Nonlinear Green Water Effects on Ships with Large-Amplitude Motions  
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ABSTRACT

A novel finite-volume strategy was developed to simulate three-dimensional green water on ship problems. The method was developed to extend the capabilities of the nonlinear 3-D ship-motion simulation program LAMP (Large Amplitude Motion Program) to account for water on deck occurrences. The shallow-water problem is solved in the time domain, taking into account the non-linearities inherent in the formulation. The model can handle different boundary and initial conditions, and it is capable of supporting arbitrary motions and general geometries of a ship deck. This approach has been validated with available experimental data and has been successfully integrated with the LAMP System.

INTRODUCTION

Over the past twelve years, LAMP (Large Amplitude Motion Program) has been developed as a multi-level time-domain simulation system for the prediction of motions, wave loads, and structural responses of ships and marine structures. As shown in Figure 1, this system consists of several closely integrated modules designed to perform specific tasks. The primary module computes time-domain ship motions, wave-frequency loads, and pressure distributions over the hull surface. The second module calculates the impact forces due to slamming. The third module computes the whipping responses using a non-uniform-section dynamic beam method. A fourth module provides an interface to detailed finite-element analysis by computing nodal load sets from the time-domain hull pressure distribution. Other tasks can be performed by the LAMP System, which further perfects its proficiency as a state-of-the-art modeling and simulation tool (see Weems et al. 1998). Part of the recent research effort has been focused on extending the capabilities of the first module to account for water-on-deck occurrences and the effects of green water on ship motions and wave loads. To this end, a green water model, capable of predicting the green water related pressures and forces, was developed. This paper summarizes the current capabilities of the LAMP System and describes the basis of the newly developed green water model. Numerical examples of the green water calculations are also given.

THE LAMP SYSTEM

One of the most important capabilities of the LAMP System is its ability to solve for the three-dimensional time-domain nonlinear ship motions and the corresponding hydrodynamic loads. The computational model is based on a potential-flow “body-nonlinear” approach (Lin and Yue, 1990, 1993; and Lin et al., 1994). In contrast to the linear approach in which the body boundary condition is satisfied on the portion of the hull under the mean water surface, the body-nonlinear approach satisfies the body boundary condition exactly on the portion of the instantaneous body surface below the incident wave surface. It is assumed that both the radiation and diffraction waves are small compared to the incident wave so that the
free surface boundary conditions can be linearized with respect to the incident wave surface. In this formulation, both the body motions and the incident waves can be large relative to the draft of the ship.

Several variations of Lin and Yue’s original body-nonlinear approach have been developed and are currently available in the LAMP System. The body-nonlinear approach described above is designated as LAMP-4; in addition to 3-D large-amplitude hydrodynamics, LAMP-4 calculates nonlinear hydrostatic restoring and Froude-Krylov wave forces. A weakly nonlinear version of the code, LAMP-2, has also been developed to calculate 3-D linear hydrodynamics; this version ignores nonlinear hydrostatic restoring and Froude-Krylov wave forces. In addition, a linear code, LAMP-1, is available for calculating 3-D linear hydrodynamics and linear hydrostatic restoring and Froude-Krylov wave forces.

**Mixed Source Formulation**

A hybrid numerical approach has been developed that uses both transient Green functions and Rankine sources (Lin et al., 1999). This approach has been implemented in the LAMP code as the “mixed source formulation.” In the mixed source formulation, the fluid domain is split into two domains as shown in Figure 2. The outer domain is solved with transient Green functions distributed over an arbitrarily shaped matching surface, while the inner domain is solved using Rankine sources. The advantage of this formulation is that Rankine sources behave much better than transient Green functions near the body and free surface juncture, and that the matching surface can be selected to guarantee good numerical behavior of the transient Green functions. The transient Green functions satisfy both the linearized free surface boundary condition and the radiation condition, allowing the matching surface to be placed fairly close to the body. This numerical scheme has resulted in robust motion and load predictions for hull forms with non-wall-sided geometries.

**Non-Pressure Forces**

In order to calculate the time-domain six-degree-of-freedom coupled motions for any ship heading and speed, LAMP also includes models for non-pressure forces including viscous roll damping, propeller thrust, bilge keels, rudder and anti-rolling fins, mooring cables, and other systems. For oblique-sea cases, a PID (Proportional, Integral, and Derivative) course keeping rudder control algorithm and a rudder servo model are implemented. Because of the time-domain approach, these non-pressure force models can include arbitrary nonlinear dependency on the motions, etc. Adjustable viscous roll damping models are available that allow the roll damping to be “tuned” to match experimental values by simulating roll decay tests.

**Equations of Motions**

Once the hydrodynamic and non-pressure forces have been computed, the general 6-DOF equations of motion are solved in the time domain by either a 4th-order Runge-Kutta algorithm or a predictor-corrector scheme. Since the forces on the right hand side of the equations of motion include the instantaneous added mass, an estimated added mass term is added to both sides of the equation of motion to achieve numerical stability. In addition to motion simulations, LAMP calculates the time-domain wave-induced global loads, including the vertical and lateral shear forces and bending moments, torsional moment, and compression force, at any cross-section along the length of the ship. Structural loads can be computed using rigid-body or finite-element beam models.

At each time step, LAMP calculates the relative motion of the ship and the wave configuration as well as the hydrodynamic pressure distribution over the instantaneous wetted hull surface below the incident wave surface. The relative motion, which can include the local wave disturbance, is used as input for the impact load and green water-on-deck calculations. The pressure distribution is used to generate an input data set for finite-element structural analysis.

**Impact Forces and Whipping Responses**

In the LAMP System, a post-processor is used for either symmetrical or non-symmetrical impact load predictions. It is assumed that the impacts do not affect the global ship
motions. The previously computed global ship motions are used to compute relative motion of the ship bow and identify events where impact forces may be significant. The relative ship motion is then used to compute impact loads on 2-D cross sections of the ship for impact occurrences. The forces from such impact events are then assimilated into an impact-force history, which can be used to evaluate whipping loads.

Once the sectional impact forces are computed, the main girder responses are computed in LAMP using a non-uniform-section dynamic beam method in order to get high-frequency global loads associated with whipping. The ship is modeled as either a uniform or a variable-mass beam. The total bending moment is obtained by combining the wave-frequency and the high-frequency bending moments with proper phasing.

Interface to Structural Finite-Element Analysis

The LAMP System calculates the pressure distribution over the instantaneous hull surface below the incident wave surface. The hull pressure information, combined with the acceleration data, can be used for finite element (FE) structural analysis. A generic interface between LAMP motion and load calculations and structural FE codes has been developed. The interface program reads nodal point coordinates and connectivity information (only surface nodes are needed) used in the FE code and computes the forces acting on the nodal points. At specified time steps, the interface program writes the nodal point forces and ship acceleration information as outputs for the finite element structural analysis program. Other outputs from the LAMP/FE interface include nodal pressure history, sectional main girder loads for FE analysis of partial ship configurations, and external forces (e.g., control surfaces) that were modeled in the LAMP simulation but were not included in the pressure distribution. The latter forces must be accounted for so that forces and accelerations are properly balanced in any subsequent structural analysis.

GREEN WATER FORMULATION

Recently, some effort has been directed to extend the LAMP computational capabilities to account for water-on-deck or green water effects. To this end, a finite-volume model has been developed, in which the equations of conservation of mass and momentum are solved in the time domain. Shallow-water assumptions are made and viscous effects are ignored. In this formulation, the driving forces parallel to the gravity field are predominantly of a hydrostatic nature (e.g., Stoker, 1957).

As shown in Figure 3, in the green water computation, the computational domain is discretized in parallelepipedal volumes of water with height \( h \), where \( h \) is the elevation of water at the control point of a given element. In Figure 3, a particular element \( e \) is shown with elements adjacent to the given element \( e \) denoted by the subscript \( q \). All finite-volume elements are kept parallel to the gravitational field during the calculations. For each element, three characteristic variables are computed: water elevation, and the two components of the flow velocities normal to the gravitational field.

![Figure 3: Finite Volume Discretization](image)

The finite-volume implementation of the equations of conservation of mass can be expressed as:

\[
\begin{align*}
    m_{ee} h_{e}^{k+1} + \sum_{i=1}^{4} m_{eq_{i}} h_{q_{i}}^{k+1} &= w_{e}^{j} \\
\end{align*}
\]

with

\[
\begin{align*}
    m_{ee} &= (\Delta C + \bar{C}^{k_{j-1}+1}) \\
    m_{eq_{i}} &= \frac{\Delta t}{4} Q_{eq_{i}} \\
    w_{e}^{j} &= \frac{\Delta t}{4} \sum_{i=1}^{4} (Q_{eq_{i}}^{k_{j-1}+1} h_{e}^{k_{j-1}+1}) \\
    &+ \frac{\Delta t}{2} \sum_{i=1}^{4} (Q_{eq_{i}}^{k} h_{q_{i}}^{k} + Q_{ee_{i}}^{k} h_{e}^{k}) + h_{e}^{k} \bar{C}^{k_{j-1}+1}
\end{align*}
\]

where \( m \) is mass, the superscript \( k \) is the time-step index, the subscript \( j \) is the iteration index, the subscript \( i \) denotes each of the four sides of each element, the characteristic area \( C \) is defined by the projection of the base area of a given element onto a normal-to-the-gravitational-field surface at the geometric center of the base of each element (in Figure 3, \( C \) is denoted by \( An \)), and \( Q \) is the flow per unit of water elevation across any lateral wall of an element \( e \). On each boundary wall of any element, the terms \( Q \) are split...
into two components corresponding to the contributions from the characteristic flow velocity of element \( e \) and from an adjacent element \( q \). Bars on top of variables indicate average values during a given time step.

The corresponding implementation of the momentum equations can be expressed as:

\[
    \mathbf{R}_{e}^{j} \mathbf{v}_{e}^{k+1} + \sum_{i=1}^{4} \mathbf{R}_{eq}^{j} \mathbf{v}_{e}^{k+1} = \mathbf{S}_{e}^{j}
\]

with

\[
    \mathbf{R}_{e}^{j} = \left( \begin{bmatrix} C_{e} \Delta H_{e}^{k+1} & \bar{h}_{e}^{k+1} + \bar{h}_{e}^{k+1} \Delta C_{e} \end{bmatrix} + \frac{\Delta t}{2} \mathbf{D}_{eq} \right) \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}
\]

\[
    \mathbf{S}_{e}^{j} = \frac{\Delta t}{2} \sum_{i=1}^{4} \mathbf{v}_{e}^{k} \mathbf{D}_{eq}^{k+1} - \mathbf{P}_{e}^{k+1}
\]

where bold-face letters represent vector quantities, \( \mathbf{v} \) is the characteristic flow speed of a given element, \( D \) is the flow across a lateral side \( i \) of any element, and \( \mathbf{P} \) is the hydrostatic and hydrodynamic forces. Analogously as \( Q \), the \( D \) terms are also split into two contributions: one from the given element \( e \) and the other from the element adjacent to the boundary \( i \) considered. Vector \( \mathbf{b} \) denotes accelerations in the plane normal to the gravitational field. Accelerations parallel to the gravitational field are added to the term \( \mathbf{P} \). The non-linearity in flow velocities comes through the products of \( \mathbf{v} \) by \( \mathbf{R} \), since the latter contains velocities through the term \( D \). This, plus the fact that the water elevations (which are also computed at each time step) are contained in the terms \( \mathbf{R} \), contributes to the non-linear nature of the problem. Analogously, in the equations of mass, the velocities present in the terms \( Q \) are multiplying the elevations \( h \).

At each time step, the finite-volume implementation of equation of conservation of mass and the two components of the momentum equations are solved simultaneously, and the corresponding green water effects are computed. An optimal time step size to obtain fast computations, while at the same time guaranteeing convergence, can be computed automatically in the current method. In this regard, a minimum water elevation is prescribed. Elements with water elevation below a given threshold are ignored when computing the equations of motion. A maximum water elevation is also computed beyond which the shallow-water assumptions would not be valid.

The next two sections provide several green water related validation cases and numerical examples. In particular, the general procedure of including green water effects in ship motions and global loads calculations are presented.

**VALIDATION OF THE GREEN WATER APPROACH**

The current green water approach has been tested thoroughly. In this section, two particular validation examples are discussed. The first example is the “dam break” problem described in Stoker (1957). In this problem, Stoker used a linear theory to solve the water profile of a suddenly removed dam. Similar conditions to those presented by Stoker were set in the current model. The water initial height is 10 meters, and the water profile is observed one second after the dam is removed. The finite-volume grids used for this calculation contained 41 elements. As can be seen in Figure 4, generally good agreement was obtained between Stoker’s linear results and those computed with the present approach. Some differences can be seen in the comparison. Those differences are mainly in the smoother manner in which the free surface perturbation back propagates with the finite-volume approach.

The second validation example is a comparison with a series of shallow-water experiments results presented by Buchner (1995). Buchner studied the effects of the sudden opening of a flap in a tank with one side initially filled with water. The dimensions of the tank and the position of the flap in his experiments are described in Figure 5(a). One of these experiments (experiment Nr. 4487001) is used in the current study. In this experiment, a sensor was positioned 1.525 meters away from the back of the tank. When the flap was removed, the water moved forward, and the water elevation was measured at the sensor location. In addition to the experiments, Buchner (1995) also developed a shallow-water model based on Glimm’s method (Glimm, 1965). The time history comparison of the
experimental measurements of the water height, the results based on Buchner’ method, and the results from the current approach are shown in Figure 5(b). In general, the comparison is very encouraging. The finite-volume grids used for the calculation contained 21 elements.

Figure 5: Validation Case – Buchner (1995)

GREEN WATER EFFECTS ON SHIP MOTIONS

The green water method is now fully integrated in the LAMP System. While considering the green water effects, the following procedures are followed:

1. Compute the deck-edge sea-water elevation. The ship motion computations in LAMP provide the relative location of the water surface and the deck edge. The water surface computed in LAMP includes the radiation and diffraction wave components.
2. Compute the amount of water entering the ship deck. A water-entry model based on the water head and a semi-empirical formula are used to determine the amount of water that enters the ship deck.
3. Apply the appropriate boundary conditions on the ship deck. The 3-D shallow-water finite-volume approach described in this paper is used to calculate the water movement on deck. Appropriate boundary conditions are applied to account for the presence of incoming water, deck edges, partially submerged elements, and the presence of possible obstacles on deck (e.g. forecastle).
4. Apply the deck-edge boundary conditions on the ship deck. The water exit at deck edges is taken as a free fall condition.

In general, the green water computations require finer time-step sizes compared to those used in the ship motion calculations, typically on the order of ten to one. The time-step size in the green water calculations can be adjusted automatically during the calculations, and the green water effects are evaluated only at the required “ship-motion” time steps. In LAMP, these effects are then added to the other hydrodynamic and non-pressure forces acting on the ship before the ship equations of motion are solved. This general approach has been tested thoroughly and proven to be robust.

An example of the integrated ship motion and green water computation is given in Figure 6. The results are shown for a deck area close to the bow. At the backside of the computational domain, a boundary condition was set to simulate the presence of a forecastle. The sides of the deck are free for water flow in and out. In this example, the ship speed is 20 knots and has a dominant non-regular pitching motion. The ship is operating in a head sea, long-crested sea-state six condition. The computational grid was comprised of 70 finite-volume elements (seven length-wise by ten beam-wise). In Figure 6(a), the deck is completely out of the water. The line below the deck is the vertical projection of the deck edge onto the water surface below it. In Figure 6(b), the deck is below the free surface, and water is pouring into it. Different stages of the subsequent green water distribution are shown in Figure 6(c) and Figure 6(d). Although the example shows a head-sea symmetrical computation, the current capability can handle the unsymmetrical green water computations as well.

CONCLUSIONS

The general capabilities of the Large Amplitude Motions Program (LAMP) have been expanded by the addition of a shallow-water model capable of describing water-on-deck occurrences. This model, which utilizes a finite-volume strategy, solves for the green water problem in the time domain using nonlinear shallow water equations. The results have been validated with theoretical solutions, other computational results, and experimental measurements. The approach has been successfully integrated into the LAMP System. The new capability can be used to evaluate the green water effects on ship motions and structural loads on decks and deckhouses caused by the green water.
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