T 402 G – Postural Stability of Ship Personnel Interacting with Unsteady Shipboard Loads

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Biography
Rob Langlois, Ph.D., P.Eng. received an engineering diploma from St. Francis Xavier University in 1987 and bachelor's, master's, and doctorate degrees in mechanical engineering from Queen's University at Kingston in 1990, 1991, and 1996 respectively. From 1996 through 2001 he was Senior Dynamicist and subsequently Manager of Dynamic Analysis at Indal Technologies Inc. (now Curtiss-Wright Flow Control Company - Indal Technologies) where he focussed primarily on helicopter/ship dynamic interface analysis. In 2001 he joined the Department of Mechanical and Aerospace Engineering at Carleton University where he is now a Full Professor teaching courses in applied dynamics and design as well as conducting research focused on shipboard dynamic systems (including aircraft, mechanical systems, and human bio-dynamics), mathematical modelling, and computer simulation.

Description
The subject of shipboard postural stability as it affects ship design, operational planning, and crew safety has been a significant concern for several decades. Mathematical modelling has focused on the frequency of motion induced interruptions (MIIs) of free standing persons. While important, it is widely recognized that personnel often experience destabilizing external forces resulting from interaction with unsteady shipboard loads. The proposed paper presents recent research that extends conventional MII modelling to include the effects of various forms of unsteady shipboard loads (specifically slung and mobile equipment type loads). The paper will summarize background literature, overview model development, discuss full-scale model validation, describe available simulation tools, and present typical results.
Abstract—The subject of shipboard postural stability as it affects ship design, operational planning, and crew safety has been a significant concern for several decades. Mathematical modelling has focused on the frequency of motion induced interruptions (MIIs) of free standing persons. While important, it is widely recognized that personnel often experience destabilizing external forces resulting from interaction with unsteady shipboard loads. This paper presents recent research that extends conventional MII modelling to include three-dimensional effects and the effects of various forms of unsteady shipboard loads (specifically slung and mobile equipment type loads). The paper summarizes background literature, overviews model development, discusses full-scale model validation, and describes available simulation tools to support MII analysis.

1. BACKGROUND

Biomechanical postural stability models were initially developed with the goal of understanding the human sense of balance, and more recently they have been identified as a potential tool in quantifying the effects of motion environments on human performance. Opportunities may exist to introduce postural stability analysis earlier in ship design cycles thereby leading to more relevant ship design and operations. Research of this type is relevant and timely, as Canada is embarking on its largest ship building programme in recent history [1].

Crew members working in a motion environment are required to perform a variety of physically and mentally demanding tasks such as walking, weapons loading, and lifting [2]. If the ability of the crew to complete these tasks is in any way impaired, the overall efficiency of the crew member decreases resulting in potential increased costs and decreased effectiveness.

The ship design community has defined that a motion-induced interruption (MII) occurs when local motions cause a person to lose balance or slide, and so interrupt any task being performed. Typically this person must take a step, grab a hold, or stop what they are doing in order to maintain balance. This concept was introduced in 1980 by Applebee, McNamara, and Baitis [3] to describe the event when ship motions cause a person to lose balance or slide on the deck. A Lateral Force Estimator (LFE) model was developed in 1983 by Baitis, Woolaver, and Beck [4], and Baitis, Applebee, and McNamara [5] to calculate the incidence of MIIs due to ship lateral motion. Subsequently, a generalized LFE model which incorporates both vertical and lateral motions was developed by Graham, Baitis, and Meyers [6] in the early 1990s. This model is based on a two-dimensional block of humanoid mass, inertia, and support base properties. It is commonly referred to as the Graham model. An MII is said to occur if the block either has a sliding event or a tipping event.

The ABCD Working Group on Human Performance at Sea facilitated experiments using a large motion simulator to expose human participants to two different motion severities while performing several tasks [7]. The resulting data were used by Lewis and Griffin to validate the Graham model, as well as provide performance characteristics for further use of the model on more complex tasks [8]. The Defence Research Agency in the United Kingdom also performed a series of experiments with a large motion simulator [9, 10, 11, 12]. In these experiments, subjects were also required to perform different tasks, such as walking, simulated weapons loading, and quiet standing. From this data, empirical MII thresholds were determined to tune the Graham MII model for more accurate MII prediction.

At this stage of development, the MII methodology enabled the prediction of the onset of an MII, and so the probability of occurrence of MIIs’s could be estimated. Subsequent developments through the 2000s reported by Crossland and Rich [12, 13] and Crossland [14], extended the methodology to include the time of recovery from an MII, which is required for modelling these problems in a real-time simulation.

Further developments in MII prediction involved the introduction of actively-controlled articulation into postural stability models in order to better account for active balancing and muscle torque limits. A bi-planar articulating model was developed by McKee for MII prediction [15]. The model consists of an inverted pendulum in the sagittal plane and a four-bar linkage assembly in the frontal plane. Similar to the McKee model, a three-dimensional inverted pendulum model was introduced by Langlois [16]. Both of these MII detection models include two rotational degrees-of-freedom representing ankle joints.

While these articulated models offer potential for improved performance and assessment of parameters beyond the prediction of MII rate, they are necessarily more complex than the quasi-static form of the Graham model. It is, however, widely accepted that the shipboard motion environment is three dimensional thereby hindering MII analysis using the original two-dimensional Graham model.
Physical activities that involve interaction between humans and mobile equipment and/or objects include: line handling during boat launch and recovery, moving stores and supplies during ship-to-ship underway replenishment at sea, and rearming weapon systems. Modelling MIIs while performing such complex activities has been approached by extending the Graham model to three dimensions and to include arbitrary external forces, and by developing other more complex models. These more advanced models can also enable assessment of the effects of wind loading on personnel performing physical activities, which is not included in contemporary MII modelling, and is therefore frequently underestimated in the presence of high winds.

To address modelling in these areas, this paper presents in subsequent sections two MII models as well as models of two common classes of unsteady shipboard loads, as well as the associated computational implementation and validation.

II. POSTURAL STABILITY MODELS

Prior to detecting MIIs, a postural stability model is first required to determine the deck reaction forces and moments needed to maintain balance in the presence of deck motions and disturbances arising from external loads to which the modelled humans are subjected. These in turn form the basis for applying MII criteria to identify the onset of MII events. Two stability models have been developed: a quasi-static model generalized to three dimensions from the planar Graham model [6] and a fully dynamic inverted pendulum model [16]. Each model offers relative advantages depending upon the intended application.

A. Quasi-static Model

The quasi-static model is analogous to a three-dimensional block placed in a motion environment and subjected to an optional arbitrary disturbance force. The block, shown schematically in Figure 1, has height $h$, length $l$, and width $w$. The specific geometric and inertial properties are defined to represent a typical, arguably stylized, human. The purpose of the model is to determine the interface forces and moments at the base of the block. Figure 1 also shows the coordinate systems used in the model derivation. The inertial frame (designated IN) is defined outside of the motion environment. The ship coordinate system (designated SH) is attached to the ship at the point of attachment of the block to the deck and is aligned with the inertial frame in the absence of ship motion. Finally, a model coordinate system (designated MO) is attached to the block and located at the interface between the block and the ship deck.

The model kinematics equations are derived first to determine the accelerations of the block centre of gravity in the model coordinate system. The system dynamics are then solved using the Newton-Euler formulation to find the forces and moments at the attachment point between the block and the deck. The solution, using Newton’s equation to solve for the forces at the base of the model, reduces to

$$\begin{bmatrix} T_{SHIN} & T_{MOSH} \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}^{MO} = \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix}^{IN}$$

$$+ \{a_a\}^{IN} + \begin{bmatrix} T_{SHIN} & T_{MOSH} \end{bmatrix} \begin{bmatrix} r_{a/cg} \end{bmatrix}^{MO} + \{F_{ext}\}^{IN} \quad (1)$$

where $[T]$ is a transformation matrix from the first subscript frame to the second subscript frame, $F$ is the deck interface force component in the subscript direction, $m$ is the mass of the block, $g$ is the gravitational constant, $\{r_{a/cg}\}^{MO}$ is the vector pointing from the centre of gravity to the attachment point of the model to the deck, and $\{F_{ext}\}$ is an externally-applied disturbance force.

Euler’s equation is then solved for the reaction moments at the attachment point which reduce to,

$$\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix}^{MO} = [I_{cg} \{a\} + \{\omega\} \times [I_{cg} \{\omega\} \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}^{MO}$$

$$- \{r_{a/cg}\}^{MO} \times \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}^{MO} - \{r_{b/cg}\}^{MO} \times \begin{bmatrix} \omega \end{bmatrix}^{IN} \end{bmatrix}^{IN} \quad (2)$$

where $\{M\}$ is the reaction moment in the subscript direction, $\{a\}$ is the angular acceleration of the model frame, $[I_{cg}]$ is the moment of inertia about the centre of gravity, $\{\omega\}$ is the angular velocity of the model frame, and $\{r_{b/cg}\}^{MO}$ is the vector pointing from the centre of gravity to the application point of the disturbance force (point b). To obtain the reaction forces and moments, Equation 1 is first solved for the reaction forces; then Equation 2 is solved for the reaction moments.

The resulting computational model is call GRM3D.
B. Dynamic Model

A more complex, and in some cases more versatile model, includes articulation at the interface with the deck. Figure 2 provides a schematic representation of a single segment spatial inverted pendulum postural stability model. Point A corresponds to the location of the interface between the ship and the inverted pendulum and point B corresponds to the centre of mass of the rigid articulated segment. Articulation of the rigid segment is tracked using the two rotational generalized coordinates \( \theta_i \) corresponding to sequential roll and pitch motions of the articulated segment relative to the ship deck. Interface forces and moments correspond to the articulation joint. It is defined by the system is tracked using the two rotational generalized coordinates \( \theta_i \) and \( \theta_j \) corresponding to sequential roll and pitch motions of the articulated segment relative to the ship deck. Interface forces and moments are tracked by \( F_x \), \( F_y \), \( F_z \) and \( M_x \), \( M_y \), \( M_z \), respectively.

Four right-handed coordinate systems, labeled in rectangular boxes in Figure 2, are used in the model derivation and numerical solution. Three of the four coordinate systems (IN, SH, and MO) are the same as those defined for the quasi-static model. One additional coordinate system called the local frame (designated LO) is required. This coordinate system is collocated with the MO coordinate system but is attached to the articulated segment. The orientation of this coordinate system relative to the MO system is tracked using the two rotational generalized coordinates associated with the articulation joint. It is defined by the \( i \cdot j \cdot k \) triad in Figure 2.

Using the above coordinate systems, the dynamics of the inverted pendulum model are derived, again using the Newton-Euler formulation. A complete derivation of this model is presented in Reference [16].

The resulting translational and rotational equations are combined into the final set of six equations that govern the motion of the three-dimensional single segment shipboard inverted pendulum. These are:

\[
\begin{align*}
-m \begin{bmatrix} T_{SHIN} & T_{MOSH} \end{bmatrix} [A] & - [I^{LO}] [E] + \begin{bmatrix} \tilde{\theta}_i & \tilde{\theta}_j \end{bmatrix}^T \begin{bmatrix} \ddot{F}_x & \ddot{F}_y & \ddot{F}_z & \ddot{F}_w & \ddot{F}_v & \ddot{F}_z \end{bmatrix} \\
+2 \begin{bmatrix} T_{SHIN} & T_{MOSH} \end{bmatrix} \{D\} + \begin{bmatrix} T_{SHIN} & T_{MOSH} \end{bmatrix} \{B\} & + \{g\} + \{F_{ext}\}_{IN} \\
\begin{bmatrix} I^{LO} & T_{MOLO} & T_{SHMO} \end{bmatrix} \{\alpha^{SH}_{IN}\} & + \begin{bmatrix} I^{LO} \{C\} \end{bmatrix} \{G\} \\
+ \begin{bmatrix} \tilde{\omega}^{LO} & I^{LO} \{\omega^{LO}\} & -[H] \end{bmatrix} \begin{bmatrix} M_x & M_y \end{bmatrix}^{MO} & + \begin{bmatrix} \tilde{r}^{LO} & [C/c] \end{bmatrix} \{F_{ext}\}_{LO} \\
\end{align*}
\]

where the notation is consistent with that for the quasi-static model. Point C is the point of application of the externally-applied load, and elements \( mathA, [E], [L], [C], \{D\}, \{B\}, \{G\}, \) and \([H]\) are vectors and matrices that, in general, vary with time and system configuration but are not expanded in the present discussion for compactness.

Solving this matrix equation results in the four unknown components of the interface force and moment. The relative angular accelerations of the articulated segment can be successively numerically integrated to track the segment orientation. The interface moment components \( M_x \) and \( M_y \) are prescribed by an ankle moment controller.

Ankle moments are prescribed by, in general, a combination of passive and active inputs to restore the articulated segment from perturbations that have arisen from ship motion or other external sources. The applied ankle moment, \( M_A \), acts about the \( x \) and \( y \) axes in the model frame (MO) such that

\[
M_A = \begin{bmatrix} M_{Ax} \\ M_{Ay} \end{bmatrix}
\]

where \( M_{Ax} \) and \( M_{Ay} \) are comprised of stiffness \( (T_{stiffness}) \), damping \( (T_{damping}) \), and active contributions \( (T_{control}) \) such that

\[
M_{Ax,y} = -(T_{x,y\ stiffness} + T_{x,y\ damping} + T_{x,y\ control})
\]
The coefficients \( k_i, c_i, \) and \( A_i \) can be scheduled as appropriate depending on the state of the articulation to reproduce the desired responses. The independent relative angles \( \theta_{rel, x,y} \) and angular velocities \( \dot{\theta}_{rel, x,y} \) are measured relative to the ship deck taking applicable transformations into account. The total angles and angular rates \( \theta_{tot, x,y} \) and \( \dot{\theta}_{tot, x,y} \) are measured relative to the absolute vertical reference in the inertial frame (IN).

Joint range and torque limits are also applied to bound joint kinematics and actuation to realistic values and ensure that MII events related to these physical limits are not ignored.

The resulting mathematical model is called PSM3D.

### III. MII Indices

In order to determine the occurrence of MIIs, the sliding and tipping frictional force thresholds must be determined. Sliding is predicted if the lateral forces are greater than the maximum achievable resisting frictional force as defined by Gehman [17]. From the solutions, the reaction force components in the plane of the deck are evaluated in the \( x \) and \( y \) directions in the model frame. The maximum frictional force can be estimated using the calculated normal force (\( z \) direction) and the frictional coefficient of the surface. So, a sliding event is said to occur if

\[
\frac{\sqrt{F_x^2 + F_y^2}}{F_z} \geq \mu
\]  

(12)

The definition of the occurrence of tipping, as defined by Gehman, is when the net moment about the corner of the block goes to zero [17]. This definition, however, does not fully define the tipping of three-dimensional models. The model's only means of resisting any applied moment about the \( x \) or \( y \) directions is through the reaction moments from the solution. Therefore, tipping in the \( x \) direction can be predicted to occur when

\[
\frac{|M_x|}{F_z} \geq r_{x,max}
\]  

(13)

\[
\frac{|M_y|}{F_z} \geq r_{y,max}
\]  

(14)

where \( r_{x,max} \) is the maximum possible distance to the edge of the block (that is assumed to be symmetrical) in the \( x \) direction, and similarly for the \( y \) direction. Also, in three dimensions the block has the theoretical potential to rotate about the \( z \) axis. This rotation would cause an MII by uncontrolled yaw. This yawing moment is only resisted by the friction from the normal force. Yaw rotation ("tipping") is predicted to occur if

\[
\frac{|M_z|}{F_z} \geq P_{yaw}
\]  

(15)

where \( P_{yaw} \) is a positive constant representing the product of the effective stance radius and the frictional coefficient.

Alternatively, the postural model's only means of resisting any applied moment about the \( x \) or \( y \) directions is through the location of the normal force. The magnitude of the normal force would not change based on the solution, therefore the method of changing the resistive moment is by the effective location of the normal force. If the normal force needs to be applied outside of the bounds of the model's footprint, it is said to tip in that direction. The distance of the normal force can be calculated in the \( x \) and \( y \) directions in terms of the required reaction moment and the magnitude of the normal force, as seen in Figure 3. Using this approach, the effects of varying stance geometries can be included.

Figure 3. Normal force location to counteract the tipping moments on the postural stability model with a generic footprint.

### IV. Unsteady Load Models

#### A. Pendulating Load

The governing dynamics for a three-dimensional shipboard pendulating load are identical to those presented in Equation 3. However, in the case of a pendulating load, the ankle torques \( (M_x \) and \( M_y) \) do not apply and are simply set to zero, and the attachment point coordinates do not necessarily coincide with the deck. The joint displacement limits as well as the stiffness and damping parameters for the joints can be used to model the actual physical characteristics of the pendulating dynamic system.

The resulting mathematical model is called PND3D.

#### B. In-plane Load

The in-plane load model is defined as a two mass system arranged as shown schematically in Figure 4. The lower mass, attached to the ship, is only able to translate, whereas the upper mass, attached to the translating mass, is only free to rotate about
Figure 5. Schematic representation of postural stability models interacting with pendulating load (left) and cart load (right).

a pin located on the lower mass. The model has been defined such that the attachment point of the upper mass to the lower mass can be anywhere on the translating mass. Similar coordinate systems have been used for this model as in the previous models, with the addition of one coordinate system at the attachment point of the rotating mass to the translating mass.

Since there are two bodies in this model, the kinematics and dynamic equations must be solved for each mass. This then results in a state vector with twelve unknowns. The state variables for the lower mass are the linear acceleration of the cart, the forces in the $y$ and $z$ directions, as well as the reaction moments in all three directions. The state variables for the upper mass are the forces in all directions, the angular acceleration about the $z$ axis in the TO frame, as well as the reaction moments in the $x$ and $y$ directions. These variables are solved using Newton–Euler equations. It should be noted that individual degrees-of-freedom can be enabled or constrained as appropriate.

The resulting mathematical model is called CRT3D.

V. COUPLING DEVICE MODEL

Figure 5 shows schematic representations of a postural model (either the quasi-static model or the dynamic model) interacting with a typical unsteady shipboard load (either a pendulating load or a co-planar (cart-type) load). In both cases, the postural model is attached to the unsteady load by the directed element shown schematically in Figure 6.

The directed element consists of a tension/compression force-producing member that can generate forces that depend upon the relative position and relative velocity between its two attachment points as well as some nonlinear behaviours. As implemented, the directed element has distinct linear stiffness properties in the tension and compression directions; distinct viscous damping properties in the tension and compression directions; as well as options for tension-only, compression-only, and no transmitted force behaviours to represent tensioned lines/cables, unattached push poles, and loss of contact situations, respectively.

This resulting mathematical model is called INTFRC.

VI. SOFTWARE IMPLEMENTATION

The postural stability, unsteady load, and interface force models presented in previous sections as well as various methods for introducing ship motion have been implemented in two forms. The first, DEPSM, is a stand-alone executable program and the second is a distributed simulation implemented using the Virtual Flight Deck – Real Time (VFD-RT) simulation architecture [18, 19].

A. DEPSM

The high-level layout of the Development Environment for Postural Stability Modelling (DEPSM) is illustrated in Figure 7. It incorporates options for generating ship motion using a simple six degree-of-freedom ship dynamic model, prescribed ship motion generated from pre-computed response amplitude operators (RAOs), and tabulated ship motion data. The postural models, unsteady load models, and directed element model are implemented such that the various permutations can be enabled as
required. The models are completely general with all parameters specified through corresponding input files. DEPSM runs in the time domain and outputs ship motion, forces and moments at the interfaces between models and the ship, MII parameters, and forces acting through the directed element. A variety of post-processing tools are available for identifying and analyzing MII events and, when possible, correlating them with available experimental data.

B. VFD-RT

The Virtual Flight Deck – Real Time was developed by the Carleton University Applied Dynamics Lab as a distributed simulation environment for integrating shipboard simulations of all types [18, 19]. Communication between simulation components uses the Microsoft Windows messaging system with a provider and client setup. A provider is an application that will send data to the main application of the VFD-RT. The main application will then store and distribute the information to the desired clients. The clients are applications that take the data from the VFD-RT. This framework also allows for the use of provider and client functions to be used in one application. These applications can provide data to the VFD-RT as well as take data. The implementation of the models described in this paper uses provider/client combined applications because of the data transfer requirements. A notable benefit of the VFD-RT architecture is that it distributes models identically to the industry-standard High Level Architecture (HLA) for distributed simulation modelling such that the VFD-RT models can be easily integrated into existing HLA federations.

The main loops of the individual applications solve the governing equations of motion. The equations of motion have been implemented in Fortran for speed and compatibility with existing library functions. The Fortran routines are wrapped using C++ and linked to the VFD-RT provider/client application so that ultimately a C++ application is running the Fortran routines. For the stability and load models, the required inputs are the ship motion and the magnitude and direction of the external force. The outputs for those models are the location of the attachment point of the external load. For calculating the magnitude and direction of the external force, the interface force model requires the location of the external force element attachment points for each of the models. It then provides the magnitude and direction of the external force. This is shown schematically in Figure 8.

VII. MODEL VALIDATION

The quasi-static (GRM3D) and dynamic (PSM3D) models when uncoupled from external shipboard loads have been validated by comparing computational models with alternative computational models as well as with available sea trial and laboratory experimental data. In the case of interaction with unsteady loads, a recent comprehensive series of validation experiments was conducted to validate the computational models against full-scale experiments. The experiments were conducted with purpose-built hardware such that the mechanical systems from which experimental data were collected closely match the computational models that were being validated.

A. Apparatus

The concept of the validation experiments is to reproduce the two basic types of coupled load cases considered. Interactions between the postural stability models (PSM3D and GRM3D) and the pendulating and cart loads (PND3D and CRT3D) are illustrated schematically in Figure 5 along with the interface force model (INTFRC).

The mechanical hardware of the validation apparatus is intended to accurately represent the dynamic models of the spacial inverted pendulum, fixed inverted pendulum, pendulating load, cart load, and interaction force models such that experimental validation of these dynamic models can be completed individually and when coupled. Motion excitation is provided by a suitably-sized 6-DOF motion platform.

The spacial inverted pendulum is represented by a custom-designed universal joint, shown in Figure 9, with control torque input from a geared servo motor setup. Control torque is applied to the drive joint through two perpendicular intersecting axes, which define the two degrees of freedom of the inverted pendulum relative to its mounting surface. The pendulating load hardware consists of a steel pipe section hung from a large support structure through a universal joint. The cart load is represented by a translating base and a rotational structure mounted on top of the translating base. This setup allows the cart load to be configured with three selectable rotation centres. A rigid tension/compression link comprised of steel pipe and threaded rod is used to connect...
the inverted pendulum to either of the two dynamic loads. It is connected through a universal joint at one end and a spherical bearing rod-end at the other to produce a link subject only to tensile or compressive forces. The fixed inverted pendulum is achieved by locking the articulation joint either with the control law or mechanically using an angle brace across the u-joint.

The mechanical validation hardware is designed at 1:1 scale with real-life equivalents of the dynamic models to make interaction with human subjects possible in the future. Use of readily available components was maximized to keep costs to a minimum and mild steel was used for custom hardware structures and components due to its high stiffness, moderate strength, good weldability, and low cost.

Figure 10 shows a photograph of the experimental setup for a coupled articulated inverted pendulum and pendulating load. The system shown is mounted on the Moog 6DOF2000E motion base that reproduces prescribed representative ship motion scaled to remain within the bounds of the motion envelope of the platform without the use of washout.

B. Instrumentation

For validation of the dynamic models and active control of the spatial inverted pendulum to be possible, several key translations, rotations, and interface forces must be measured and recorded from the mechanical hardware while it is subject to simulated ship motion from the 6-DOF motion platform. Interface forces and moments between the inverted pendulum and its mounting surface are measured using a 6-axis load cell, while the tensile or compressive force in the connection link between the inverted pendulum and the dynamic loads is measured using a single axis load cell. Rotation of the inverted pendulum and the rotation and translation of the cart load are measured by quadrature encoders. Rotation of the pendulating load is measured using an optical tracking system, which facilitates tracking via strategically placed reflective markers and an array of eight infrared cameras.
TABLE I. Test cases for the independent stability and load models.

<table>
<thead>
<tr>
<th>PSM3D</th>
<th>GRM3D</th>
<th>PND3D</th>
<th>CRT3D</th>
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<tbody>
<tr>
<td>sinusoidal surge</td>
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<td>sinusoidal surge</td>
<td>sinusoidal surge</td>
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<tr>
<td>general ship motion</td>
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TABLE II. Test cases for the coupled stability and load models.

Coupled models with 1:1 mass ratios

<table>
<thead>
<tr>
<th>GRM3D &amp; PND3D</th>
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</tr>
<tr>
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Coupled models with 1:2 mass ratios

<table>
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<tr>
<th>GRM3D &amp; PND3D</th>
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<th>GRM3D &amp; CRT3D</th>
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National Instruments software and hardware cards are used to actively control the spatial inverted pendulum and record data from the various force, displacement, and rotation sensors.

C. Test Plan

A comprehensive test plan was developed to validate the mathematical models with the experimental results. The models were first tested independently to ensure that the individual models are valid. Experiments were then run with postural models coupled to load models. When coupled, two mass cases were investigated, one where the added mass on the stability and load models are the same and another where the load model has 70 lbs of additional weight over the postural model.

Initially, single degree-of-freedom sinusoidal translational and rotational motion profiles were used. These motions consisted of sinusoidal surge and roll motions with amplitudes of 0.1 metres or radians and a frequency of 0.5 radians per second. Next, frequency sweeps were performed to determine the frequency responses of the systems. These had amplitudes of 0.1 metres or radians and swept from 0.1 to 0.5 radians per second. The final motion profile represented general six degree-of-freedom ship motion generated from RAOs.

The specific experimental validation cases run are listed in Tables I and II.

D. Validation Results

Simulations using the models described in this paper were run using the corresponding physical parameters and motion profiles and the corresponding force and displacement results were compared for all cases. It was determined that the computational models are valid for their intended purpose of assessing deck interface forces and moments when the postural models are run individually and when coupled to unsteady shipboard loads. As a result, the MII indices can be evaluated for situations prevalent in the shipboard working environment when personnel are interacting with unsteady shipboard loads.

VIII. Conclusion

The following conclusions are drawn from this and recent related work.

- MII modelling capability has recently been extended based on conventional models as well as recent research to increase the practical utility of MII models both for investigating stand-alone MII occurrence rates as well as MII rates when interacting with unsteady dynamics loads.
- Various models are currently available to support design and operational planning requirements.
- Continuing theoretical developments combined with ongoing at-sea and laboratory experiments will continue to improve upon existing modelling capability.
- Greater use of available models early in the ship design and operational planning cycles offers the potential to promote greater postural safety and contribute to the improvement of overall ship efficiency.
REFERENCES


