ANALYSIS OF THE DYNAMICAL BEHAVIOUR OF AN OFFSHORE SUPPLY VESSEL WITH WATER ON DECK

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SUMMARY

This paper describes a study of the influence of the water on deck on the dynamical behavior of an offshore supply vessel with a large open aft deck. The deck under certain load and sea conditions can become partially or totally immersed. This study focuses on the roll motion that can be of large amplitude and therefore has implications and risks for the ship's safety. The Glimm's method is used to model the three-dimensional flow of shallow water on the deck. A parametric study is made in order to show the effect of the relevant parameters. It is shown that the water on deck has a significant influence on the ship's dynamical response.

1. Background

After 15 years (Dillingham and Falzarano, 1986), we have returned to our water on deck simulation computer program. Over the last 10~20 years the capsizing community has split into two groups the physical and numerical simulators and the nonlinear dynamists. Many believe these two approaches are mutually exclusive however nothing could be further for the truth. Nonlinear dynamic analysis is complementary to model tests and simulation studies. Essentially the simulation experts attempt to actually simulate the large amplitude motion of a vessel in six-degrees of freedom in a realistic seaway. They find critical environment and operating conditions in order to assess the capsizing risk of a particular design. However, in the critical operating region the capsizing is dependent upon initial conditions. This sensitive dependence upon initial conditions is exactly what is predicted by nonlinear dynamical analysis. Nonlinear dynamics models are generally restricted to being expressed in explicit terms of the state variables and time and are hence rather simplified (Troesch and Hicks, 1994). However, if formulated properly they can capture the critical dynamics. These results can then guide physical and numerical simulators to perform simulations in critical parameter regions or can be used to formulate dynamics based vessel stability criterion. The limitation of nonlinear dynamics analysis is often the physical system modeling. However this limitation can be overcome with approximation models, a system identification procedure and a understanding of the limitations of and a approximation inherent in the physical models used.

In model test and simulation studies the analyst typically concentrated on determining which ship and environmental conditions will lead to capsizing and non-capsizing (see e.g., DeKat and Thomas, 2000). A boundary is then determined between the conditions which leads to capsizing and those that do not. Unfortunately the initial conditions are often set as trivial or not uniformed. However it is in the critical region where initial conditions are most important. Obviously with small wave amplitude the initial conditions at angles less than the angles of vanishing stability and corresponding energy levels will be safe. As the wave amplitude increases this is no longer the case. As the wave amplitude increases beyond a critical amount the boundary between safety and capsizing is no longer a single curve but a complicated intersected region. As the wave amplitude increases still further, the complicated intersected region dominates the whole state space and virtually any initial condition will lead to capsizing.

2. Introduction

Like most vessels, an offshore supply vessel (Figure 1) must be operational during most of her life. The problem that has motivated this study was the particular characteristics of this kind of ship and the environmental conditions in which they must operate. These vessels have a very wide-open aft deck area used to carry their cargo. This area is exposed to the elements and very likely to be flooded and a bad design choice of the dimensions of the bulwarks and/or the scuppers, can lead to a very large volume of water being trapped inside the deck.

There are studies and reports of maritime accidents in which after a total loss of a ship by flooding of the deck and capsizing the investigators cannot give a deterministic explanation. The investigators point to reasons such as overloading or badly stowed cargo, failure of the hatches resulting in flooding, or instability as a result of deck flooding.

The effect of the entrapped water on the ship's static stability is a very well known subject in the naval architecture field. Although there are several studies on the water on deck problem, these are mainly focused on fishing vessels (e.g. Storch [1], Caglayan and Storch [2], Dillingham [3], Falzarano and Troesch [4]) or RO-RO ships (Chang and Blume [5]). The authors could not find any study of water on deck of an offshore supply vessel although there are some reports of accidents involving capsizing and total loss of the ship where water on deck could have been one of the causes (e.g., [6,7]).

The problem addressed here is to determine the effect of the trapped water on the deck upon the ship's motions. This problem can be divided into two sub-problems: 1) the static part that can be calculated with the classic methods used on a damage stability analysis and 2) the dynamic effect, which is much more difficult to model and simulate. The second effect is dependent on the flow of water on deck that is further dependent on the vessel's motions, which are dependent on the global forces acting on the ship. In order to deal with this problem, two coupled problems must be solved simultaneously.

The flow computation problem is a shallow water wave problem, this means, the wavelength is much larger compared to the water depth. This problem can be formulated as a boundary value problem with non-linear boundary conditions.

Figure 1: Offshore supply vessel

The greatest difficulty in solving this problem is the inevitable existence of hydraulic jumps. There is a linear theory that can be used to solve a single hydraulic jump moving periodically. This theory has limitations and it is not sufficient when the deck is partially or totally (temporarily) dry.

To overcome this problem, the random choice method, or Glimm's method, is implemented. The method was introduced by Glimm [8] and later developed as a very useful numerical tool by Chorin [9, 10]. This method allows the computation of the velocity and depth of the water on deck. Although a grid is used this method is not a finite difference method. With this method neither the hydraulic jumps nor the dry parts of the deck need special treatment. Using Glimm's method, it is possible to obtain a good approximate solution for the flow of the water on deck in the time domain, which can then be coupled to the time domain simulation of the ship's motions. Dillingham [3] has previously used this method for a bi-dimensional flow and Dillingham and Falzarano [11], Falzarano [12], Pantazopoulos [13], Zhou, et al. [14] used it for three-dimensional flow. The flow analyzed herein is three-dimensional.

The common practice to solve the ship's response in a certain sea state is to assume small amplitude motions and incident waves. This assumption allows the equations of motion to be linearized around a certain equilibrium point such that a method, like the strip method can be used to determine the ship's hydrodynamic coefficients. In our approach it is necessary to add an additional step to obtain a time domain solution. It is well known that the hydrodynamic coefficients are frequency dependent and in a random seaway time domain simulation cannot be introduced as constants into the equations of motion. The frequency dependence can be taken into account by using the impulse response technique of Cummins [15] adopted by Perez y Perez [16] and Fonseca and Guedes Soares [17]. The final solution is a synthesis of the two techniques, the impulse response for the ship motions in a six-degree of freedom system and Glimm's method to solve the flow of the water on deck.

3. Equations of Motion

It will be assumed in the analysis that the motions of the ship and the waves are small so that linear theory is applicable. Assumptions of conservation of mass, incompressibility and irrotationality of the flow allows us to use the potential flow formulation. The hull is slender enough to use the strip theory.

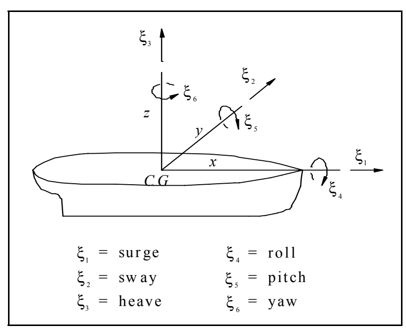

Figure 2: Coordinate system used

Although beam seas is investigated herein, considering this heading to be the most critical, other heading may also be critical such as stern or bow quartering seas as has been previously investigated by Mulk and Falzarano [18, 19].

Consider the coordinate system indicated in Figure 2, where:

- x, y, z is a direct coordinate system in which x is positive from aft to fore and y positive to portside;
- ξ_1, ξ_2, ξ_3 the translation motions and ξ_4, ξ_5, ξ_6 the rotation motions in x, y, z;

Assuming that the ship has a linear response the equation of motion with six degrees of freedom can be written for a periodic motion as follows

$$\sum_{k=1}^{6} m_{jk} \ddot{\xi}_k + R_{jk}\xi_k = \int_{S_0} p_j n_j dS, \qquad j = 1,2,...6 \quad (1)$$

where $m_{jk} = m\delta_{jk}$, $j,k = 1,2,3$ and m is the displacement of the vessel and $m_{jk} = I_{jk}$, $j,k = 4,5,6$ where I_{jk} are the moments and products of inertia; δ_{jk} is the Kronecker delta. Likewise, the R_{jk} are the restoring forces and moments acting on the vessel when displaced from the equilibrium floating point. On the right hand side of the equation the pressures p_j are integrated over the wetted hull surface S_0. These pressures can be of three kinds: 1) pressure due to incident waves, 2) the diffracted waves and 3) the radiated waves. Rearranging Equation (1) and defining hydrodynamic added mass, damping and forcing the following set of six coupled differential equations may be written

$$\sum_{k=1}^{6}\left[\left(m_{jk} + A_{jk}\right)\ddot{\xi}_k + B_{jk}\dot{\xi}_k + C_{jk}\xi_k\right] = \mathrm{Re}\left[F_j e^{i(\delta_j - \omega t)}\right] \quad (2)$$

$$j = 1,2,...,6$$

where m_{jk} is the mass matrix, A_{jk} and B_{jk} are the mass and damping coefficients, C_{jk} hydrostatic restoring coefficients, F_j the generalized forcing, ω excitation frequency and ϕ the phase angle.

For a linear system described by the set of equations above, a pseudo-dynamic solution may be sought if the following transformation is done

$$\xi_k = \mathrm{X}_k e^{i(\beta_k - \omega t)} \quad (3)$$

where X_k is the amplitude of motion and β_k it's a phase angle. The following equation results from the substitution of the new amplitude in Equation (2),

$$\sum_{k=1}^{6}\left[-\omega^2\left(m_{jk} + A_{jk}\right) - i\omega B_{jk} + C_{jk}\right]\mathrm{X}_k e^{i\beta_k} = F_j e^{i\delta_j} \quad (4)$$

$$j = 1,2,...,6$$

which may be solved for amplitude of motion X_k and phase β_k by matrix inversion.

In random sea waves the equation of motion is written as above except that the added mass and damping coefficients are functions of the wave frequencies. This case of random sea waves implies that these radiated waves must appear as convolution integrals (see e.g. Chakrabarti [20]). Thus, the Equation (2) becomes:

$$\left(m_{jk} + A^*_{jk}\right)\ddot{\xi}_k + \int_{-\infty}^{t} B^*_{jk}\,\dot{\xi}_k(\tau)d\tau + C_{jk}\xi_k = F_j(t) \quad (5)$$

where

$$B^*_{jk} = \frac{2}{\pi}\int_0^{\infty} B_{jk}(\omega)\cos\omega t d\omega \quad (6)$$

and

$$A^*_{jk} = A_{jk}(\omega) - \frac{1}{\omega}\int_0^{\infty} B^*_{jk}(t)\sin\omega t d\omega \quad (7)$$

This set of equations can only be solved using a time domain analysis.

The flow on the deck is three-dimensional and the vessel is free to move in the six degrees of freedom so that the equation needs to be analyzed in their complete form taking into account the various couplings. The rotation order imposed by the Euler angles must also be taken into account. This means that the yaw (ξ_6) is always measured relative to the vertical axis (z), the pitch (ξ_5) is always measured relative to an Earth parallel axis already rotated by the yaw (y') angle and the roll (ξ_4) is always measured relative to an axis already rotated by the yaw and pitch angles (x'') as showed in Figure 3. This coordinate system is fixed to the vessel's center of gravity.

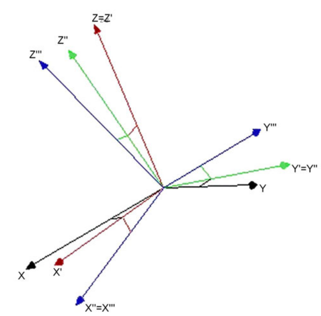

Figure 3: Euler angles (1^{st}- ξ_6, 2^{nd}- ξ_5, 3^{rd}- ξ_4)

The deck can be modeled as a rectangular tank with length equal to the deck length, width equal to the ship's breath and height equal to the height of the bulwark. The water flows and sloshes freely according to the ship's motions. The generalized forces in the right hand side of Equation (2) must include the forces due to the ocean waves and the ones produced by the flow of water on deck. The forces due to the flow of water on deck are solved in the time domain using Glimm's method. Therefore, in order to relate the resulting forces of water on deck and the ship motions, it is necessary to develop a time domain solution for the last. As shown above, Equation (5) can only be solved by a time-domain analysis and since this is a linear equation it is possible to use the superposition principle to build the solutions for the exciting functions with time varying amplitudes. The equations are in the necessary form to apply the impulse response technique.

In this work a strip theory computer program has been used to obtain frequency dependent hydrodynamic coefficients and exiting forces for a given sea state. This computer program is based on the linear theory and computes the sectional hydrodynamic coefficients according to the Frank close fit method (e.g. Beck and Troesch [21]).

4. Water on Deck Problem Formulation

The problem of determining the motions of water on deck on a oscillating ship is formulated assuming that the water depth is small compared to the amplitude of the waves that appear on the deck and that the free surface of the undisturbed water is a plane parallel to x', y'.

The three-dimensional flow is, due to its formulation, a bi-dimensional problem. Stoker's formulation [22] for the shallow water wave in one dimension is extended to two dimensions taking an average on the vertical dimension. The free surface is $\eta(x,y,t)$ the following equations appear from the satisfaction of the conservation of mass and moment, and the application of the kinematical boundary condition on the free surface and bottom (deck):

$$\begin{aligned} &\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial \eta}{\partial x} \\ &\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial \eta}{\partial y} \\ &\frac{\partial}{\partial x}(u\lambda)+\frac{\partial}{\partial y}(v\lambda)=-\frac{\partial \lambda}{\partial t} \end{aligned} \qquad (8)$$

where $\lambda=\eta+h$ and h water on deck depth and u,v,w the velocities in x,y,z respectively. This equation set is valid for a level ship at rest. In order to take into account the ship's motions the above equations must be transformed to a coordinate system coupled to the ship's center of gravity. This transformation is described by Dillingham [3], for a bi-dimensional flow and by Dillingham and Falzarano [11], for a three-dimensional flow.

Figure 4 shows a schematic representation of the complete system.

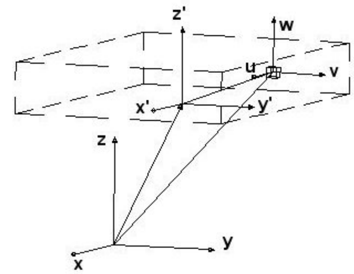

Figure 4: Coordinate system configuration

where x,y,z is an inertial coordinate system, x',y',z' the center of gravity-coupled coordinate system and u,v,w the water on deck particle velocities.

After the transformations one can obtain the equations for the water on deck particles and Equation (8) becomes the following system of equations related to the inertial coordinate system:

$$\begin{aligned} &\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-a_z\frac{\partial \eta}{\partial x}+f_1(x) \\ &\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-a_z\frac{\partial \eta}{\partial y}+f_2(y) \\ &\frac{\partial}{\partial x}(u\lambda)+\frac{\partial}{\partial y}(v\lambda)=-\frac{\partial \lambda}{\partial t} \end{aligned} \qquad (9)$$

where the forces $f_1(x)$ e $f_2(y)$ are defined as follows:

$$\begin{aligned} f_1(x)=\;&\ddot{\xi}_1\cos\theta-\ddot{\xi}_2\sin\phi\sin\theta+\ddot{\xi}_3\sin\varphi\sin\theta-2\dot{\phi}\dot{\theta}x \\ &\times\sin\phi\sin\theta\cos\theta-\dot{\phi}\dot{\theta}y\cos\phi\cos\theta-\dot{\phi}\dot{\theta}z_d\sin\phi \\ &\times(\sin^2\theta-\cos^2\theta)+\dot{\phi}^2x\sin^2\theta-\dot{\phi}^2z_d\sin\theta\cos\theta+\dot{\theta}^2x \\ &\times(1-\sin^2\theta\sin^2\phi)-\dot{\theta}^2y\sin\theta\sin\phi\cos\phi+\dot{\theta}^2z_d\sin\theta\sin^2\phi \\ &\times\cos\theta+2\dot{\phi}v\sin\theta-2\dot{\theta}\sin\phi\cos\theta+\ddot{\theta}y\sin\phi\cos\theta \\ &-\ddot{\theta}z_d\cos\phi+g\sin\theta\cos\phi \\ f_2(y)=\;&\ddot{\xi}_2\cos\phi-\ddot{\xi}_3\sin\phi+\dot{\phi}^2y-\dot{\theta}x\sin\theta\sin\phi\cos\phi \\ &+\dot{\theta}^2y\sin^2\phi+\dot{\theta}^2z_d\sin\phi\cos\phi\cos\theta-\dot{\phi}\dot{\theta}x\cos\phi\cos\theta \\ &-\dot{\phi}\dot{\theta}z_d\sin\theta\cos\phi-2\dot{\phi}u\sin\theta+2\dot{\theta}u\sin\phi\cos\theta-\ddot{\phi}x\sin\theta \\ &+\ddot{\phi}z_d\cos\theta+\ddot{\theta}x\sin\phi\cos\theta+\ddot{\theta}z_d\sin\phi\sin\theta-g\sin\phi \end{aligned} \qquad (10)$$

where z_d is the vertical distance between the center of gravity and the deck. These equations represent the shallow water waves coupled to the ship motions. If the ship is level and at rest, the following holds:

$$\ddot{\xi}_i=\dot{\xi}_i=\xi_i=\phi=\theta=0$$

and the Equation (9) becomes the Equation (8).

5. Solution Method

The coupled system equations (Equation (9)) are solved using Glimm's method, which is a random choice method. Dillingham [3] analyzes the bi-dimensional case, which results in solving a one-dimensional problem. Dillingham and Falzarano [11] analyzed the three-dimensional flow which results in solving a two dimensional problem. As stated before, this method is particularly attractive because it solves relatively complex flows with many hydraulic jumps with no special treatment of discontinuities. This method is also capable of handling the discontinuous case of a partially or totally dry deck at some time instants.

The method determines the solution for the water depth and velocities u and v by solving the nonlinear hyperbolic system of partial differential equations. The deck is divided into a grid parallel to the x', and y' and the differential equations are solved for each grid cell. For each time step in the x' or y' direction the Riemman, or dam breaking, problem is solved in one dimension (see e. g. Stoker [22]). For detailed information about this formulation and solution method to this problem see Dillingham [3], Pantazopoulos [13], Dillingham and Falzarano [11], and Zhou, et al. [14].

6. Forces and Moments due to Sloshing of Water onto Deck Bulwarks

The results from Glimm's method solution are the water depth and velocities at every point on the deck and the variation of these properties with time. So, in order to compute the applied forces and moments on the deck and bulwarks, simple hydrostatics will be used. From these assumptions the forces and moments are given by

$$\vec{F}(x,y,z) = \iint_S p(x,y,z)\,\vec{n}\,dS \qquad (11)$$

$$\vec{M}(x,y,z) = \iint_S p(x,y,z)\,\vec{r}\,\vec{n}\,dS \qquad (12)$$

where

$p(x,y,z) = \rho a_z(x,y)z$ is the hydrostatic pressure,

$\vec{n}$ is the external normal vector,

$\vec{r}$ is the position vector of the applied force and

S is the bulwark surface.

7. Computational Procedure

The computational procedure can be summarized as follows. First to determine the ship mass, damping and linear hydrodynamic characteristics it is necessary to run a linear strip theory computer program. This program gives M_{ij}, C_{ij}, $A_{ij}(\omega)$ and $B_{ij}(\omega)$. The hydrodynamic added mass and damping are given for a series of frequencies considered adequate. The external wave forces are obtained from the same program and for the same frequency range.

All this data plus the geometric and other vessel characteristics and sea wave spectrum are input into the six-degree of freedom computer program that solves the equations of motion taking into account the external and internal (water on deck) forces.

For each time step the ship motion is computed by convolving the exciting forces with the impulse response function according to the method described in Perez y Perez [16]. The motion of the water on deck, if the deck is wetted, is computed knowing the motion of the ship in the actual time step and the motion of the water on deck of the previous time step solved by the implemented random choice or Glimm's numerical method. Knowing the position of the ship relative to the sea surface, the external water level can easily be determined and the flow over the bulwarks and in or out of the scuppers be computed. Once the level of deck flooding is known the forces can be computed and the equilibrium between the water on deck and external wave can be achieved and the next time step and ship position computed. This procedure goes on until the maximum time of simulation or if capsize occurs.

8. Simulation and Results

This section shows some results of simulations done with the six-degree of freedom water on deck ship dynamics program. The following plots where made using a time history of the given sea states for a range of significant wave height.

The sea surface elevation is determined from a Pierson-Moskowitz spectrum using non-uniform frequency interval.

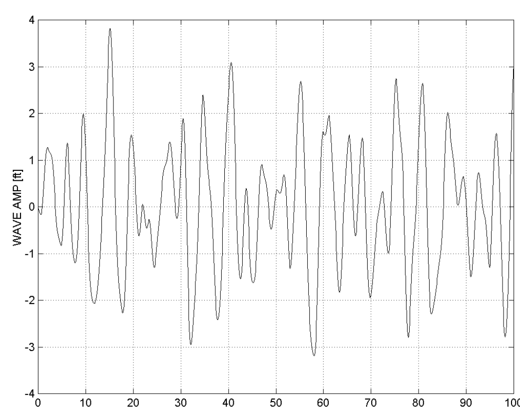

Figure 5: Wave simulated time history (SWH = 6ft)

The various sea states are all unidirectional and, as previously stated, of beam seas. So, by imposing a 90º angle between the sea and the vessel directions, an extreme situation has been considered. Beam seas may be forced upon a fishing vessel due to a fixed course operation while fishing.

Next some simulations of the roll dynamics of the considered vessel will be shown. This vessel as the following characteristics:

Table 1: Vessel characteristics summary

Length, ft	215.71
Beam, ft	43.0
Draft, ft	15.05
Block coefficient	0.55
GM_T, ft	11.87
XCG relative to midships, ft	-1.20
ZCG, ft	-3.38
Displacement, LT	1972.32
Bulwark height, ft	5.0
Deck length, ft	113.55
Radius of gyration, K_{xx}	15.05
Radius of gyration, K_{yy}	53.93
Product of inertia, I_{46}	0.56E+06
Critical roll damping (linear), ft.lb/sec	0.91E+08
Roll natural period, sec	5.0

The simulations aimed at determining the effect of the water on deck on the roll dynamics. This influence can be of two kinds depending on phase relation: (1) positive damping and (2) negative damping. By positive or negative damping we refer to the sign of the water on deck force in phase with the roll velocity. The second kind is the most dangerous for the operation and safety of the ship. It is important to know that water comes into the deck from the side openings if the ship rolls, without heave and calm sea, ≈20º to the deck height (8.20 ft) relative to the mean water line.

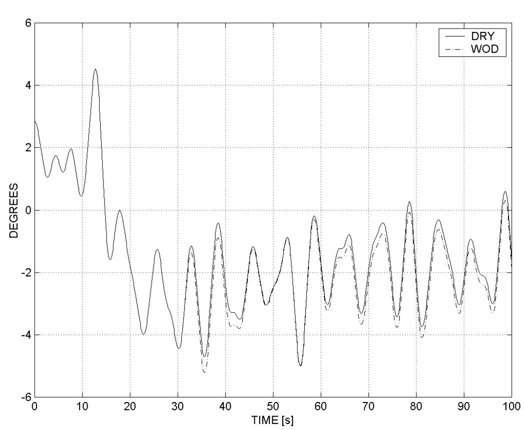

Figure 6: Roll time history. Case 1 (SWH = 6.0ft)

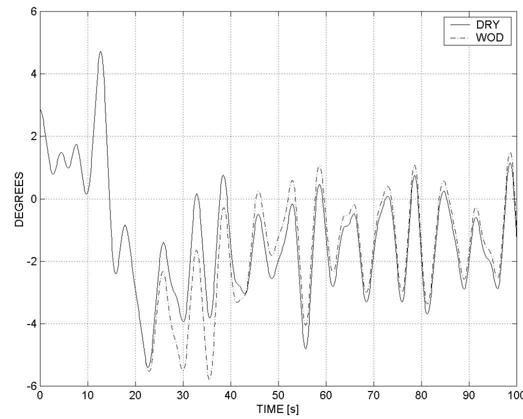

Figure 7: Roll time history. Case 2 (SWH = 7.0ft)

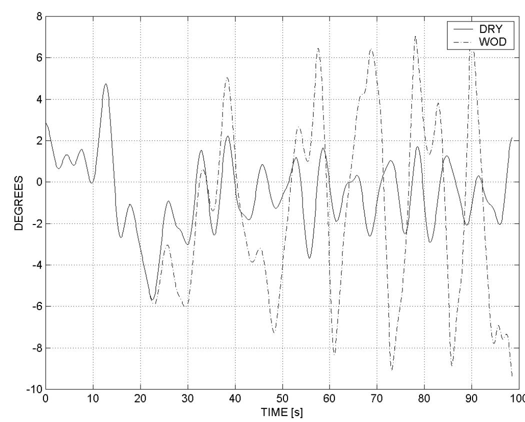

Figure 8: Roll time history. Case3 (SWH = 7.5ft)

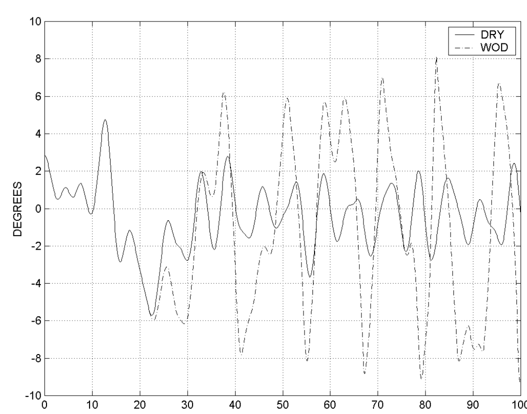

Figure 9: Roll time history. Case 4 (SWH = 8.0ft)

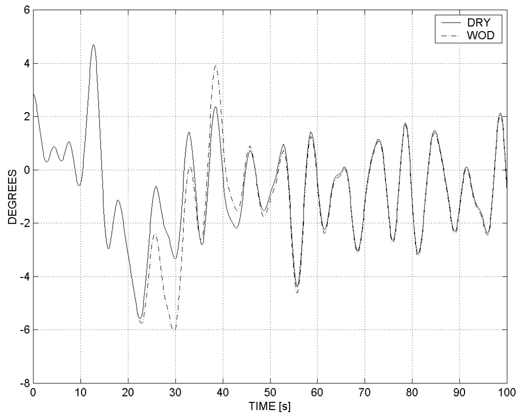

Figure 9: Roll time history. Case 5 (SWH = 8.5ft)

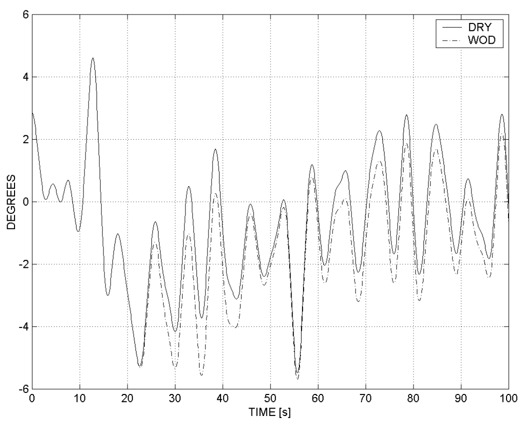

Figure 10: Roll time history. Case6 (SWH = 9.0ft)

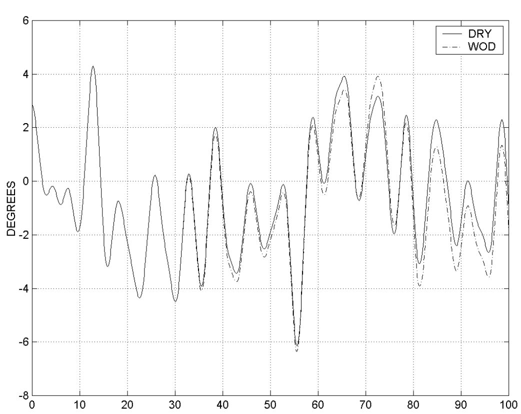

Figure 11: Roll time history. Case 7 (SWH = 10.0ft)

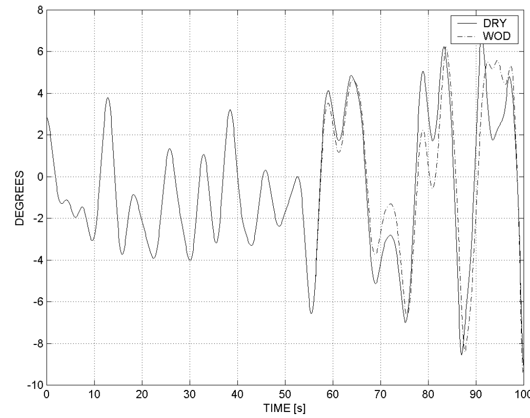

Figure 12: Roll time history. Case 8 (SWH = 11.0ft)

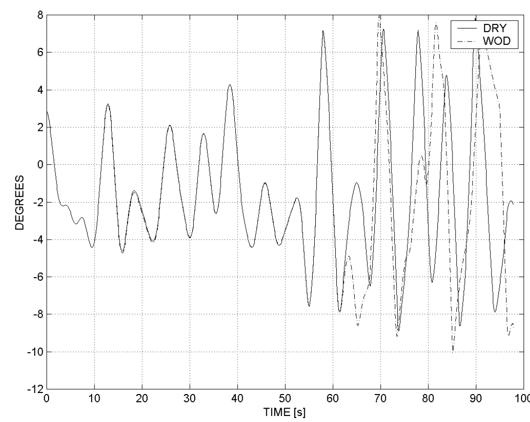

Figure 13: Roll time history. Case 9 (SWH = 12.0ft)

From the previous simulations, the influence of the water on deck on the ship roll dynamics is clear. Although not dramatic, the simulations clearly show the kind of influence that the water on deck has onto the ship's roll dynamics. It is clear that the water on deck influence is not always a positive damping but more often a negative one. This means that water-on-deck will generally amplify the natural roll behavior under certain conditions can lead to vessel capsizing. Case 3 and Case 4 are good examples of the negative effect that the water on deck can have on the ship's roll dynamics. Also it should be noted that in these cases the sea spectrum peak is near the roll resonance frequency.

Next it is important to analyze the maximum roll angles achieved under the various conditions with and without water on deck. This can be analyzed in Table 2, and the simulation plots. Indeed the water on deck is not a positive damper in this case.

Table 2: Maximum roll angles in case studies

Case 1 SWH = 6.0 ft	DRY	5.0º
	WOD	5.2º
Case 2 SWH = 7.0 ft	DRY	5.4º
	WOD	5.8º
Case 3 SWH = 7.5 ft	DRY	5.7º
	WOD	9.4º
Case 4 SWH = 8.0 ft	DRY	5.7º
	WOD	9.3º
Case 5 SWH = 8.5 ft	DRY	5.6º
	WOD	6.1º
Case 6 SWH = 9.0 ft	DRY	5.5º
	WOD	5.7º
Case 7 SWH = 10.0 ft	DRY	6.2º
	WOD	6.4º
Case 8 SWH = 11.0 ft	DRY	9.1º
	WOD	9.4º
Case 9 SWH = 12.0 ft	DRY	8.9º
	WOD	10.0º

8. Conclusions

This paper presents a survey of the state of the art and the previous work done on ship dynamics with water on deck. This has shown that there is no work developed on the specific case study of an offshore supply vessel. The authors believe this type of vessel is an important case study because of its specific geometry and mission. The large deck area can result in large amounts of water being trapped and flowing freely on the deck.

Other authors have concluded that small amounts of water on the deck could act as a positive damper and increase the dynamic roll stability. The present results lead to a different conclusion (see case SWH = 6.0 ft) and it seems that the reason is the amount of free area that a large offshore supply vessel aft deck provides to the shallow water flow. The large breath can increase the flow velocity that, when hitting the bulwarks, can also increase the roll-induced moment. A large amount of water flowing freely on the deck reduces the effectiveness of a supposed water damper although the increased roll-induced moment.

The random choice method or Glimm's method is adequate to simulate the shallow water flow on the deck. This method, when combined with a time domain six-degree of freedom ship dynamics simulator, can produce good results and, with it, it is possible to observe the influence of the water on deck dynamic loading on the ship roll dynamics.

A series of model tests is a good way to prove the kind risks that this kind of vessels are exposed to. In the model tests the deck can be partially occupied trying to simulate a loaded condition.

There is considerable room for further investigation involving this kind of vessel. The increasing demand in the offshore field, the search for larger and faster offshore supply vessels and the increasingly harsh environmental conditions where this kind of vessel is pushed to work in, gives much room for future work. This work can also be extended to consider water-on-deck of jack-up drilling rigs in tow or liftboats in transit; both of which are known to experience this problem.

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10. REFERENCES

[1]. Storch, R. L., 1978, "Alaskan King Crab Boat Casualties", *Marine Technology*, Vol. 15, No. 1.

[2]. Caglayan, I. and Storch, R. L., 1982, "Stability of Fishing Vessels with Water on Deck: A Review", *Journal of Ship Research*, Vol. 26, No. 2.

[3]. Dillingham, J. T., 1981, "Motion Studies of a Vessel with Water on Deck", *Marine Technology*, Vol. 18, No. 1.

[4]. Falzarano, J. M. and Troesch, A. W., 1990, "Application of Modern Geometric Methods for Dynamical Systems to the Problem of Vessel Capsizing with Water on Deck", *4th Int. Conf. on Stability of Ships and Ocean Vehicles*, Naples.

[5]. Chang, B. and Blume, P., 1998, "Survivability of Damage Ro-Ro Passenger Vessels", *Ship Technology Research*, Vol. 45.

[6]. NTSB, Jan. 1978, "Sinking of the Offshore Supply Vessel M/V Sabine Seashore in the Gulf of Mexico", *NTSB/MAR-79/10*.

[7]. NTSB, Nov. 1983, "Marine Accident Report Capsizing of US Offshore Vessel Laverne Herbet Gulf of Mexico", *NTSB/MAR-84/06*.

[8]. Glimm, J., 1965, "Solutions in the Large for Nonlinear Hyperbolic Systems of Equations", *Communications on Pure Mathematics*, Vol. 18.

[9]. Chorin, A. J., 1976, "Random Choice Solution of Hyperbolic Systems", *Journal of Computational Physics*, Vol. 22, No. 4.

[10]. Chorin, A. J., 1977, "Random Choice Method with Applications to Reacting Gas Flow", *Journal of Computational Physics*, Vol. 25, No. 3.

[11]. Dillingham, J. T. and Falzarano, J. M., 1986 "Three-Dimensional Numerical Simulation of Green Water on Deck," *3rd International Conference on the Stability of Ships and Ocean Vehicles*, Gdansk, Poland.

[12]. Falzarano, J. M., 1988, "An Investigation of the nonlinear aspects of ship dynamic stability: Phase I (Sept. 1986 - Dec. 1988)", *Final Report to US Coast*

Guard Merchant Marine Technical Division, Dept. of Naval Architecture University of Michigan.
[13]. Pantazopoulos, M. S., 1988, “Three-Dimensional Sloshing of Water on Decks”, *Marine Technology*, Vol. 25, No. 4.
[14]. Zhou, Z. Q., de Kat, J. O. and Buchner, B., 1999, “A Nonlinear 3-D Approach to Simulate Green Water Dynamics on Deck”, *Report No.82000-NSH* 7,MARIN.
[15]. Cummins, W. E., 1962, “The Impulse Response Function and Ship Motion”, *Schiffstechnik*, Band 9, Heft 47.
[16]. Perez y Perez, L., 1972, “A Time Domain Solution to the Motions of a Steered Ship in Waves”, *U. S. Coast Guard Report No. CGD-19-73*.
[17]. Fonseca, N. and Guedes Soares, C., 1998, “Time-Domain Analysis of Large-Amplitude Vertical Motions and Wave Loads”, *Journal of Ship Research,* Vol. 42, pp. 139-153.
[18]. Mulk, T. U. and Falzarano, J. M., 1994,“Complete Six Degrees of Freedom Nonlinear Ship Rolling Motion”, *ASME Journal of Offshore Mech. and Arctic Eng.,* Vol. 116, No. 3.
[19]. Falzarano, J. M. and Mulk, T. U., 1994, “Large Amplitude Rolling Motion of an Ocean Survey Vessel”, *SNAME Journal of Marine Technology*, Vol. 31, No. 4.
[20]. Chakrabarti, S. K., 1994, *Hydrodynamics of Offshore Structures*, Computational Mechanics Publications.
[21]. Beck, R. F. and Troesch, A. W., 1989, *User Manual to SHIPMO*, University of Michigan.
[22]. Stoker, J. J., 1994, *Water Waves: The Mathematical Theory with Applications*, Wiley, John & Sons, Incorporated.
[23]. Lee, T., Zhou, Z. and Cao, Y., 2002, “Numerical Simulations of Hydraulic Jumps in Water Sloshing and Water Impacting”, *ASME Journal of Fluids Engineering*, Vol. 124.
[24]. Amy, J., Johnson, R. and Miller, E., 1976, “Development of an Intact Stability Criteria for Towing and Fishing Vessels”, *SNAME Transactions.*
[25]. J. DeKat and WL Thomas, “Extreme Rolling, Broaching, and Capsizing-Model Tests and Simulations of a Steered Ship in Waves,” 22nd ONR Hydrodynamics Symposium, 2000.
[26]. A. Troesch and J. Hicks, “The Efficient Use of Simulation in Planning Hull Motion Analysis,” Naval Engineer’s Journal, January 1994.