TEMPEST — A New Computationally Efficient Dynamic Stability Prediction Tool

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ABSTRACT

The US Navy has embarked upon the development of a new computational tool for simulating the responses of a ship operating in severe sea states. This new tool, TEMPEST, is designed to be computationally efficient to support real-time training simulators as well as high-resolution evaluation of surface-ship, dynamic-stability performance across a wide range of possible environmental conditions. TEMPEST aims to improve the state-of-the-art for real-time computations through the inclusion of nonlinear (body-exact) hydrodynamic perturbation forces and physics-based, viscosity-influenced lift and cross-flow drag forces. Slender-ship and low-aspect-ratio lifting-surface theories provide the ability to maintain computational efficiency while including the dominant nonlinearities within the dynamic stability problem. This paper argues for the efficacy of TEMPEST's theory in reconciling the need for accurate predictions with computational efficiency.

KEYWORDS

Large amplitude motions, nonlinear dynamics, body-exact hydrodynamics, bilge-keel forces, TEMPEST, maneuvering in waves

INTRODUCTION

Ship operability and safety are often linked to its motions in waves and eventually to its dynamic-stability risk. Evaluation of dynamic-stability risk is primarily achieved through the gathering of performance data in the wave environment and speed-heading condition of interest. The performance data can be obtained from model tests or simulations. Model tests are expensive, limited in flexibility (wave conditions, run length), and can have scale effects. If the design changes, or even the loading condition changes, an entire new model test needs to be executed. Simulations offer the opportunity to include scale effects, provide nearly any environmental input desired, and are generally easier to re-run when geometry or loading conditions change. However, there is a significantly higher burden on simulations to validate the theory for full-scale ship performance. Regardless, there remains a need for the designers or regulatory authorities who need to evaluate dynamic-stability risk to have several tools at their disposal. Model tests, high-fidelity computational tools (like CFD), and fast simulations all have their roles.

The number of conditions that must be simulated depends upon the resolution to which dynamic stability needs to be characterized. If the failure modes are not known *a priori*, it may be necessary to obtain motion statistics over a complete range of environmental and ship operating conditions. If the matrix of conditions includes multi-directional seas with two or more wave systems (swell is more than likely not correlated to the wind-driven system), the total number of simulations quickly grows. For a nominal speed-heading resolution of every 5 knots and 15 degrees, each environmental condition could have approximately 150 conditions for which extreme value statistics need to be generated. Because of this, there is a need for computational efficiency. However, computational speed does not provide the designer or regulatory authority any benefit if the answer is wrong. The goal then is to generate sufficiently accurate results as computationally efficiently as possible. The evolving understanding of the relevant physics allows for theory to be only as complex as needed. It is with this objective that the U.S. Navy has embarked upon the development of a new dynamic-stability simulation tool called TEMPEST.

PHYSICAL PROBLEM

A simulation tool needs to be able to include the physical phenomena that are relevant to the full-scale problem. As such, the first step in developing a computational tool is to identify what the physical problem is and decompose it in a manner that can be modeled. At the highest level, the physical problem can be described by the ambient environment, the ship control condition, and the forces acting on the ship. **Figure 1** illustrates the physical problem to be modeled.

Environment

The definition of the ambient environment for the dynamic stability problem must include both the wind and wave environments. In realistic sea conditions, the wave environment is generally considered multi-directional. An example polar spectrum showing two distinct wave systems is shown within **Figure 1**. It is important to be able to include multiple wave directions in a computational model because of the unique physics that occur in such a situation. For example, one wave system may degrade transverse hydrostatic stability while another may provide a rolling moment.

Another aspect of the wave environment that is strongly correlated to dynamic-stability risk is the steepness of the seas. Steep seas have a more significant impact on the change in wetted geometry, which has a large effect on the forces felt by the hull. Within steep seas, nonlinear effects become stronger, such as the asymmetry of the wave profile and the nonlinear pressure and particle kinematics.

The wind environment may or may not be aligned with the wave systems, which produces another variable in the dynamic stability assessment matrix. Therefore, in addition to a reference mean speed, the wind environment includes a mean direction.

In order to determine the force on the ship due to wind in high sea states, the wind profile must be understood at the "local" scale, meaning that the effect of the nearby wave shadowing is included. This results in an apparent gustiness from the effect of being in the trough versus being on the crest. It is unclear whether or not capturing these effects has a significant effect on the final ship-motion results, but it is has been decided that the effects should be included until otherwise deemed unnecessary.

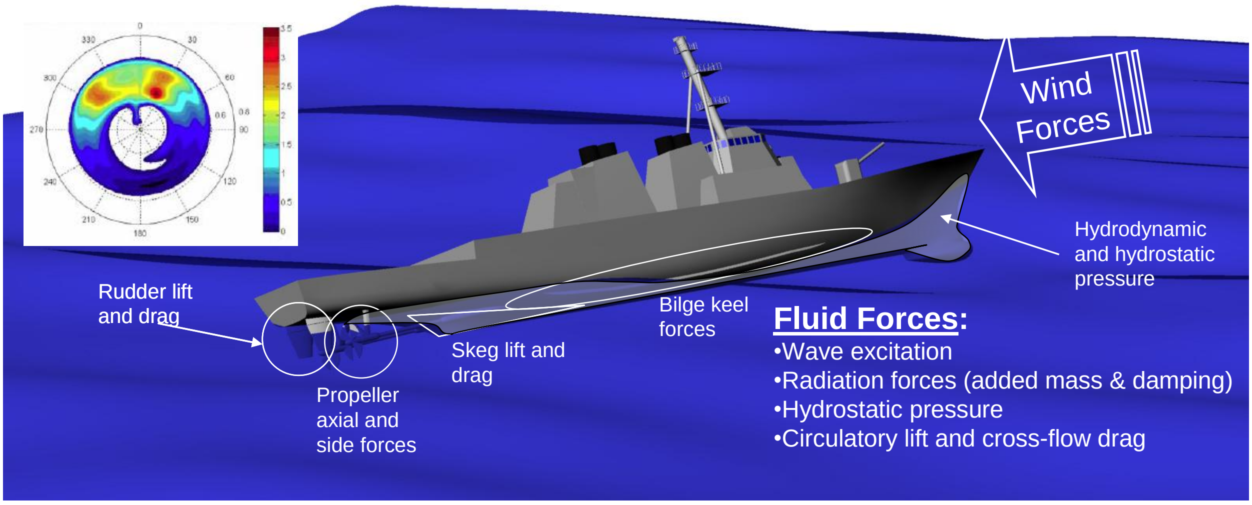


Figure 1: Illustration of the physical problem to be simulated

Ship control

In a traditional "seakeeping" framework, the ship's speed and heading is considered known or prescribed. The solution of the seakeeping problem is the characterization of the motions about this nominally constant speed and heading. This framework is adequate and appropriate for determining the non-rare motion statistics, such as the RMS or significant values.

In the characterization of the large amplitude, or rare motion problem, it is necessary to consider the forces and responses that arise from large deviations from the constant speed-heading condition. These may include, but are not limited to, surf-riding and broaching. To allow for these, the ship must be *self-propelled* and *self-steered*. As such, the physical problem is best characterized as the maneuvering-in-waves problem.

To be self-propelled means that a propulsor model of some sort provides a thrust to balance the resistance forces present due to the air and water. Rather than prescribing a speed, the thrust and resistance, both of which can be time-dependent, determine the speed.

Self-steered means that a rudder, azimuthing propulsor, or other steering device is used to provide a yaw moment that counters a yaw moment induced by the aerodynamic and hydrodynamic forces on the hull. The time-changing balance of these forces and moments leads to the time-changing heading of the ship.

Forces

The forces acting on the vessel in the defined ambient environment for the ship under self-propulsion and self-steering control largely follow from the typically understood seakeeping and maneuvering problems. The unique aspects of the dynamic stability problem are the coupling of the forces and the effect of large amplitude motion and/or large amplitude waves.

The fluid forces on the hull consist of hydrostatic pressure, wave excitation (Froude-Krylov and diffraction), radiation forces (*i.e.*, the added-mass and wave-making damping effects), resistance forces, and circulatory lift and cross-flow drag that arise from viscosity. In a high sea state, these forces can act on a hull with large changes in wetted geometry.

In the special case that the deck is submerged, the fluid flow must be treated as a "green water" problem. The green water problem describes the time delay in the force due to the time it takes for the fluid to cover the deck, as well as the shipping of water as the deck reemerges.

In addition to the bare hull, the bilge keels provide a lifting force or a cross-flow drag, as well as contribute to the added mass. As with other parts of the hull, the bilge keels can exit and re-enter the free-surface.

Propeller forces depend on the advance coefficient, J, which in turn is affected by the ambient environment (via wave-orbital velocities) and ship motions. In large waves the propellers can exit and re-enter the water, which will affect thrust and consequently speed of the ship. Furthermore, in the extreme motion and wave conditions present, large inflow angles of attack can result that lead to side forces that can be up to 40% or more of the axial force.

The rudder forces are coupled both with the propeller thrust and the ambient wave environment. As with other appendages, the rudders are subject to exit and re-entry through the free surface.

Finally, the wind environment imparts forces and moments on the exposed parts of the hull. The wind loads are dependent upon the time-changing, wind-speed profile acting on the ship.

IMPORTANCE OF NONLINEARITY

There are a number of nonlinearities that manifest themselves in the prediction of motions of ships in extreme seas and dynamic stability. These range from: the equations of motion, to the geometry of the vessel, to the hydrodynamics as exemplified by the nonlinear free-surface boundary condition applied to the ambient wave field and the hydrodynamic disturbance (radiated and diffracted waves), and to Bernoulli's equation for pressure. The use of the fully nonlinear equations of motion is endemic among dynamic-stability codes, but otherwise there are as many differences as there are choices as to which nonlinearities are important and need to be included.

Hydrostatics and Froude-Krylov

That nonlinearities are important for large-amplitude motion predictions has been recognized for many years, and is illustrated by the extensive use of "blended" methods that combine linear and nonlinear forces to predict large-amplitude vessel motions (Beck & Reed, 2001). Blended methods typically incorporate nonlinear hydrostatic-restoring forces and nonlinear Froude-Krylov exciting forces due to the incident waves, with linear radiation and diffraction forces. Both the nonlinear hydrostatic-restoring forces and Froude-Krylov exciting forces account for body nonlinearities, particularly in the presence of large-amplitude waves and extreme motion responses.

The nonlinear hydrostatic-restoring forces arise from integrating the gZ term in Bernoulli's equation over the instantaneous wetted surface of the vessel in the incident waves, so there is little ambiguity as to what is to be computed (cf, de Kat & Paulling, 1989). The issue here is how is the "incident wave" defined—is it purely linear, or does it include nonlinear (second-order or higher) terms? Since the mid 1800's, it has been known that steep second-order waves have higher crests and shallower troughs than linear waves (Stokes, 1847), which will clearly affect the instantaneous wetted surface of the vessel and thus the hydrostatic-restoring force on the vessel. (More on the ambient wave description later in this section.)

The Froude-Krylov contribution to the exciting forces results from integrating the hydrodynamic terms of Bernoulli's equation ($\phi_t + 1/2\nabla\phi\cdot\nabla\phi$), which result from the incident waves over the immersed surface of the ship's hull. In this case, it is not as clear what terms should be integrated as it was for the hydrostatic term. Many codes linearize Bernoulli's equation to either ϕ_t or $\phi_t + U\phi$, where U is the forward speed of the vessel, either instantaneously or on the average. This leaves the possibility of significant variation in results for the Froude-Krylov component of the force without even considering the representation of the incident wave. Telste & Belknap (2008) present and discuss some examples of this type of variation. The representation of the wave which will be presented later adds even more variation.

Hydrodynamic Forces

To develop an understanding of the hydrodynamic forces and moments on a vessel undergoing large-amplitude motions, a numerical experiment was performed using a variety of computational tools. These computational tools ranged from linear, to blended, to fully nonlinear. The complete experiment is documented in a massive report (15,240 p.), Telste & Belknap (2008). Belknap & Telste (2008) and Reed (2009) contain summaries of the results.

In the numerical experiment, thousands of the force and moment calculations were made and compared for two hulls: oscillating in various modes of motion in calm water (Task 1), fixed in waves (Task 2), and simulating large-amplitude motions by contouring waves (Task 3). The results are presented in the form of time-history plots showing simulated forces and moments at two speeds, for a variety of headings and wave/motion amplitudes. It was not the purpose of the study to evaluate any one code relative to another, but rather to evaluate the differences between various complexities of theory; and in general, codes with a consistent level of theory produced quite consistent results.

Figure 2 shows a time history of ship-fixed vertical force from predictions for a hull undergoing forced heave in calm water at $F_N = 0.3$ and $\omega = 1.1$ rad/sec, with heave amplitude/draft of 0.8. Many of these Task 1 force and moment predictions demonstrate the importance of nonlinearity in the radiation forces. An obvious indicator of nonlinearity is the departure of the components of force and moment from a simple sinusoidal form. This is seen in the predictions by the three nonlinear codes shown in Figure 2. A surprising finding was that the body-exact strip theory is capable of capturing these important nonlinearities—comparable to the two fully nonlinear, 3-dimensional codes. This result provides hope for the development of fast codes to predict dynamic-stability failures on the order of real time.

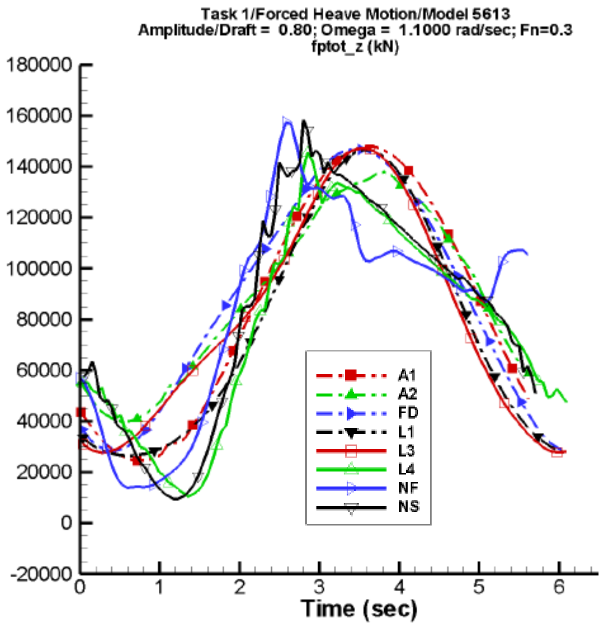
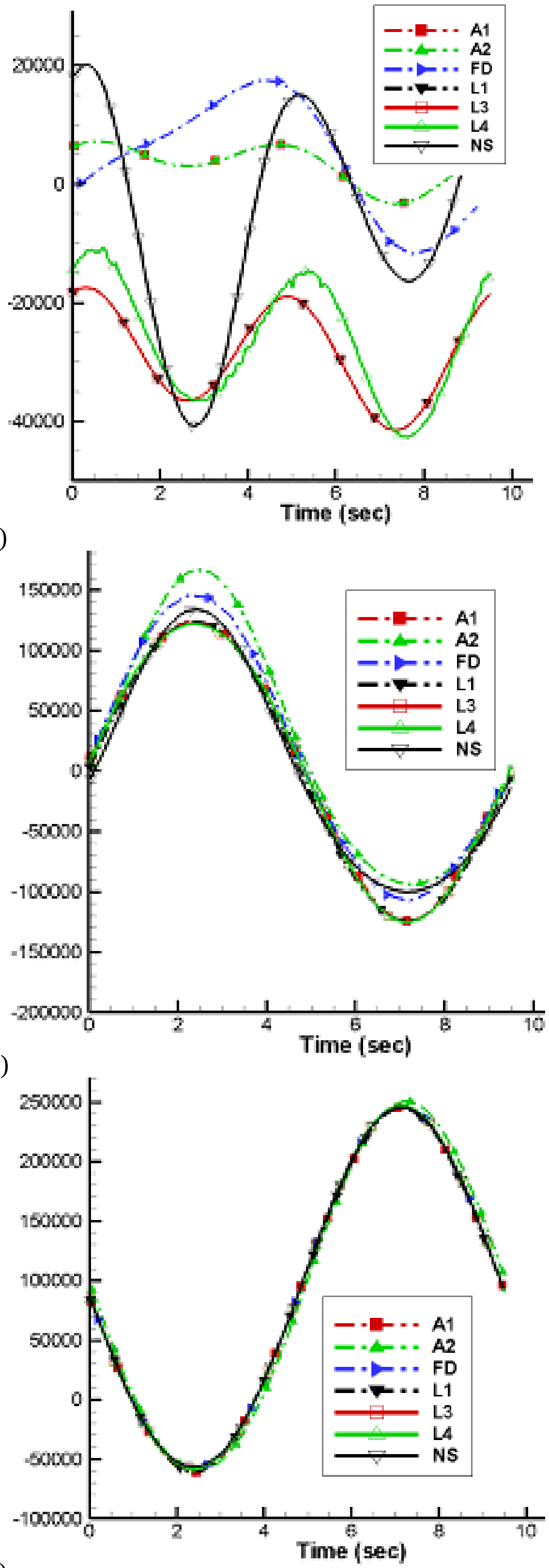


Figure 2: Time-history of ship-fixed vertical force from Task 1 predictions for ONRTH hull undergoing forced heave at F_N = 0.3 and ω = 1.1 rad/sec, with heave amplitude/draft of 0.8. (Belknap & Telste, 2008)

Figure 3 provides a time-history of ship-fixed vertical forces [hydrodynamic (*i.e.*, radiation and diffraction); Froude-Krylov; hydrostatic] on a hull which is contouring waves in following seas at F_N = 0, λ/L = 2, and H/λ = 1/20. From these Task 3 computations, it was found that the hydrostatic and Froude-Krylov forces are an order of magnitude greater than the hydrodynamic forces. The hydrostatic and Froude-Krylov forces calculated by all of the codes are in remarkable agreement—there is no difference in the hydrostatic force, and the differences in the Froude-Krylov force predictions are small. The hydrodynamic forces show significant variation between the codes. As it was impossible to distinguish between the radiation and diffraction components of the hydrodynamic force, one cannot identify the sources of the difference. However, the hydrostatic and Froude-Krylov forces are 180° de-



a)

b)

c)

Figure 3. Time history of ship-fixed vertical force from Task 3 predictions for Model 5514 hull, while contouring following seas at F_N = 0, λ/L = 2, H/λ = 1/20, a) hydrodynamic force, b) Froude-Krylov force, c) hydrostatic force. (Belknap & Telste, 2008)

grees out of phase with each other, so they largely cancel each other. Thus the difference between the hydrostatic and Froude-Krylov forces is the same order of magnitude as the hydrodynamic force, which means an accurate calculation of the hydrodynamic force is very important.

Second-Order Waves

As discussed earlier, nonlinear ambient-wave models have the potential to significantly influence predictions of dynamic stability. Two aspects of this are important: the shape of the wave profile; and the pressure within the wave. Stokes (1847) showed that the second order waves had steeper crests and shallower troughs than linear waves. According to linear theory, the pressure in wave crests (that portion of the wave above the calm free surface) is not zero at the free surface, which leads to significant errors in the predicted forces and moments on the ship's hull, particularly when the ship is in the wave crest in steep waves.

Figure 4 illustrates this for a wave of steepness (H/λ) of 1/10. It shows the pressure contribution from the zeroth- [$p_0/(\rho g) = -z$], first- [$p_1/(\rho g) = 2Ae^{\nu z}\cos\theta$], and second-order [$p_2/(\rho g) = -2\nu A2e^{2\nu z}$] terms in the pressure. As can be seen, the sum of the zeroth- and first-order pressure terms ($p_0 + p_1$) differs significantly from zero—providing an over prediction of the actual pressure at the free surface.

One method of dealing with this discrepancy with linear waves is the so called Wheeler stretching (Wheeler, 1970), where the origin of the vertical coordinate is essentially shifted to the wave surface from the calm-water equilibrium surface, resulting in zero pressure at the free surface. The Wheeler-stretching approximation leads to much more realistic pressure distributions, and thus forces, than those forces which result from no stretching.

In the case where one is employing second-order wave theory to obtain realistic wave profiles in extreme seas, the use of second-order theory for the wave pressures leads to accurate predictions of the pressure within the wave profile for regular waves.[1] The sum of the zeroth-, first-, and second-order pressure terms ($p_0 + p_1 + p_2$) in Figure 4 provides an example of the second order pressure distribution, which comes quite close to zero at the free surface, much closer than the first-order approximation ($p_0 + p_1$).

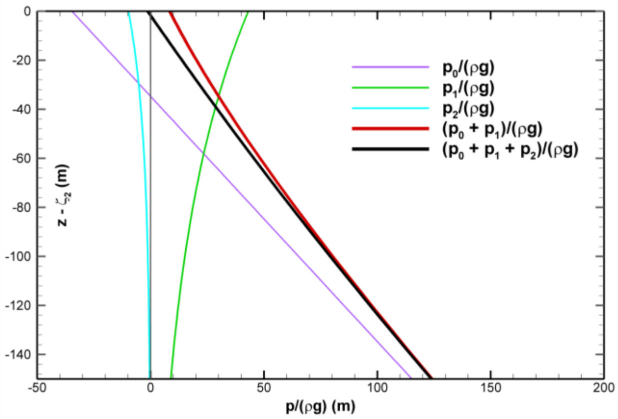


Figure 4: Pressure under a wave crest through second order divided by ρg, as a function of the distance below the crest: $H/\lambda = 1/10$, $\zeta_1 = 2A\cos\theta$, $\zeta_2 = 2A^2\nu\cos(2\theta)$, $p_0/(\rho g) = -z$, $p_1/(\rho g) = 2Ae^{\nu z}\cos\theta$, $p_2/(\rho g) = -2\nu A2e^{2\nu z}$ (Courtesy of J. Telste)

A consistent implementation of second order wave theory for irregular seas leads to sums containing exponentials of sum- and difference-frequency terms. The exponential sum terms can become quite large near the wave crests, resulting in extremely unrealistic pressures near the free surface of wave crests. This is illustrated in Figure 5 for two waves of differing frequencies such that the ratio of their wavelengths is 10.

There are several possible approaches that can be used to resolve the sum-frequency issue for irregular seas. One suggestion is to use a 2- or 3-term Taylor series expansion of the exponential rather than an exact function evaluation. Stansberg, *et al*. (2008) propose the use a low-pass filter applied to the linear horizontal velocity. The reason for such a filter is given by Gudmestad (1993), who states that the exponential term becomes very large near wave crests if the low-pass filter is not used.

[1] The second-order pressure equation does not require second-order wave theory, it can be used with linear wave theory.

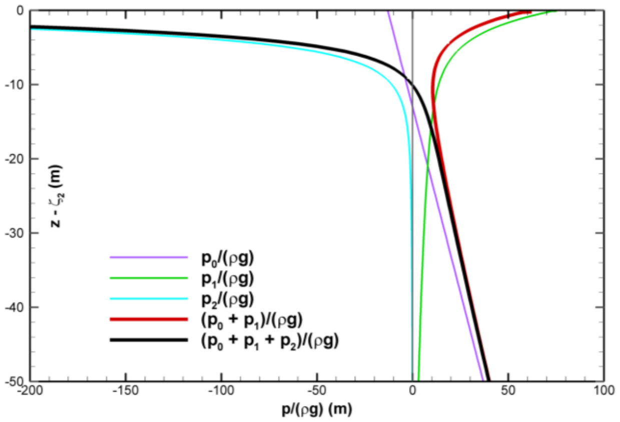


Figure 5: Pressure under a wave crest through second order, $(p_0 + p_1 + p_2)/\rho g$, for the sum of two waves versus the distance below the crest, $z - (\zeta_1 + \zeta_2)$, for two frequencies: $\lambda_1/\lambda_2 = 10$, $H/\lambda = 1/10$, $(\theta_1, \theta_2) = (0, 0)$. (Courtesy of J. Telste)

Second-Order Forces

As a ship maneuvers in steeper and steeper waves, there are greater and greater interactions between seakeeping and maneuvering, to the point that one cannot predict maneuvering in steep waves by simply superimposing seakeeping and maneuvering in a linear fashion (cf, Reed, 2009). One of the reasons for this is the fact that in steep waves the second-order hydrodynamic forces and moments (second-order drift forces and moments, and added resistance in waves) begin to play a significant part in the maneuvering behavior of the ship—slowing it down and speeding it up as it executes a turn in waves (Skejik & Faltinsen, 2008). For this reason, it is important to have a comprehensive model of the physics that includes these forces. The Froude-Krylov forces and moments capture a portion of these forces and moments, but only the component due to ambient waves. There is a significant hydrodynamic component that must be captured accurately.

Nonlinear Dynamical System

Finally, it needs to be recognized that a ship undergoing large-amplitude motions in extreme seas represents a nonlinear dynamical system. As a consequence, the vessel response can change drastically with small increases in excitation—this is particularly true near and beyond the peak in the righting-arm curve, where the restoring moment remains essentially constant or even decreases as the heel angle (roll angle) increases. Conceptually this is easy to understand in calm water, but in a seaway, there is even more variability due to the ship's being posed on a wave—as the wave passes along the hull the magnitude of the righting arm will fluctuate relative to the calm-water righting arm and the angle corresponding to the peak of the righting arm will vary. Whether the peak of the righting-arm curve increases or decreases in magnitude and the angle at which the peak occurs is a function of the shape of the hull above and below the calm-water waterline and the phase of the wave along the hull. Statistically, this says that there will be significant uncertainty as to the response of the ship under these circumstances. This has significant implications for the validation of computational tools and it is important for one to understand these concepts when validating the tools.

CODE APPROACH OPTIONS

Having identified the components of the maneuvering-in-waves physical problem and understanding the importance of nonlinearity within the dynamic-stability problem, several modeling approaches were evaluated for implementation in TEMPEST. Vassalos, et al. (1998) provide an overview of the numerical tools and approaches available for predicting dynamic stability events. Further evaluation of options relied on experience with existing ship-motion computational tools, though physical considerations played a large role as well. One reason for this is that existing tools are fallible; *e.g.*, some of the tools may not have been adequately verified, meaning that seemingly poor validation results can not be separated from potential bugs in the code. A key argument for developing a tool from scratch is that it allows for best verification practices (thorough documentation, unit tests, etc.) to be built in from the beginning.

Perhaps the first high-level-approach question to consider is whether to follow a complete flow solver (such as RANS or Euler VoF) or a potential flow-based track. While the option to compute a total solution of the fluid flow is attractive because it would include nearly the entire physical problem in a single computation, the computational cost is prohibitive given the number of conditions that need to be simulated. For that reason, a framework that follows the traditional seakeeping decomposition of a radiation and diffraction potential-flow solution added to a circulatory-lift solution is the only practical path. The argument for such an approach is that there is weak and/or one-way coupling between the hull radiation and diffraction (or "hydrodynamic disturbance") force and the lift and cross-flow drag on the appendages and the hull itself. While this assertion requires validation, there is no apparent alternative that meets computational speed requirements.

There are two basic paths that can be followed within the framework described above. One approach is to combine a maneuvering theory with a seakeeping theory, such as the two-time scale model employed by Skejik & Faltinsen (2008) that attempts to break the problem into its low-frequency part (maneuvering) and high-frequency part (seakeeping). The difficulty with this approach is avoiding any double-counting of forces. The attractiveness of this option is that trusted maneuvering models can be used. The second approach is to attempt to model the circulatory lift problem by itself, thereby avoiding double-counting issues. The challenge then is providing a robust model for this force.

Table 1: Computational efficiency (computational seconds / simulated seconds)

	Linear	**Blended**	**Nonlinear**
2D	**O(10^{-3})**	**O(10^{-1})**	**O(10^{0})**
Slender ship			***est. O(10^{1})***
3D*	**O(10^{1})**	**O(10^{1})**	**O(10^{3})**

* Time-domain solution of hydrodynamic disturbance for Linear and Blended methods

Within the community of potential flow approaches, a code can be described in simple terms by how 3-dimensional it is and how much nonlinearity is captured. In general, the more 3-dimensional and the more nonlinear a code, the less computationally efficient it will be. Table 1 provides a high-level view of the computational expense within the matrix of nonlinearity and slenderness assumption ranges. "Linear" denotes potential flow codes that are completely linear, whereas "Blended" includes nonlinear (body-exact) hydrostatic and Froude-Krylov forces. The term "Nonlinear" refers to codes with nonlinear hydrodynamic-disturbance forces as well as nonlinear hydrostatic and Froude-Krylov forces. Slender-body approximations range from "2D", which is strip theory, to "Slender ship", which includes some 3D effects, to a fully 3D code. The cells of the table are colored green if the computational speed is considered acceptable for providing a sufficient level of data resolution for dynamic-stability risk characterization while red is considered unacceptable.

Table 2 is organized identically to Table 1, but rather than color-coding according to computational speed, the cells are color-coded based on an intuitive assessment of the code's ability to capture the relevant physical phenomena. This assessment largely follows the arguments laid out on the importance of nonlinearity to the dynamic stability problem.

Table 2: Capturing physics & nonlinearity

	Linear	**Blended**	**Nonlinear**
2D			
Slender ship			
3D			

These tables may provide simplistic views of the code-approach options for the solution of the hydrodynamic forces, but they help the theory developer navigate the solution space.

TEMPEST APPROACH

The philosophy driving the development of TEMPEST's theory was to include all aspects of the maneuvering in waves physical problem as described earlier and model these components such that they capture the important nonlinearities. The review of code-approach options has given the development team confidence that a computationally efficient approach is feasible as long as the simplifying assumption of ship slenderness is adopted. This is supported by Table 3, which provides an estimated composite ranking of the hydrodynamic-solution approaches within the criteria of accuracy and speed. As noted earlier, accuracy is weighted more heavily than speed, because quick but incorrect data is of no value to the user. The result is that the TEMPEST approach is based on a fully body-nonlinear hydrodynamic solution with advanced models: for the environment; for circulatory lift and for cross-flow drag on the hull and appendages; and for other superimposed forces.

Table 3: Estimated composite ranking of computational efficiency and ability to capture the relevant physics

	Linear	**Blended**	**Nonlinear**
2D			
Slender ship			
3D			

Environment

As input to the force models, the modeling of the environment becomes just as important as the force models themselves. While the user generally describes the wave spectrum and wind speed, it is the environmental models that interpret these higher level inputs to provide ambient pressures and velocities at many places on the hull at every time step.

Waves In TEMPEST, the seaway is modeled by second-order waves with arbitrary directionality. Though the modelling of second-order waves adds significant computational cost relative to linear waves, it was determined that the steep waves that lead to dynamic-stability events are best captured by a second-order model. It is believed that the pressure and particle-velocity profiles obtained from the second-order model, while requiring additional validation, are more accurate than linear waves with Wheeler stretching in the "surf zone" above $z = 0$.

To alleviate some of the computational cost, FFT techniques are used to accelerate the computations. An additional feature of the TEMPEST wave model is the availability of an integral-equation iterative solution in the special case of unidirectional seas to find the linear input spectrum, when given the target second-order spectrum.

Long-term solutions may include a higher-order wave model that solves for the evolving wave field. This may significantly increase computational time, but may be necessary if the pressures and velocities are found not to be accurate enough in the steepest waves using lower-order wave models.

Wind The TEMPEST ambient wind environment model defines the vertical wind speed profile above the free surface at any point in space and time. The notable attribute of the TEMPEST wind model is that it attempts to account for the effects of shadowing near large steep waves. This model is currently in development using environmental data obtained from a North Sea oil rig.

Hydrodynamic Forces

The hydrodynamic forces acting on the ship are composed of:

- Hydrostatic & Froude-Krylov
- Hydrodynamic disturbance (radiation & diffraction)
- Green water on deck
- Resistance
- Bilge-keel
- Hull circulatory lift and cross-flow drag
- Propeller
- Rudder
- Wind

In all the force components, the effect of geometric nonlinearity is included by accounting for the position of the hull and appendages relative to the incident waves.

Froude-Krylov and Hydrostatic Forces The Froude-Krylov and hydrostatic forces are obtained by integrating the ambient-wave dynamic and static pressures, respectively, over the instantaneously wetted hull. The wetted hull is determined by the position of the ship and the undisturbed incident wave. To best capture the longitudinal force, the pressures are evaluated on 3D panels. An illustration of the body-exact Froude-Krylov plus hydrostatic pressure on a 3D mesh is given in Figure 6.

Hydrodynamic-Disturbance Forces The force that captures the traditional seakeeping radiation and diffraction forces is the hydrodynamic-disturbance force. TEMPEST obtains this disturbance force by solving the time-domain potential-flow boundary-value problem on the time-changing wetted surface of the hull. The conclusion of the theory development team was that applying a slender-ship approximation would still capture the dominant physics while allowing the computations to occur at or near "real-time" speed. The theory behind this approach is given in a report to be published by Sclavounos, *et al*. (2010).

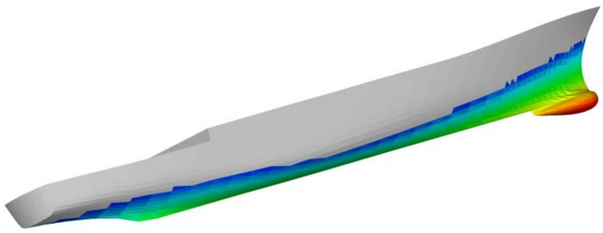
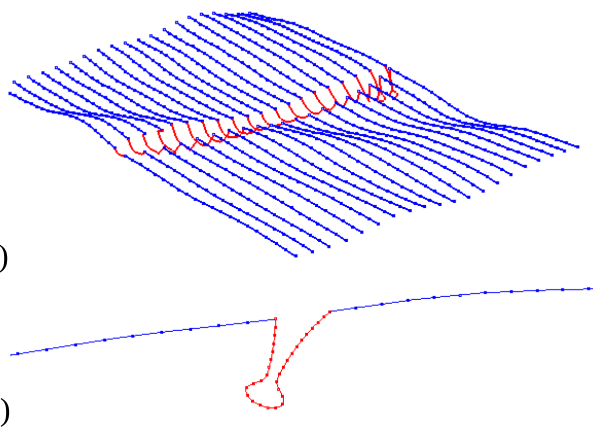


Figure 6: Sample ambient-wave pressure on a 3D meshed hull

The body-exact hydrodynamic disturbance solution in TEMPEST is being implemented in a two-phase process. In Phase 1, a strictly 2D approach is taken via a body-exact strip theory. Phase 2 implements a slender-ship theory, built upon body-exact strip theory that incorporates 3D effects.

The body-exact strip theory in Phase 1 follows the theoretical and numerical approach presented by Bandyk (2009). In this approach, impulsive and wave-memory problems are solved on 2D strips at each time step, an example of which is shown in Figure 7. The boundary value problem is numerically solved by a 2D Rankine panel method where the body section has sources distributed on 2D panels and the free surface uses desingularized panels. An example of this is shown in Figure 8. Memory effects are automatically captured in the solution of the free-surface panels' source strengths.

In the Phase 2 hydrodynamic-disturbance potential solution, 3D effects are added through the use of a 3D time-domain Green function that operates on the impulsive source strengths determined on 2D sections. While this approach is presumably more computationally intensive than the body-exact strip theory, it may include 3D effects that are significant to the dynamic-stability problem. In this approach, as opposed to the body-exact strip theory in Phase 1, the wave-memory effects are obtained through evaluations of convolution integrals within the Green function. To address the computational burden, efficiency may be gained by simplifying the convolution integral functions and/or determining equivalent impulsive source-dipole line distributions within the interior of the wetted hull.



a)

b)

Figure 7: Illustration of the body-exact strip theory problem for a) the entire ship, and b) a single 2D section.

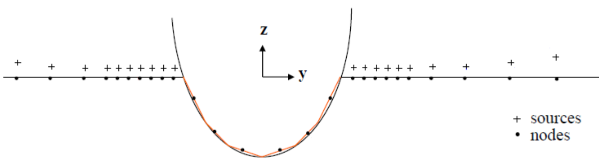


Figure 8: Numerical solution of the time-domain boundary value problem for an example section (from Bandyk (2009)).

In both implementations of the body-exact hydrodynamic-disturbance problem, the force can be calculated from the velocity potentials through pressure integration or a momentum formulation. Calculating pressure for the 2D problem involves the difficult task of determining *x*-derivatives. Bandyk (2009) describes the use of radial-basis functions to overcome this difficulty. The momentum formulation (see Sclavounos, *et al*. 2010) simplifies the force evaluation by requiring only a time-derivative on the integrated potentials.

Finally, hydrodynamic-drift forces that arise from the disturbed free-surface elevation are included. This is done in a simplified manner by evaluating a waterline integral that provides a hydrostatic correction due to the disturbance-wave elevation around the hull.

<u>Green Water on Deck</u> To account for the physics of deck submergence and re-emergence, a semi-empirical green-water model is included. This model has been implemented and successfully tested in LAMP (Liut, *et al*. 2002). This model uses empirical relationships to get water height on deck given the deck-edge exceedence following Zhou, *et al*. (1999). A notable attribute of this model is that it does not capture the lag in elevation across the deck due to the flow of water on and off the deck. However, until it can be shown that the lag effect is important to the dynamic-stability problem, computational efficiency requirements dictate the use of the semi-empirical model.

<u>Ship Resistance</u> The TEMPEST resistance model uses a user-supplied resistance curve with the wave drag removed via a series of speed-calibration runs. The calibration runs remove any double-counting with the hydrodynamic disturbance force. To account for body nonlinearity, the resistance curve is modified to account for the instantaneous wetted surface. The quasi-steady resistance is then obtained based on the instantaneous velocity through the water which includes the influence of wave orbital velocities.

<u>Bilge-Keel Forces</u> Low-aspect-ratio lifting-surface theory is the foundation of the TEMPEST bilge-keel force model (cf, Greeley & Peterson, 2010). The work of Bollay (1936) inspired the model by showing that the trailing vortex sheet comes off the edge of the surface at an angle equal to half the angle of attack. By prescribing this trajectory of a trailing vortex sheet, a vortex-lattice method can be used to solve for the circulation strength and determine the (quasi) steady and unsteady forces due to lift. This method breaks down at angles of attack greater than about 50 (generally low-ship-speed conditions) where there is no true lift, so a Morison equation-based model is used. An "instantaneous" Keulegan-Carpenter (KC) number is estimated through the use of a short-time spectral analysis of normal velocity using a discrete Fourier transform. In large amplitude roll cases, the effect of the bilge keels piercing the free surface is captured by means of a piece-wise damping model that accounts for various pieces of the hull entering and leaving the water (Bassler, *et al*., 2010).

<u>Hull Lift and Cross-Flow Drag</u> Similar to the hydrodynamic disturbance force, the hull lift and cross-flow drag force model is being implemented in a two-phase manner. The initial model uses low-aspect-ratio lifting-surface theory to estimate time-changing (due to waves and motion) side force and yaw moment coefficients. These coefficients are calibrated based upon user-supplied coefficients. This lift force is phased out over increasing drift angle, β, through a $\cos^2 \beta$ multiplier that approximates stall. A cross-flow drag force is also calculated at each section for the time-changing geometry. This force follows a $\sin^2 \beta$ behavior due to the fact that the only influence is the square of the cross-flow velocity. The cross-flow drag coefficients can be user-supplied or estimated based on shape coefficients. Reynolds number dependence of cross-flow drag coefficients is included.

The second phase of the hull lift and cross-flow drag force model implementation will apply the vortex-lattice techniques developed for the bilge-keel force model.

<u>Propeller Forces</u> The propeller forces are included as external forces to the hull. The key attribute of the TEMPEST propeller-force model is that it includes not just the axial force but also side forces when the inflow velocity provides an angle of attack to the propeller.

The inflow velocity includes the effects of body velocity (including rotations), wave orbital velocities, and an estimate of the viscous wake due to the presence of the hull.

The forces developed by the propellers due to the time-varying inflow are determined by a blade-element model. The blade-element model will properly account for partial or full emergence of the propeller. Pending more study, scale effects may be included to account for lost of thrust due to cavitation

Rudder Forces The TEMPEST rudder-force model provides the forces due to lift and drag only. The contribution to the radiation and diffraction problem is not considered. To account for body-nonlinearity, the rudder force is scaled by the immersed area of the rudder.

Wind Forces Wind forces are determined on the hull following a horizontal strip-theory approach similar to that given by Gould (1982). The benefit to a strip-theory approach is that it allows the use of an arbitrary wind-speed profile while still taking advantage of calibrated wind-drag and moment coefficients. Given the need to include non-traditional wind profiles due to the local presence of large, steep waves, such an approach is necessary.

CONCLUSIONS

TEMPEST is a new dynamic-stability simulation tool currently in development by the US Navy. The requirements of the tool are accuracy and computational speed.

After careful study of the physical problem, a comprehensive set of environment and force models has been described that is expected to provide a viable solution to the dynamic-stability prediction problem that advances the state-of-the-art. The fundamental argument behind the TEMPEST approach is the requirement for body-nonlinearity in all force models, including the hydrodynamic-disturbance force (radiation and diffraction).

The TEMPEST development will be followed by extensive validation at the component level and as a system.

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REFERENCES

Bandyk, P. (2009) A Body-Exact Strip Theory Approach to Ship-Motion Computations. Ph.D. Thesis, Univ. Michigan, Dept. Naval Architecture and Marine Engineering.

Bassler, C. C., A. M. Reed & A. J. Brown (2010) A Method to Model Large-Amplitude Ship Roll Damping. *Proc. 11th Int'l Ship Stability Workshop*, 10 p.

Beck, R. F. & A. M. Reed (2001) Modern Computational Methods for Ships in a Seaway. *Trans. SNAME*, 109:1–51.

Belknap W. & J. Telste (2008) Identification of Leading Order Nonlinearities from Numerical Forced Motion Experiment Results. *Proc. 27th Symp. Naval Hydro.*, Seoul, Korea, 18 p.

Bollay, W. (1936) A New Theory for Wings with Small-Aspect Ratio. Ph.D. Thesis, Caltech, ii+86 p.

de Kat, J. O. & J. R. Paulling (1989) The simulation of ship motions and capsizing in severe seas. *Trans. SNAME*, 97:139–68.

Gould, R. W. F. (1982) *The Estimation of Wind Loads on Ship Superstructures*, Maritime Technology Monograph No. 8, The Royal Institution of Naval Architects.

Greeley, D. S. & B. J. Petersen (2010) Efficient Time-Domain Computation of Bilge Keel Forces. *Proc. 28th Symp. Naval Hydro.*, Pasadena, CA, 17 p.

Gudmestad, O. T. (1993) Measured and Predicted Deep Water Wave Kinematics in Regular and Irregular Seas. *Marine Structures*, **6**:1–73.

Liut, D. A., K. M. Weems, and W. M. Lin (2002) Nonlinear Green Water Effects on Ship Motions and Structural Loads. *Proc. 24th Symp. Naval Hydro.*, Fukuoka, Japan.

Reed, A. M. (2009) A Naval Perspective on Ship Stability, *Proc. 10th Intl. Conf. Stability of Ships and Ocean Vehicles*, St. Petersburg, Russia.

Sclavounos, P. D., J. G. Telste & A. M. Reed (2010) Nonlinear Response Modeling of a Vessel in Steep Random Waves. Carderock Division, Naval Surface Warfare Center Report NSWCCD-50-TR–2010/039.

Skejic, R. & O. M. Faltinsen (2008) A unified seakeeping and maneuvering analysis of ships in regular waves. *J. Mar. Sci. Tech.*, 13:371-394., DOl 10.1007/s00773-008-0025-2

Stansberg, C. T., O. T. Gudmestad & S. K. Haver (2008) Kinematics under Extreme Waves. *J. Offshore Mechanics and Arctic Engineering*, 130(2) 020201.1–021013.8.

Stokes, G. G. (1847) On the theory of oscillatory waves, *Trans. Cambridge Philosophical Society*, Vol. 8, Part IV, No. XXXIII, pp. 441–455.

Telste, J. G. & W. F. Belknap (2008) Potential Flow Forces and Moments from Selected Ship Flow Codes in a Set of Numerical Experiments. Carderock Division, Naval Surface Warfare Center Report NSWCCD-50-TR–2008/040, 15,240 p.

Vassalos, D., M. Hamamoto, J. O. de Kat, D. Molyneux & A. Papanikolaou, (1998) The State of the Art in Modelling Ship Stability in Waves, Proc. 25th ATTC, Iowa City, Iowa, 8 p.

Wheeler, J. D. (1970) Method for calculating forces produced by irregular waves. *J. Petroleum Technol.*, **249**:359–367.

Zhou, Z.Q., J. O. De Kat, and B. Buchner (1999) A Nonlinear 3-D Approach to Simulate Green Water Dynamics on Deck, *Proc. 7th Int'l Conf. Numerical Ship Hydro.*, Nantes, France.