Design and Assessment of Ship Motion Control Systems with Advanced Numerical Simulation Tools

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ABSTRACT

The accurate characterization of ship motions in different seaways is a basic requirement in the design of an effective ship motion control system. Traditionally, ship motion characteristics are obtained either by conducting model tests or by using numerical simulation based on simplified theories. However, model tests are typically expensive and time-consuming, and simplified theories may not be suitable for advanced hull forms such as wave piercers or multi-hulls and for ships operating at high speeds. More advanced numerical simulation tools are needed. In this paper, an advanced numerical simulation method is described that incorporates nonlinear, time-domain wave-body hydrodynamics and control system models for the design and assessment of motion control systems. Sample results using these control systems are shown to demonstrate the efficacy of these systems.

1.0 INTRODUCTION

The overall objective of the Conference is to keep ship crews and transported personnel fit to accomplish their mission by reducing noise and vibrations levels, shocks, and ride movements. Two specific objectives are an improvement of systems reliability and endurance by reduction of vibration and shocks levels in the vehicles, and an improvement of the vehicle effectiveness as a weapons or sensors platform. These objectives are to be considered both for the design of new ships and systems as well as possible retrofitting or modification of existing systems.

Motion control of a ship operating in rough seas has long been a topic of interest in ship design and operation. In recent years, this topic is becoming increasingly important due to the need for high-speed long-distance deployment of men and material and the emphasis on smaller, lighter assets. In these operation scenarios, crew factors are often the limiting criteria for cruise speed or operational effectiveness in a seaway, so the reduction of ship motions can have a significant impact on operability. In order to design an effective ship motion control system, an accurate characterization of ship motions in different seaways is required. Given the cost and time required for model tests, it is natural that significant effort has been made toward developing numerical tools for characterizing the motions and loads of a ship operating in a seaway.

Over the past 15 years, the U.S. Navy has been supporting the development of the Large Amplitude Motion Program (LAMP). LAMP is a nonlinear time-domain simulation program for ship motions, wave loads, and structural responses. LAMP's seakeeping calculation includes multi-level (body-linear, approximate body-nonlinear, and body-nonlinear) hull surface model, a linear and 2nd order free surface model, nonlinear

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external force and control models, and load calculations using rigid body and dynamic beam models. The LAMP System also includes a pressure interface code for developing detailed time-dependent loads set for Finite-Element structural analysis and a whipping post-processing code for predicting the impact loads due to hull bottom and bow flare slams and the resulting structural response.

While the LAMP System was initially developed primarily for predicting the structural loads on ship in large seas, its time-domain approach and general solution of the 6-DOF equations of motion make it very well suited for integrating models of force generators such as fins and other appendages as well as active or passive control systems. At the present time, a series of roll control system models have been developed and implemented as standard "extensions" to LAMP [Weems and Lin 2002]. These models include:

- U-tube type anti-rolling tank that calculates the motion of the fluid in the U-tube tank and determines the coupled nonlinear loads acting on a floating body in full six degrees of freedom
- Moving mass system
- Force or deflection-specified anti-rolling fins
- Rudder roll stabilization.

These models can be used in the LAMP dynamic simulation environment to provide a quick and efficient way to test the effectiveness of different motion control systems. The combined numerical simulation environment can also be used as a test bed to develop and test the effectiveness of motion control algorithms.

In addition to these "standard" models, the framework of the LAMP code allows more sophisticated force or control models to be implemented for the analysis of specialized configurations or systems. One such system used an actively controlled horizontally mounted wing to mitigate pitch and heave for a high-speed multi-hull ship. Another system included a self-learning neural network controller to actuate the rudder and a pair of anti-rolling fins for combined roll and course control [Liut *et al.* 2001].

In the current paper, Section 2 describes the general formulation of the LAMP ship dynamic simulation environment and the solution of the wave-body hydrodynamic problem, while Section 3 describes the motion control models currently implemented in LAMP and presents the results of sample calculations that demonstrate the effect of the motion control systems.

2.0 THE LAMP SYSTEM

2.1 A Brief Description of LAMP

The LAMP System is a time-domain simulation model specifically developed for computing the motions and loads of a ship operating in extreme sea conditions. LAMP System development began with a 1988 DARPA project for advanced nonlinear ship motion simulation, and has continued under the sponsorship of the U.S. Navy, U.S. Coast Guard, the American Bureau of Shipping (ABS), and Science Applications International Corporation's (SAIC) IR&D program.

LAMP uses a time stepping approach in which all forces and moments acting on the ship, including those due to the wave-body interaction, appendages, control systems, and green-water-on-deck, are computed at each time step and the 6-DOF equations of motions are integrated in the time-domain using a 4^{th}-order Runge-Kutta algorithm. In addition to motions, LAMP also computes main hull-girder loads using a rigid or elastic beam model and includes an interface for developing Finite-Element load data sets from the 3-D pressure distribution [Shin *et al.* 2003; Weems *et al.* 1998].

The core of the LAMP System is the 3-D solution of the wave-body interaction problem in the time-domain [Lin and Yue 1990, 1993]. A 3-D perturbation velocity potential is computed by solving an initial boundary value problem using a potential flow boundary element or "panel" method. A combined body boundary condition is imposed that incorporates the effects of forward speed, the ship motion (radiation), and the scattering of the incident wave (diffraction). The potential is computed using either a hybrid singularity model that uses both transient Green functions and Rankine sources [Lin *et al.* 1999], or a Rankine singularity model with a damping beach condition. These models are described in more detail in the subsequent sections. Once the velocity potential is computed, Bernoulli's equation is then used to compute the hull pressure distribution including the second-order velocity terms.

The perturbation velocity potential can be solved either over the mean wetted surface (the "body linear" solution) or over the instantaneously wetted portion of the hull surface beneath the incident wave (the "body nonlinear" approach). In either case, it is assumed that both the radiation and diffraction waves are small compared to the incident wave and the incident wave slope is small so that the free-surface boundary conditions can be linearized with respect to the incident-wave surface. Similarly, the incident wave forcing (Froude-Krylov) and hydrostatic restoring force can also be computed either on the mean wetted surface or on the wetted hull up to the incident wave.

The combinations of the body linear and body nonlinear solutions of the perturbation potential and the hydrostatic/Froude-Krylov forces provide multiple solution "levels" for the ship-wave interaction problem. These levels are:

- LAMP-1 (Body linear solution): Both perturbation potential and hydrostatic/Froude-Krylov forces are solved over the mean wetted hull surface
- LAMP-2 (Approximate body nonlinear solution): The perturbation potential is solved over the mean wetted hull surface while the hydrostatic/Froude-Krylov forces are solved over the instantaneous wetted hull surface
- LAMP-4 (Body nonlinear solution): Both the perturbation potential and the hydrostatic/Froude-Krylov forces are solved over the instantaneous wetted hull surface.

For the majority of problems, the most practical level is the "approximate body-nonlinear" (LAMP-2) solution, which combines the body-linear solution of the perturbation potential with body-nonlinear hydrostatic-restoring and Froude-Krylov wave forces. This latter approach captures a significant portion of nonlinear effects in most ship-wave problems at a fraction of the computation effort for the general body-nonlinear formulation. However, body-nonlinear hydrodynamics and nonlinear incident wave effects can be important depending on ship geometry and operating conditions.

2.2 Mixed Source Singularity Model

In the context of time-domain potential-flow boundary-element methods, the most commonly used approaches fall in two categories: (1) methods that use transient Green functions and (2) methods that use Rankine sources [Weems *et al.* 2000]. In view of the pros and cons of these two approaches, a hybrid numerical approach was developed to use both transient Green functions and Rankine sources [Lin *et al.* 1999]. This approach is implemented in the LAMP System as the "mixed source formulation." In the mixed source formulation, the fluid domain is split into two regions, as shown in Figure 1. 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 the transient Green functions near the body and free surface juncture, and 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.

Another advantage of the mixed formulation is that the local free surface elevation is part of the solution, and no additional evaluation is needed as in the case of the transient Green function approach. In addition, a nonlinear free surface boundary condition can be implemented at modest computational cost. In the LAMP System, a 2^{nd}-order free surface boundary condition can be applied on the local portion of the free surface; see more details in [Weems *et al.* 2000]. However, in the case of nonlinear free-surface boundary condition in the local portion of the free surface, the matching surface must be placed further away from the body to minimize errors caused by a mismatch of the free surface condition.

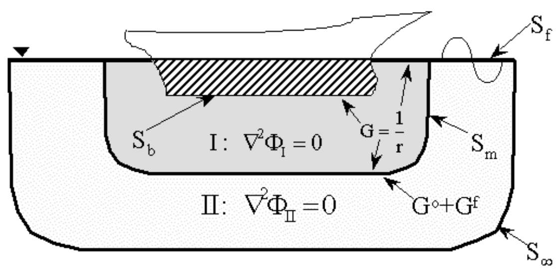

Figure 1 : Domains of the Mixed Source Singularity Model

2.3 Rankine Singularity Model with Damping Beach

While the mixed source singularity model works very well for low to modest speeds ($Fr \leq 0.5$), it can be difficult to obtain a stable solution at higher speeds. For this reason, an alternative singularity model has been implemented that replaces the external domain and the matching surface with a numerical damping region on the outer edge of the inner region's free surface. The body and free surface boundary conditions are otherwise identical to the mixed source singularity model. While this singularity model typically requires a considerably larger free surface grid then the mixed source model, it has been successfully applied at Fr=0.85. The model also allows shallow water to be modeled in the hydrodynamic problem by panelizing the bottom or using image sources.

2.4 IRF-Based Formulation

A drawback to time domain hydrodynamics is the computational cost. To mitigate this, an Impulse Response Function (IRF) based hydrodynamic formulation [Kim and Weems 2000] was integrated into the LAMP System to complement the mixed source formulation. In the IRF formulation, velocity potentials are pre-computed for steady forward speed, impulsive motion in up to six modes, and impulsive incident waves for each speed and heading angle. The hydrodynamic problem is reduced to a convolution of the IRF potentials with the actual ship motions and incident wave elevation, thereby allowing numerical simulations to be performed faster than real time using modest computational resources and without compromising the accuracy of the hydrodynamic calculation. The IRF potentials are convoluted and summed on a panel-by-panel basis, so that the complete potential distribution of the hull can be computed in the time domain. This allows the panel pressure to be computed directly, including the nonlinear terms in Bernoulli's equation, in the same fashion as in the mixed source formulation. The only restriction is that the IRF formulation can only be used with body linear (LAMP-1) and approximate body nonlinear (LAMP-2) hydrodynamics.

2.5 Non-Pressure Force Models

LAMP also includes a number of models for effects that are not included in the pressure distribution computed using the potential flow solution of the wave-body interaction but that still exert a force or moment that will impact the motion and/or loads on the ship. These “non-pressure” force models include effects such as viscous roll damping, propeller thrust, bilge keels, rudder and anti-rolling fins, mooring cables, internal tanks, and other systems. Because of the general time-domain approach, these non-pressure force models can include arbitrary nonlinear dependency on the motions, etc. For example, adjustable viscous roll damping models have been implemented with up to multiple order terms in the roll angle and velocity that allow the roll damping to be “tuned” to match experimental values by simulating roll decay tests.

Many of these non-pressure forces are implemented using multi-level models of varying accuracy and complexity. For example, the forces exerted by lift-generating appendages such as rudders or fins can be computed using a built-in semi-empirical formula, specified lift curve data derived from external tests or calculation, or an integrated unsteady vortex lattice calculation [Liut *et al.* 2001].

Because these non-pressure force models run concurrently with the hydrodynamic calculation in the time domain, the models can include active or passive control systems that can be defined with the same types of physical inputs and outputs as the actual ship-board system. Standard built-in control models include a PID (Proportional, Integral, and Derivative) course-keeping rudder control algorithm and a rudder servo model for maintaining proper ship heading in oblique or short-crested seaway cases.

The LAMP code is structured so that new or modified time domain models of force actuators and/or control systems can be implemented into the motion and loads calculations in a fairly straightforward way. LAMP’s ability to implement such models, coupled with its nonlinear physics-based solution of the wave-body hydrodynamics problem, makes it a very promising tool for developing and assessing motion control systems.

2.6 Solving the Equations of Motions and Computing Loads

Once the hydrodynamic and non-pressure forces have been computed, the general 6-DOF equations of motions 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 motions include the instantaneous added mass, an estimated added mass term is added to both sides of the equation of motions to achieve numerical stability. In addition to motion simulations, LAMP calculates the time-domain wave-induced global loads, including the vertical and lateral bending and torsional moments and shear forces, 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 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.

3.0 LAMP MOTION CONTROL SYSTEM AND SAMPLE RESULTS

This section describes several of the "standard" roll stabilization systems currently implemented in LAMP and presents the results of some sample studies. These anti-roll system models include: (1) a U-tube type anti-rolling tank model, (2) a moving mass model, (3) force- and deflection-specified anti-rolling fin models, and (4) a rudder roll stabilization model. The sample calculations include the suppression of parametric roll in a large, modern container ship using the U-tube tank system, and the general reduction of roll of Series 60 cargo ship using the other systems.

3.1 Model of Anti-Rolling Tank

One of the most promising ways to damp out the ship roll motion of a large ship is through the use of a U-tube type anti-rolling tank. A schematic of such an anti-roll tank is shown in Figure 2. In order to evaluate the tank's effect on roll motion, a model was incorporated into LAMP that solves for the 1-DOF fluid motion in the U-tube tank and determines the coupled nonlinear 6-DOF forces acting on the ship. The tank model runs concurrently with the wave-body hydrodynamics solver in the time domain. The tank model includes expressions for the shear stress on the tank walls and energy losses in the elbows, but does not account for "sloshing" in the vertical columns themselves. The tank can be run either as a passive system or as an active system with a pump installed in the cross-tube. The theoretical description of the model can be found in [Youseff *et al.* 2002].

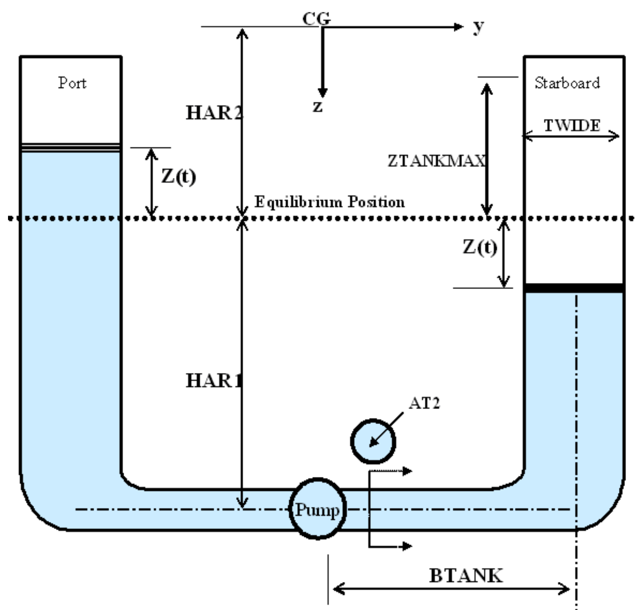

Figure 2 : Schematic of a U-tube Anti-Roll Tank

A series of calculations were performed to determine the effectiveness of the passive anti-roll tank system in reducing the ship's susceptibility to parametric roll. Parametric roll is a highly-nonlinear phenomenon in which large, sudden roll motion can be excited for certain types of ships in head or following storm seas and has been cited as the probable cause of recent cargo loss casualties in large modern container ships [France *et al.* 2003]. Figure 3 shows the predicted maximum roll angles for a large containership in regular head seas as a function of encounter frequency. A large (5 degree) initial roll perturbation was used so that the steady state parametric rolling could be reached quickly.

The range of encounter frequency for which this particular ship might be susceptible to parametric roll is indicated by the curve for the case with no anti-roll tanks. The natural roll frequency for the ship in this case is 0.251 rad/sec, which corresponds to a 25 second period, so parametric rolling would be expected near an encounter frequency of 0.502 rad/sec, which is clearly shown in the results. This ship yielded a wide range of encounter frequencies where parametric roll is predicted, indicating that it is very susceptible to parametric roll.

Additional curves plotted in Figure 3 show the response for the ship with a single passive anti-roll tank where the tank mass is equivalent to 0.27, 0.35, 0.71, and 1.4 percent of the ship's displacement. In each case, the natural period of the tank system is designed to be equal to the ship's natural roll period of 25 seconds. The 0.27% case shows a small reduction in the bandwidth where parametric roll occurs, but there is still a region of large roll angles. Both the 0.35% and 0.71% cases show virtually no roll larger than the initial 5-degree roll. The 1.4% case shows a region of slightly elevated roll motion (<10 deg.) for low encounter frequencies due to the inertia of the large mass of water in the tank system, which is not in equilibrium at the beginning of the simulation. The tank fluid continues to oscillate for a short period of time until it eventually damps out as the simulation progresses.

To check the performance of the U-tube tank in extreme irregular seas, simulations were made for the ship operating at various speed and headings in short-crested seaway with a significant wave height of 11.49 m, which corresponds to sea state 8. For head seas at 10 knots, the 0.71% tank system reduced the maximum roll angle from 48 degrees to less than 10 degrees.

Overall, anti-rolling systems like the U-tube anti-roll tank appear to have a great deal of promise in the mitigation of the large roll motions caused by parametric roll. However, the optimization of such a system for maximum benefit at minimum cost will likely require a fairly sophisticated simulation system coupled to advanced probabilistic methods.

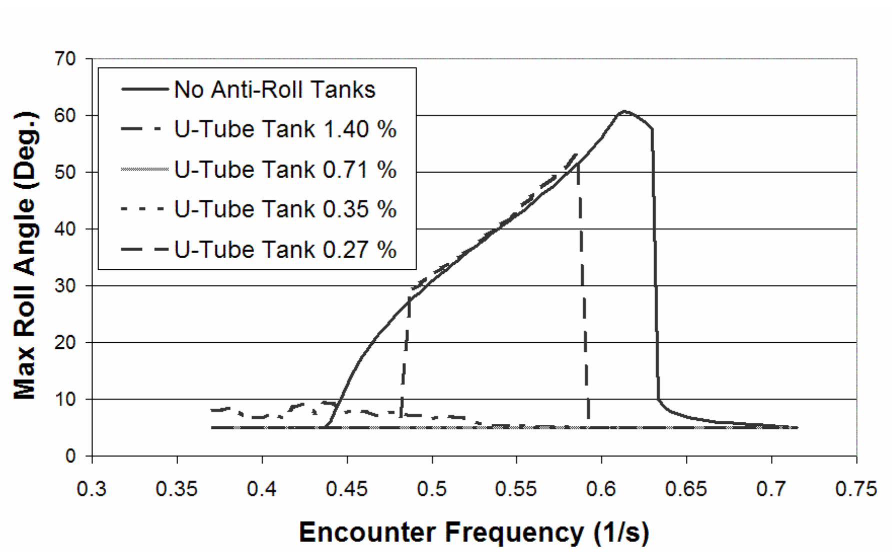

Figure 3 : Parametric Roll Response with different volume of anti-roll tank

3.2 Moving Mass System for Roll Control

LAMP's moving mass model simulates the effect of an on-board motion control system that uses a moving mass to direct the roll motion of a ship in a seaway. The time-domain model tracks the position of a "point" mass as it moves along a ship-fixed track and computes the 6-DOF reaction force and moment that the moving mass system exerts on the ship. The reaction force and moment is applied to LAMP's calculation of ship motion and sectional loads as an external (non-pressure) force.

The moving mass system can be modeled as a passive system or as an active system. For a passive system, the position of the moving mass is computed by solving a 1-DOF spring-mass-damping system that is forced by the ship motion. For an active system, a target position of the mass is computed from the roll motion and specified control gains, and an actuator force is applied to the mass to try to get it there. The active system is modeled using a simple servo equation and a PID control law. In both the active and passive systems, the coupling between the mass system and the ship motion is fully 6-DOF and nonlinear, so the mass motion will include the effect of all modes of body motion and the resulting force will be computed as the general 6-DOF force/moment acting on the ship. This model can also be used to provide a simple model of an anti-rolling tank system in which the moving point mass represents the mass center of the water in the anti-rolling tank.

To demonstrate the effect of the moving mass system, sample calculations were made for the Series 60 ship in beam seas with both active and passive control. Figure 4 compares the predicted roll motion for a ship with the passive moving system to a ship without a system.

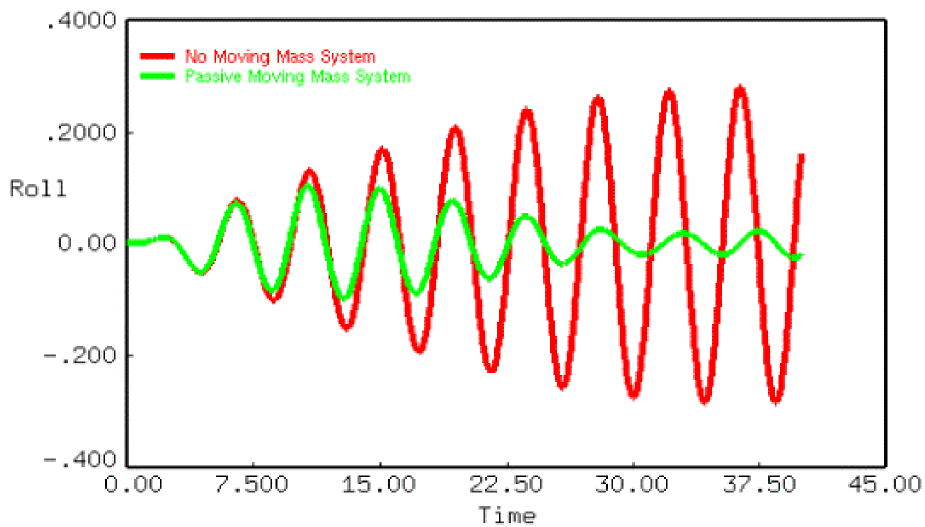

Figure 4 : Roll Response for Series 60 with Passive Moving Mass System

3.3 Force- or Deflection-Specified Anti-Rolling Fins

Anti-rolling fins are by far the most common roll motion control system currently in use. The LAMP System contains both force-specified and deflection-specified anti-roll fin models. The force-specified anti-rolling fin model simulates the effect of a modern active roll-control fin system that senses the load on the fin and adjusts its deflection in order to produce a fin force corresponding to the desired anti-rolling moment. The required fin force is computed from a simple command law based on the ship's roll motion. The LAMP implementation of the force-specified anti-rolling fin model is somewhat idealized in that:

- The control law calculates the required fin force as the product of a specified linear gain term and the instantaneous roll velocity
- The fin system is assumed to be sufficiently responsive that the effects of control lag or limited deflection rates can be neglected
- The drag of the fin system is not considered.

The deflection-specified anti-rolling fin model uses a simple control algorithm to deflect one or more fins modeled using LAMP's fin appendage input. The system simply computes a commanded fin deflection that opposes and is proportional to the roll velocity by a specified gain. A fin dynamics calculation is then used to compute the realized fin deflection angle for each controlled fin. The fin dynamics calculation is very similar to the one used for rudder dynamics but has its own set of dynamic properties (deflection rates, etc.). The forces on the fin(s) are then computed using LAMP's appendage lift model, which defaults to low-aspect ratio aerofoil theory, but can be used with specified lift-curve data or an integrated vortex lattice calculation.

Figures 5 and 6 show the effect of these fin systems on a Series 60, C_B=0.7 ship operating at *Fr*=0.2 in regular, bow oblique seas. Figure 5 shows the resulting roll motion for a ship with and without a force-specified anti-rolling fin system. Both calculations include LAMP's default viscous roll damping model, bilge keels, and a rudder that is also used for course control. Note that the frequency of encounter in this test case is near the ship's natural frequency in roll.

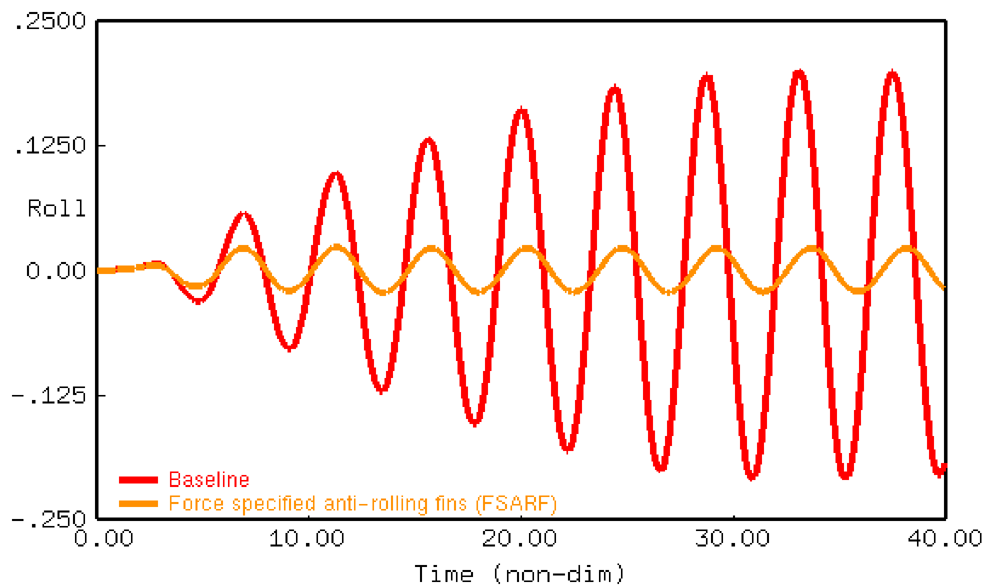

Figure 5 : Effect of a Force-Specified Anti-Rolling Fin System on the Roll Response (in Radians) of Series 60, C_B=0.7 in Bow Oblique Regular Wave

Figure 6 shows the roll response for the same ship in the same seaway with no fins, fixed fins, and actively deflected fins.

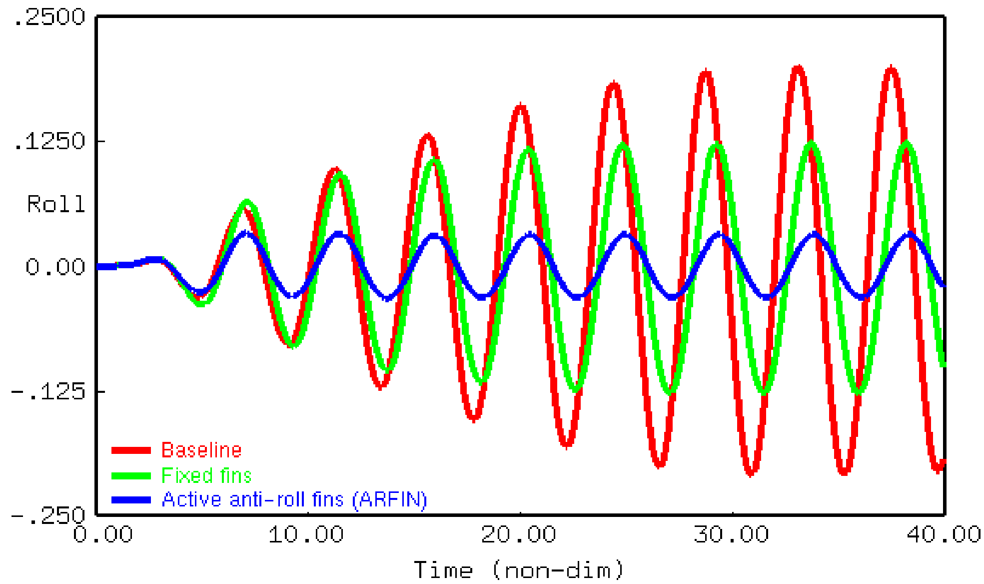

Figure 6 : Effect of a Fixed and Active Anti-Rolling Fins on the Roll Response (in Radians) of Series 60, C_B=0.7 in Bow Oblique Regular Wave

3.4 Rudder Roll Stabilization

LAMP's rudder roll stabilization model invokes a simple control system that deflects the ship's rudder in order to reduce roll motion. The system simply computes a commanded rudder deflection that opposes and is proportional to the roll velocity by a specified gain. The computed deflection command for roll stabilization is added to any deflection command for the course-keeping autopilot and is applied to each fin marked as a rudder. The rudder dynamics calculation is then used to compute the realized rudder deflection angle. The force on the rudder is then calculated using LAMP's appendage lift model, which defaults to low-aspect ratio aerofoil theory. For ships with reasonably large rudders and fairly high rudder deflection rates, rudder roll stabilization can be very effective in moderate sea conditions. Figure 7 shows the resulting roll motion for a Series 60 ship with and without rudder roll stabilization for the same conditions as in Section 3.3.

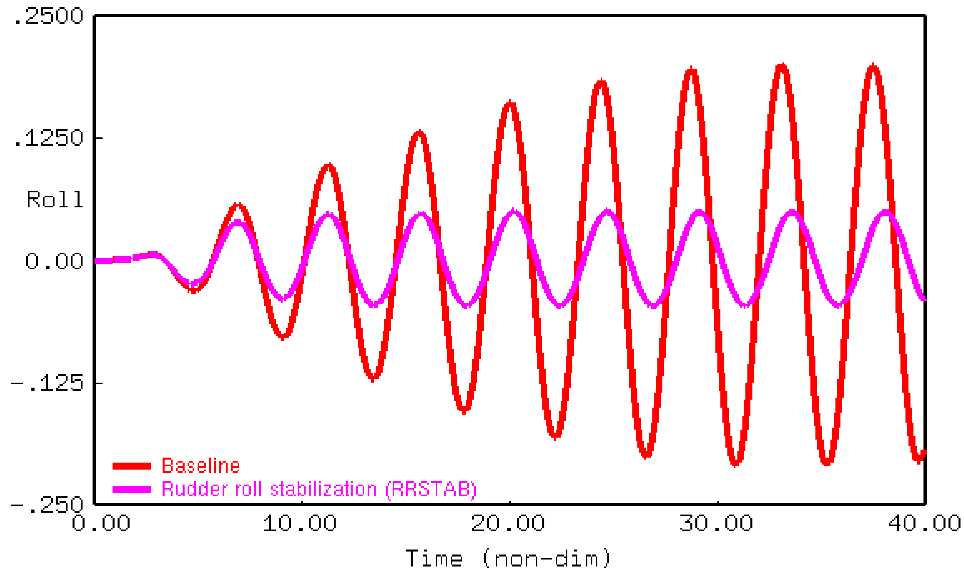

Figure 7 : Effect of a Rudder Roll Stabilization on the Roll Response (in Radians) of Series 60, C_B=0.7 in Bow Oblique Regular Wave

3.5 Anti-Rolling Fin Model with Neural Network Control

The motion control systems described above represent the "standard" models implemented in the LAMP System. In addition to these "standard" models, the framework of the LAMP code allows more sophisticated force or control models to be implemented for the analysis of specialized configurations or systems. One such system that is currently under development incorporates a concurrent time-domain vortex lattice calculation for the forces on a set of dynamically actuated fins and a self-learning neural network controller that minimizes the ship's roll motion. In this system, a separate but concurrent unsteady 3-D vortex lattice calculation is done in order to calculate the unsteady forces on fins as a result of the ship's motion and the actuation of the fins.

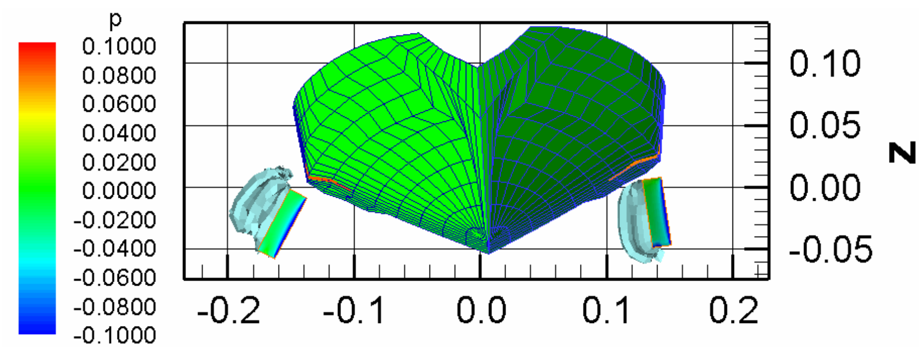

Figure 8 : Vortex Lattice Calculation for Active Fin System

In earlier work, this system was used to actuate the rudder and a pair of anti-rolling fins for combined roll and course control of a CG-47 cruiser [Liut *et al.* 2001]. In more recent work, the system has been used to control a set of "flapping" foils on a 45-foot boat. In this calculation, the fins are actuated up-and-down (flap) and fore-and-aft (sweep) as well as being deflected. This additional flap motions allow the generation of larger flap forces at low ship speeds. A series of simulations were made for the boat operating in beam Sea State 3 at 5 knots in order to test various control strategies and methods for computing the fin forces. Figure 8 shows a front view of the pressure on the fins at one time step of the vortex lattice calculation. The cyan surfaces behind the fins show a portion of the unsteady fin wake. Figure 9 shows the roll response for the boat without fins and with two of the fin control options. With the neural network controller, a 34.9% reduction of the maximum roll angle was achieved despite the low speed, small fin size, and limited fin actuator power.

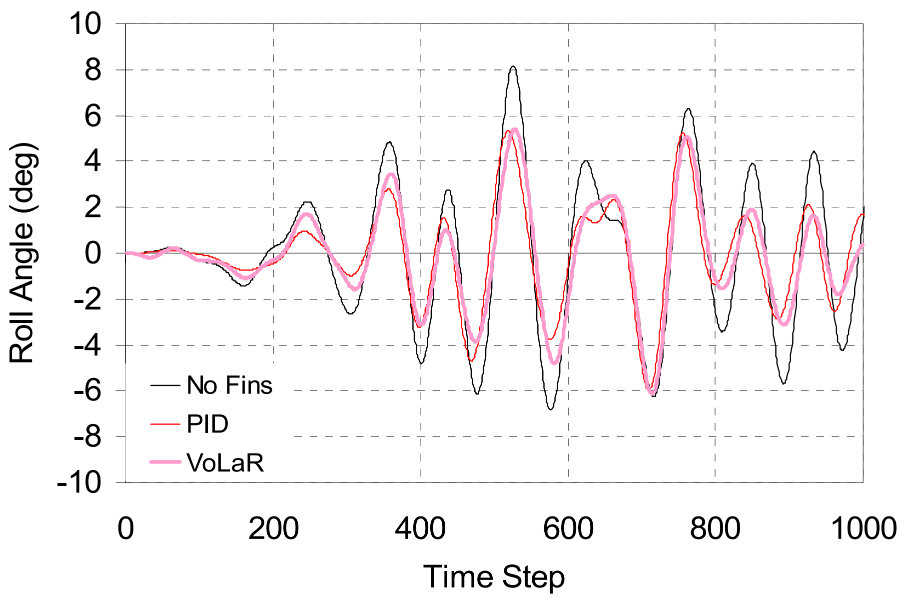

Figure 9 : Roll Response for 45-foot Boat with Neural Network Controlled Fins

4.0 CONCLUDING REMARKS

As crew factors are often the limiting criteria for cruise speed or operational effectiveness in a seaway, ship motion control is an area of considerable interest in ship design and operation. In order to design an effective ship motion control system, an accurate characterization of ship motion in different seaways is required. A general nonlinear time-domain simulation method, LAMP, has been described in this paper that incorporates a potential flow solution of the nonlinear wave-body hydrodynamics interaction with models for non-pressure forces and control systems. Results for several roll motion control systems, including U-tube tanks and actuated fins, were presented. The LAMP code is structured so that new or modified time domain models of force actuators and/or control systems can be implemented into the motion and loads calculations in a fairly straightforward way. With its physics-based formulation and the ability to implement such models, LAMP is a very promising tool for developing and assessing motion control systems and algorithms.

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Detailed Analysis or Short Description of the AVT-110 contributions and Question/Reply

The Questions/Answers listed in the next paragraphs (table) are limited to the written discussion forms received by the Technical Evaluator. The answers were normally given by the first mentioned author-speaker.

P36 W.M Lin, K.M. Weems, D. Liut ' Design and Assessment of Ship Motion Control Systems with Advanced Numerical Simulation Tools', (Sciences Applications International Corporation, US)

The author described the LAMP model (see paper 29) and several of the "standard" roll stabilization systems currently implemented in LAMP: he also presented the results of some sample studies and drew our attention on the new implementation of a self-learning neural network controller that minimizes the ship's roll motion.. He concludes on the fact that LAMP may be considered as a very promising tool for developing and assessing motion control systems and algorithms.

Discussor's name: M-C Tse
Q. How large is the fin required relating to the wave size? What foil frequency should be operated in order to control the stability? And also how to ensure no flow operation?
R. Depend on the force requirment and the objective functions of the control algorithm. In the example case, the fin is 2.5ft x 1.25ft
The frequency is not unique. For flopping foil operation, there are many different ways to generate same amount of forces. We do want to have flow operation. The large lifting forces are coming from manipulating vorticity.

Discussor's name: C. Petiau
Q. How do you numerically modellise the fluid dynamics of the water unfurling on the deck in your container ship example?
R. We have a green water model as part of LAMP. It consists of 3 steps:
Water inflow: based en the relative motion of the ship and wave.
Slashing on deck: based on either shallow water or 3D approach.
Exit condition: calculated how much the flow will exit the deck.

Discussor's name: B. Masure
Q. To calculate the motions of a ship with the LAMP (Large Amplitude Motion Program) you must define the incident wave. How do you know or define the true incident wave for a ship in real conditions (I mean: at sea)?
R. We have the ability to input wave condition form real measurement Allen Engle in an earlier paper (paper 29) described a method to measure the actual wave in the model tests and use that as input wave conditions to LAMP. Other ways to generate incident waves include using wave spectrum information.