions with little oil flow infrastructure (pipelines), as the Brazilian coast. These units are exposed throughout their lifetime to roll motion, which has an impact on the design and of related structures.

Ikeda et al. (1977a) studied the damping component that generates vortices (eddy damping), and concluded that this component is proportional to the square of the frequency and amplitude of roll motion. Ikeda et al. (1977b) concluded that the pressure on a ship hull surface due to the bilge keels is proportional to the square of the oscillation frequency, and the negative pressure coefficient behind the bilge keel depends on the Keulegan Carpenter (KC) number. Himeno (1981) described the state of the art of the ship roll damping prediction. It showed that it is possible to estimate the roll damping of typical hull ship with reasonable accuracy. He commented that the damping of the bilge keel not merely shows a quadratic nonlinear behavior, but it depends on the amplitude and frequency in a more complex form. Downie et al. (1988) concluded that for rectangular hulls, the damping by wave radiation is small and viscous effects are particularly important on roll damping. Yeung et al. (1998) developed an experimental program to measure the hydrodynamic coefficients of rectangular cylinders and the results were compared with the FSRVM method (Free-Surface Random Vortex Method) developed by Yeung and Vaidhyanathan (1994). Aloisio and Felice (2006) conducted a study of the flow around the bilge keel using a PIV system. It was concluded that the vortex shedding is the main mechanism involved in the damping of the roll motion, and the vorticity shed from the bilge keel is proportional to the amplitude of the motion. Jaouen et al. (2011) reproduced numerically the experimental tests of forced roll oscillation of Ikeda et al. (1977a), and only compared the viscous damping. The numerical code that they have developed and used, REFRESCO, did not consider the effect of wave radiation. The results showed good agreement, and also showed that, in rectangular hull sections, the sharp bilges show greater added mass and damping than the rounded bilges. Avalos (2012) and Avalos et al. (2014) simulated the roll damping decay of a middle section of FPSO with bilge keel through the numerical solution of the Navier-Stokes equations in 2-D. The computer code was developed using the finite volume method and the TVD upwind scheme of Roe (1984) and Sweby (1984), in an unstructured dynamic mesh, and neglecting the wave radiation effects. The results showed the influence of the bilge in the damping, and the difference of the vortex generation mechanism with and without bilge keel.

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Nomenclature

a_{44}	Added mass coefficient of roll
B	Beam of the model
b_{44}	Damping coefficient of roll
c_{44}	Restoring coefficient of roll
C_p	Pressure Coefficient
F_r	Froude number
g	Acceleration of gravity
KC	Keulegan-Carpenter number
L	Length of the model
M	Mach number
M_H	Hydrodynamic moment
$M_{\theta p}$	Pressure moment with respect to center of gravity of the model
$M_{\theta v}$	Viscous moment with respect to center of gravity of the model
m	Mass of the model
$\vec{n}$	Normal vector pointing out of the object
p	Pressure of the fluid
p_∞	Pressure of free-stream
R_e	Reynolds number
S	Area of the cell boundary
T	Draft of the model
T_p	Period
t	Time
u	x-velocity component
u_{ref}	Reference velocity
v	y-velocity component
V	Volume of the cell
x	Horizontal Cartesian coordinate
y	Vertical Cartesian coordinate
$\vec{w}$	Local velocity of the surface of the control volume
ε	Phase of angle
θ	Angle of inclination
$\bar{\bar{\tau}}$	Viscous stress tensor
Ψ	Flux limiter
∇	Displacement volume

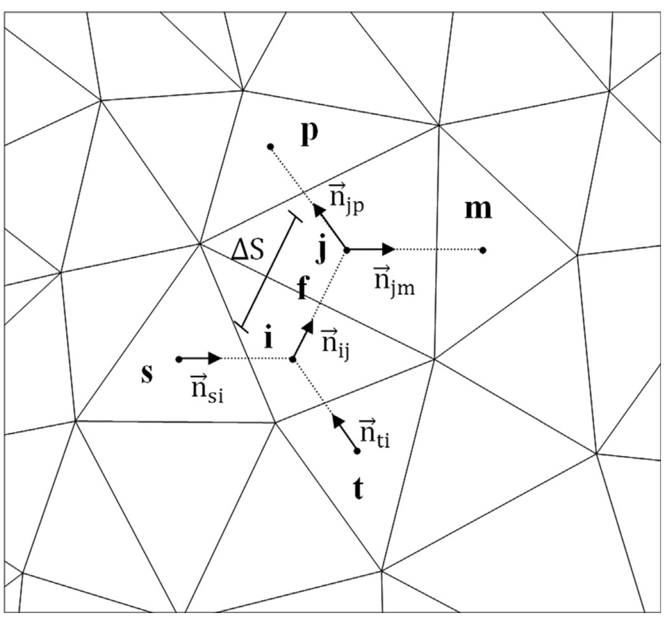

Fig. 1. Location of the elements *m, p, s* and *t* respect to the face *f* between the elements *i* and *j*.

The bilge keel has been the most used appendage to reduce the roll motion of stationary floating units for reasons of simplicity and cost efficiency. Studies of large-width bilge keels impacts in roll behavior that can be mentioned for instance are Thiagarajan Krish and Braddock (2009), Oliveira (2011). New forms of bilge keels were studied by Matsuura et al. (2001), Na et al. (2002), Kinnas (2005) and Lee et al. (2010). The Computational Fluid Dynamics (CFD) tools have the potential to improve prediction of local loads, improving the integrity of this appendage, which has become critical to ensuring the satisfactory operation of the production units.

The present study aims the development of a 2D computational code able to calculate the roll damping of FPSOs with new forms of bilge keels. The numerical code was developed in Avalos (2016) and represents an evolution of the works of Avalos (2012) and Avalos et al. (2014). This code should help to understand how the bilge keels influence the roll damping with respect to its shape and size, thus it identifies the main features required for new bilge keel projects. Numerical results obtained in this study are compared with experimental results of Thiagarajan Krish and Braddock (2009), Na et al. (2002) and Ikeda et al. (2004) to validate the developed computational code. After the numerical code validation, new bilge keel configurations were studied.

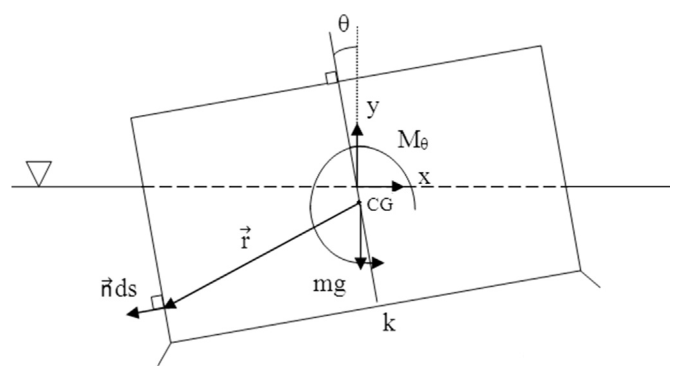

Fig. 2. Moment acting on the cross section of a FPSO.

2. Mathematical formulation

In the present investigation, wave radiation was not considered. The body is completely submerged in the numerical tank and the Navier-Stokes equations are solved for the entire flow around the body without considering the source term of the gravity. When the forces acting on the body are calculated, the effect of pressure and viscous stress of this flow acting on the body is considered only in the part of the body below an imaginary flat free surface, defined by the draft. The effect of gravity (hydrostatic pressure) is considered in this calculation as well.

The slightly compressible Navier-Stokes equations are solved numerically using the finite volume method and the upwind TVD scheme of Roe (1984) and Sweby (1984) for the flow around a FPSO section in forced roll oscillation. Eq. (1) presents the governing equations in two-dimensional Cartesian coordinates and written in the conservative