Ocean Engineering 166 (2018) 191–207

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

# Linear and non-linear roll damping of a FPSO via system identification of a third order equation with sway-roll coupled damping effects

Antonio Carlos Fernandes, Peyman Asgari*, Joel Sena Sales Junior

*Ocean Engineering Department, COPPE - Federal University of Rio de Janeiro, P.O. Box 68508, CEP 21945-970, Rio de Janeiro, RJ, Brazil*

## ARTICLE INFO

*Keywords:*
Roll damping
Roll center
Sway-roll coupled damping

## ABSTRACT

This work focuses on roll decay experiments performed on hulls normally used as FPSOs. Considering the practical case of beam seas, Newton's second law and the Newton-Euler theorem lead to coupled sway, heave and roll equations for an arbitrary pole. Assuming symmetry, the heave equation is uncoupled, leaving the sway and roll equations coupled. The research shows that, even if inertia is decoupled, damping coupling is unavoidable and cannot be neglected. Nevertheless, a third order equation dealing only with roll can be constructed. The latter is used to develop a robust approach that uses system identification techniques to obtain damping properties from the decay tests. In this approach, non-linear damping is assessed using a cycle-by-cycle linear approach that uses system identification to match all the information obtained from the decay test. Both held-over and pre-oscillation tests are discussed, and new concept is presented: the coupled damping number (CDN), which relates the product of the main diagonal damping terms with coupling damping coefficients. The CDN is proven to be null for potential flows, and turns out to be very small even when viscous effects are present such as in decay tests, at least for typical FPSO hulls.

## 1. Introduction

Since the start of the use of FPSOs (Floating Production Storage and Offloading Platforms) in the 1960's, roll motions have revealed to be a major concern for operators of these units. Roll motion prediction for FPSOs are traditionally based on the knowledge established for conventional ships, and very few works oriented to issues specific to FPSOs have been published. Nonetheless, very large roll motions, with values above design predictions, have been reported for FPSOs over the last years, implying uncomfortable conditions for the crew, process plant downtime and degradation of the structural integrity of topside supports, hull, bilge keels and risers. It should be stressed that even though many similarities can be found between an FPSO and a ship, these structures differ in many aspects (lack of maneuvering capability; weight distribution with regard to topsides; and unconventional anti-roll system), which affects their roll behavior and places a question mark on the adequacy of currently employed methods for roll motion prediction.

In fact, numerous works related to the estimation of roll damping in oil tankers have been published during the last decades. Nevertheless, most have two fundamental issues which may propagate errors to damping estimation. The first is related to the lack of a unique definition of the pole necessary for rotational equations, despite the fact that the importance of this definition for damping estimation has been shown by some researchers. This pole is in principle arbitrary, as known from theory, and is known as either the “roll center” or the “center of roll”. However, these names prove to be meaningless, as they have no clear definition. A better understanding of the pole would definitely improve roll estimation procedures. The second fundamental issue is related to the understanding of the coupling of roll with other degrees of freedom. These two issues are addressed below.

Froude (1861) was one of the first to recognize the importance of roll motions for the operability of ships. Froude formulated roll damping in a linear plus quadratic velocity-dependent form to account for dissipation of energy during roll motion. He studied the effects of wave height and steepness on the rolling of ships and the influence of this phenomenon on the design of ship hull shape. Based on this work (Froude, 1861), he suggested designing the hull in such a way as to move the ship's natural roll frequency away from synchronization with the excitation waves. His work also supported the use of bilge keels to stabilize roll motion. Froude's method uses decay tests equating the potential energy lost to damping in each half cycle to the work done by the equivalent linearized damping moment during the same period. This produces an expression for the slope of the roll decay curve as a function of the linear and nonlinear damping coefficients. Later on, Dalzell (1976) extended Froude's method to the case of a linear-plus-

---

* Corresponding author.
*E-mail address:* p-asgari@oceanica.ufrj.br (P. Asgari).

https://doi.org/10.1016/j.oceaneng.2018.08.006
Received 22 March 2018; Received in revised form 18 June 2018; Accepted 6 August 2018

cubic damping model.

Vugts (1968) conducted several experimental assessments to determine hydrodynamic coefficients of swaying, heaving and rolling cylinders in free fluid surfaces. His work has been used as the basis for numerous studies assessing the roll damping of floating bodies. Ikeda et al. (1978a) proposed a new technique to estimate roll damping based on decay tests. This technique separated roll damping into components, but ignored their interactions, and therefore the coupling of roll damping to other degrees of freedom was not taken into account (Ikeda et al., 1978a). Himeno (1981) provided a good review of roll damping phenomena in a very thorough literature survey of Japanese and worldwide literature on the subject. This review is largely based on the work of Ikeda et al. (1978b).

Faltinsen (1993) described another approach to predict damping. In his approach, energy loss is evaluated in terms of a linear equivalent damping coefficient, equating the energy loss of an equivalent sinusoidal behavior to the energy dissipation from a quadratic equation.

The vast majority of roll damping studies since Froude has focused on studying roll in a single degree of freedom, neglecting any coupling. But Ikeda et al. (1981) also conducted a number of forced sway and roll experiments. His paper deals with viscous effects on forces and moments acting on a ship in sway and roll motion at zero forward speed, and investigates roll damping and coupling terms in velocity-phase of roll into sway and sway into roll. From this work it can be concluded that damping coupling terms are large, having the same order of magnitude as the main diagonal dampings.

Bass and Haddara (1989, 1991) performed an extensive series of experiments to determine roll damping characteristics for a number of small fishing vessels. In the experiments, the models were attached to a dynamometer with only 2 degrees of freedom. The model was free to roll and heave, but restrained in all other modes. His investigations included not only roll damping but also roll-sway coupled damping. He clearly showed the influence of roll-sway and sway-roll coupling on roll damping, which has a non-linear dependence on the position of the roll axis (the axis on which the model is free to rotate).

Standing (1991) also conducted many model tests to investigate viscous roll damping and the effect of sway and heave motions on the roll response of a transportation barge. Numerical examples suggest that the roll and sway equations may be decoupled if the motions are defined relative to a certain ‘roll center’. His work assumes that the roll, sway and heave equations are coupled only through the relative velocity term in the roll damping moment. The equations are otherwise decoupled by defining them relative to the ‘roll center’. This ‘roll center’, however, is not clearly defined.

During the past 40 years much more information has become available supporting that roll damping prediction is influenced by the position of the ‘roll center’. The first serious discussions emerged during the 1980s, when Ikeda, 2004 carried out forced roll tests on four fishing boat models. He observed that lowering the position of the rotation axis of the forced test (the ‘roll center’) led to decreased roll damping. Bass and Haddara (1989) showed that the equivalent non-dimensional linear roll damping coefficient increases along with the distance between the position of the rotation axis (‘roll center’) and the center of gravity. Chun et al. (2001) arrived at the same conclusion. Park et al. (2000) studied the effects of the position of the rotation axis (again called the ‘roll center’) on damping for FPSO sections using decay experiments. They also considered a symmetric section of an FPSO and positioned the rotation axis on the symmetry plane. Their findings indicate that roll damping is sensitive to the position of the axis (‘roll center’) on the symmetry plane. Roll damping will increase if the rotation axis is placed above the still-water level.

Thus far, previous studies have confirmed the importance of the position of the rotation axis. However, for a freely floating body there is no fixed rotation axis, hence a clear definition of the ‘roll center’ is not traceable in the literature, and in effect each researcher has his/her own interpretation. In the classical Principles of Naval Architecture - PNA a quote states that “a very rough estimate for the location of the roll center is halfway between the center of gravity and the center of buoyancy”, implying that the ‘roll center’ lies on the symmetry plane.

Overall, all relevant studies of roll motion highlight the need for a better understanding of the ‘roll center’. Different definitions may be found: ‘center of gravity’ (Vugts, 1968), ‘still-water level’, ‘center of buoyancy’ and others have all been considered as the ‘roll center’. This difficulty can even be found in Ikeda's formulations: in Ikeda et al. (1978a) and Ikeda et al. (1977) the quantity known as OG represents the distance from the still-water level to the roll axis (vertical position of the ‘roll center’). In other papers, such as Ikeda (1984) and Ikeda et al. (1993), OG is defined as the distance from the still-water level to the center of gravity.

Stewart et al. (1979) mentioned an instantaneous ‘roll center’. According to his work, the roll center is instantaneously at rest as the vessel moves through waves, but tends to wander wildly, and may move from well above to well below the vessel in irregular waves. The main reason why Stewart's formulation was not taken up by other researchers is not very clear. Roberts and Dacunha (1985) identified the ‘roll center’ as a point where the roll equation decouples from sway, which is in fact impossible since damping coupling still remains (see below). Later on, Standing (1991) proposed the following definition: “When there is significant damping, the ‘roll center’ may be defined as the point of minimum sway response in a forced-roll or free-decay type of experiment or simulation, when a pure moment is applied”. This is an obscure sentence, at least for the present authors. In both references, the position of the ‘roll center’ is assumed to be constant and independent of frequency. The mismatch of ‘roll center’ definitions may have motivated Molin (2002) to call it the “mystérieux center du roulis” (mysterious roll center, in French). Recently, Fernandes et al. (2015, 2016) have noticed that the instantaneous center of rotation (ICR), that is, the point with zero velocity, varies in time, as predicted by Newtonian mechanics. Fernandes et al. (2015, 2016) also proposed the concept of a “Most Often Instantaneous Roll Center” – MOIRC value, as also discussed below. Of course this MOIRC value could be called the ‘roll center’, but the authors see no reason to do that. In fact, the ‘roll center’ (and the ‘center of roll’, for that matter) seems indeed to be a fantasy that does not help those working with roll damping estimation.

Based on the challenges described above, this work presents an innovative, robust approach to assess roll damping of FPSOs, taking into account a correct definition of the pole on which to center the motion equations as well as the influence of the unavoidable coupled damping for sway and roll damping estimation, using both numerical and experimental techniques.

## 2. Third order equation

The motion of a floating body exposed to external forces such as wind, wave and currents takes place in six degrees of freedom. The motion equations can be derived using the Newton-Euler or Lagrange equations. Clayton and Bishop (1982) expressed general, fully nonlinear equations of rigid-body kinetics in a vectorial framework. In order to construct the governing motion equations, the following assumptions and simplifications are made:

(i) The floating body is slender and rigid, with a symmetry plane;
(ii) Motion amplitude is small, so that equations can be linearized;
(iii) The effects of viscosity are neglected except for roll motion;

A right handed co-ordinate system $(x, y, z)$ is considered with respect to an arbitrary position O, as shown in Fig. 1. The translation displacements in $x$, $y$ and $z$ directions with respect to the origin, denoted by $\eta_1$, $\eta_2$ and $\eta_3$ indicate surge, sway and heave, respectively. The angular displacements about the same set of axis, $\eta_4$, $\eta_5$ and $\eta_6$, indicate roll, pitch and yaw, respectively.

Under the above assumptions, three linearly coupled differential