Some Results from a New Time-Domain Bilge Keel Force Model

David S. Greeley
Applied Physical Sciences Corporation

ABSTRACT
A new non-linear, time domain bilge keel force model was recently developed for inclusion in the new time-domain seakeeping/maneuvering in waves code TEMPEST, being developed by NSWCCD. This bilge keel force model combines a full unsteady extension of Bollay's non-linear low aspect ratio lifting surface theory for cases with adequate forward speed with a more conventional approach for cases with zero or low forward speed, using Morison's equation. This paper presents some representative results from the new bilge keel force model for a surface combatant for various roll amplitudes, roll periods, and forward speeds.

KEYWORDS
Bilge-keel forces; time-domain seakeeping ; unsteady lifting surface theory

INTRODUCTION

The calculation of forces on ship bilge keels continues to be a challenging but important aspect of ship hydrodynamics, because of the large effect of these forces on rolling, and the consequent possibility of capsizing and loss of the ship. In the past, the estimation of these forces for ship motion simulations has traditionally relied on experimental data, and semi-empirical techniques derived largely from experimental data (Himeno 1981). More recently, an assault on this problem using modern computational techniques has begun to bear fruit. Before getting to the results which are central to this paper, it is worthwhile to review some "big-picture" aspects of the forces on bilge keels:

1) Except for some exceptional cases such as yaw or rudder-induced rolling, ships roll because of the excitation from incident waves in the ocean. It is obvious from first principles that the forces on the bilge keels are not dependent strictly on the roll and roll rate (or even complicated functions of these variables alone!), but rather on the relative motion between the bilge keels and the water. This relative motion includes *all* motions of the ship, the forward speed of the ship, the incident wave orbital velocities, and the velocities associated with the wave diffraction, the body radiation, and the steady waves generated by the ship. It makes little sense to get completely caught up with an elaborate analysis and fancy curve fits of free roll decay data from a still water model test (either stationary or with forward speed) in an attempt to discern new "physics" of rolling in a seaway, when this relative motion situation is ignored. A thorough analysis may someday indicate exactly under what conditions the relative motion problem may be ignored and roll decay data obtained from still water roll decay data constitutes the "right" input to a seakeeping code, but to the author's knowledge no such analysis has yet been done. The relative motion is largely ignored today because the tools to handle it are just being developed.

2) Ship motion researchers commonly refer to possible hydrodyamic "memory" in a seakeeping problem as being associated only with free surface waves. However, unsteady shed vorticity (associated with time-varying circulation) also constitutes a powerful mechanism for hydrodynamic "memory". In the case of bilge keels, if it is assumed that only "linear" lift is generated (where the trailing vorticity is shed only from the trailing edge), this shed vorticity will have minimal impact. However, numerous URANS calculations and PIV measurements (Irvine 2006) have shown that for low aspect ratio bilge keels, trailing vorticity is shed from the entire *side* edge of the bilge keel, and this shed vorticity has a *large* impact on the forces developed on the middle and aft parts of the bilge keel. Bilge keel force models for zero or low forward speed that use the Morison equation

implicitly capture this memory effect, in that the data used in the Morison equation depends on the history of the flow through the Keulegan-Carpenter parameter. For the situation with forward speed, either URANS calculations or an unsteady lifting surface theory that explicitly deals with side edge vortex shedding and the correct accounting for unsteady shed vorticity is necessary to capture this memory effect. The memory is dependent on all of the past motions of the ship and the incident waves, not just roll motion.

3) It is common to recognize that bilge keels contribute to the added roll moment of inertia of the ship. It is also common to assume that this contribution is constant and may be easily estimated from the added mass of a 2D flat plate. However, if one uses a zero speed bilge keel force model based on the Morison equation, then the effect of shed vorticity on the bilge keel added mass (ship roll moment of inertia) is implicitly included because of the dependence of the inertia coefficient in the Morison equation on the Keulegan-Carpenter parameter. In the case with forward speed, the situation is more complicated and the added moment of inertia of the bilge keels, like the lifting forces which contribute to roll damping, are in fact dependent on the history of the motion because of the unsteady shed vorticity.

4) It is typical within the ship motion community to refer to any force that cannot be modeled in a potential flow sense with a single-valued velocity potential as a "viscous" force. This implies, especially to newcomers to the field, that these forces can only be addressed in the context of RANS or URANS calculations. Obvious examples are the side force and yaw moment on a yawed ship hull, and the forces on bilge keels. This is tantamount to ignoring all of the excellent work for calculating lifting potential flows about arbitary bodies done by John Hess and others, starting in the 1970's (Hess 1972), which became the main aerodynamic design tool for airplanes until Euler and RANS techniques supplanted them because these new techniques could deal with Mach numbers approaching or exceeding 1. In fact, many (but certainly not all) situations in ship hydrodynamics are perfect for the application of lifting potential flow techniques: a) high Reynods numbers, b) low Mach numbers, and c) sharp edges which fix flow separation locations. It is the author's opinion that the community would be better served if "lifting forces" were clearly differentiated from true "viscous" forces.

5) For large roll angles, which are the most important to consider when considering ship safety, bilge keel interactions with the free surface are a distinct possibilty, even to extent of partial or complete bilge keel emergence. It is almost certainly more important to try to account for this effect, at least approximately, than to get into protracted arguments about the correct functional form of the bilge keel damping for high roll angles so that low roll angle data may be extrapolated to high roll angles.

6) Many of the considerations above argue for a time-domain treatment of the bilge keel force problem, in order to handle the inherent non-linearities and memory effects. Much current effort, including the author's, is in this direction. However, recognizing the usefulness of frequency-domain seakeeping calculations, it would be worthwhile to see if current and future advancements in time-domain calculations could be transferred to the frequency domain, perhaps using harmonic balance techniques.

NEW BILGE KEEL FORCE MODEL

In (Greeley 2010a) a new time-domain bilge keel force model was presented, which was developed to be incorporated into the US Navy's new seakeeping / maneuvering in waves code TEMPEST (Belknap 2010). The main constraint on this new force model, besides the obvious requirement for maximum accuracy, was that it execute quickly so that the final TEMPEST code could run in near real-time. This obviously meant that URANS approaches could not be considered. In the end, a hybrid time-domain force model was developed that is based on the relative motion between the bilge keel and the water (as described above), and consists of two components:

1) For zero or low forward speeds, where the unsteady angle of attack of the bilge keels exceeds 45 degrees, the force model uses the Morison equation with the empirical database for flat plates in unsteady flow presented by Sarpkaya

(2006). Two different techniques were developed and evaluated for determing the Keulegan-Carpenter parameter from the relative motion history, which is a necessary input to the Morisson equation database.

2) For those situations with forward speed where the angle of attack of the bilge keel is 45 degrees or less, Bollay's theory (Bollay 1936) for low aspect ratio wings was extended for unsteady flow with an arbitrary distribution (in time and space) of normal and tangential onset velocities to the bilge keel. The vorticity, which is assumed to be continuously shed from the *side* edge (as well as the trailing edge) of the bilge keel according to Bollay's theory, is rigorously accounted for in an unsteady lifting surface fashion, and the full non-linear Bernoulli equation is used to compute the forces on the bilge keel. This model has been demonstrated to closely replicate URANS force results, even at an unsteady angle of attack of 24 degrees.

The final bilge keel model (Greeley 2010b) contains the above two modules, all appropriate logic to switch between the force modules as appropriate, and a model for the unsteady pressure forces (due to bilge keel action) acting on the hull surface (which uses the exact shape of the hull adjacent to the bilge keels). In addition, the final model includes an approximate but physically-based model for the change in bilge keel forces as a bilge keel emerges from the water, and a model for the slam forces on the bilge keel as it re-enters the water.

This new bilge keel force model is currently being implemented into TEMPEST by the TEMPEST team, so no results are yet available from the new bilge keel model actually used with TEMPEST. We present below some computations using the new bilge keel force model for a ship rolling in calm water.

EXAMPLE CALCULATIONS

The case chosen for the example calculations presented here is the U.S Navy pre-contract DDG-51 hull form, as represented by NSWCCD model 5415. This hull form has been widely studied around the world. In particular, Miller (2008) has presented calm water roll decay measurements (at Fr=0.0 and Fr=0.280) for Model 5415 and corresponding CFD results, done using CFDShip-Iowa. These results were presented at model scale so that the experiments and CFD computations could be compared directly; we have done our example computations at ship scale, but we present the results in terms of non-dimensonal coefficients so that model and full size results may be compared directly. The major results that we will use for comparison are roll decay coefficient versus average roll angle and roll period versus cycle number, as shown in their Figure 9 (reproduced below as Figure 1).

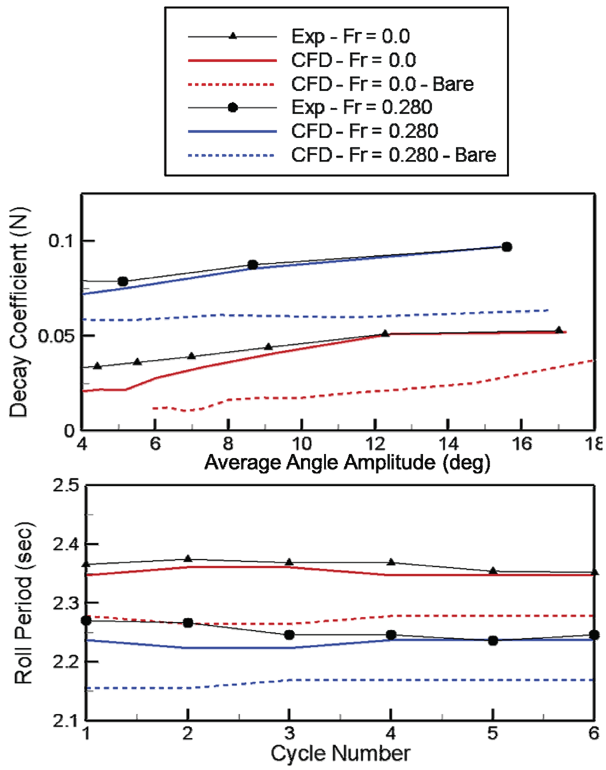

Fig. 1: Decay Coefficient and Roll Period for DTMB Model 5415 (from Miller 2008) (scale ratio = 24.84)

The excellent match between CFD and experiment (at the higher roll angles) allows one to have confidence in the contributions of the bilge keels to the motions, as determined by the difference in CFD computed motions with and without bilge keels. From the data presented, we can pick off the difference in roll decay coefficient due to the bilge keels, and the difference in roll period due to the bilge keels. For convenience, these values have been converted to equivalent linear damping coefficients b_{44} and added moment of inertia coefficients a_{44}, and we present here their non-dimensional forms as recommended by Himeno (1981):

$$a_{44}' = \frac{a_{44}}{\rho \nabla B^2} \quad (9)$$

$$b_{44}' = \frac{b_{44}}{\rho \nabla B^2 \sqrt{\frac{2g}{B}}} \quad (10)$$

where B is the beam of the ship, and g is the acceleration due to gravity. These coefficients are terms in the single degree of freedom equation for the roll of the ship:

$$(I_{44} + a_{44})\ddot{\phi} + b_{44}\dot{\phi} + c_{44}\phi = M(t) \quad (11)$$

The inflow to the bilge keel for our example calculations is determined by using a lifting potential flow model, following the work of Hess (1972). The hull surface is paneled using source panels to enforce the zero normal velocity boundary condition on the ship hull, and an interior vortex lattice system is used to represent the lifting action of the sonar dome and hull. A non-linear, equal pressure Kutta condition is applied at the trailing edge of the sonar dome and skeg in order to determine the strengths of the interior vortex lattice system. Because the rolling motion considered is of relatively high frequency, the best approximation of the free surface available in this potential flow calculation is that the calm water surface be considered a plane of zero perturbation potential (Newman 1977): this may be realized by using a negative image above the waterplane for all of the singularities representing the hull.

The bilge keel calculations for each operating condition were done by computing the starboard bilge keel inflow (both tangential and normal velocity distributions along the bilge keel) for a series of roll angles and roll velocities corresponding to one sinusoidal roll cycle, using these velocities to "drive" the new bilge keel force model for several cycles to ensure that the hydrodynamic memory effects associated with the shed vorticity had reached a steady sinusoidal pattern, and then analyzing the force results for the last complete roll cycle in the calculations. Both the normal pressures on the bilge keel and the computed pressures acting on the nearby hull were used to compute the bilge keel roll moments, to be consistent with the previously mentioned CFD computations. A typical plot of the computed roll moments (for the starboard bilge keel only) is shown below.

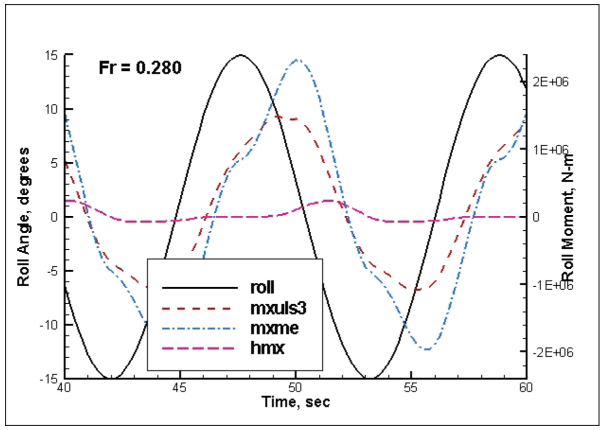

Fig. 2: Computed Starboard Bilge Keel Roll Moments at Froude No. = 0.280 (full scale)

Figure 2 shows the roll angle, the bilge keel roll moment from the unsteady lifting surface subroutine (mxuls3) which is the correct roll moment to use in this case, the corresponding roll moment if just the zero-forward-speed Morison equation were used (mxme), as well as the computed roll moment due to bilge-keel induced pressures on the hull (hmx). As is well known, the bilge keel forces decrease with forward speed, so the unsteady lifting surface computation shows a smaller roll moment at this medium Froude number than the zero-forward-speed Morison equation would indicate.

The computed roll moments versus time were then least squares fitted with a model with 4 terms: one for the added moment of inertia, and 3 for the roll damping moment assuming that the roll damping can be expressed in the following form (Himeno 1981):

$$b_{44}(\dot{\phi}) = b_1\dot{\phi} + b_2\dot{\phi}\left|\dot{\phi}\right| + b_3\dot{\phi}^3 \quad (12)$$

The equivalent linear damping for this Froude number, roll frequency, and roll angle amplitude is then computed from these three components and used to compute the final b_{44}:

$$b_e(Fr,\omega,\phi_A) = b_1 + \frac{8}{3\pi}\omega\phi_A b_2 + \frac{3}{4}\omega^2\phi_A^2 b_3 \qquad (13)$$

$$b_{44} = b_e(Fr,\omega,\phi_A) \qquad (14)$$

Figure 3 shows the computed bilge keel contribution to the added moment of inertia and equivalent linear damping coefficients for the DDG-51 hull form at various Froude numbers, for a roll amplitude of 15 degrees and a full scale roll period of 11.2 seconds. The added moments of inertia due to the bilge keels inferred from the data of Miller (2008) are two to three times the values shown in Figure 3. The reason for this large discrepancy is unknown at present – it may be related to fact that during the experimental work and CFD computations, the model was forced to oscillate about its center of gravity. With the coupling of roll and sway due to added mass terms, perhaps a two degree of freedom model (roll and sway) is required to model the forced roll experiment and the influence of the bilge keels on the added moment of inertia in a meaningful way. In any event, this large discrepancy requires more study in the future.

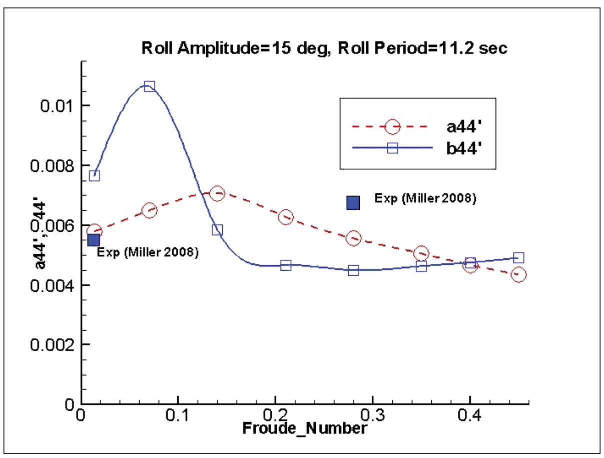

Fig. 3: Computed Bilge Keel Contribution to Added Moment of Inertia and Equivalent Linear Damping

Two experimental/CFD data points for the non-dimensional bilge keel damping are also shown in Figure 3 – these were deduced from the experimental / CFD results for the model shown in Figure 1. A perfect match between the current bilge keel model calculations and these points should not be expected, given the approximate nature of the bilge keel inflow calculations (not having a proper representation of the free surface in the hull potential flow computations). Still, the reasonable agreement for the bilge keel damping values is encouraging.

The most unusual feature of the predicted damping due to the bilge keels shown in Figure 3 is the large increase in damping expected at Fr=0.07. This comes right out of the unsteady lifting surface model. This lifting surface model, since it only responds to the normal and tangential velocities supplied to it, does not care about the actual Froude number. Rather, this Froude number of 0.07 with a roll amplitude of 15 degrees and roll period of 11.2 seconds happens to correspond to an unsteady angle of attack and reduced frequency combination at which the vorticity shed from the side edges of the bilge keel on the forward third of the bilge keel has a *huge* impact on the load experienced on the after half of the bilge keel – the biggest computed unsteady pressures on the bilge keel are in fact near 75% chord! This kind of hump in the bilge keel damping is not expected according to generally used bilge keel force models or seen in most model testing. In fact, there is sometimes a dip seen in the bilge keel damping in this Froude number region. However, Irvine (2006) shows large scale effects on bilge keel forces in this Froude number range for geosims of Model 5415 tested at various facilities, with the smaller models showing significantly less damping than the larger models, so there are a number of issues that need examing here: 1) re-examination and possible additional testing and CFD runs for this Froude number (reduced frequency) range, and 2) comparison (if possible) between model scale predicted roll damping and full scale ship roll damping in this Froude number range to make sure we understand the nature of possible scale effects, and possible shortcomings in the unsteady lifting surface model as currently implemented.

Additional computions with the new bilge keel model were done to look at variations in roll amplitude and roll period (for the full scale ship). Figure 4 shows the computed variation in a_{44} and b_{44} with roll period for a Froude number of 0.280 and a roll amplitude of 15 degrees, while Figure 5 shows a similar variation with roll amplitude for Froude number=0.280 and a roll period of 11.2 sec (full scale). As expected, since the roll damping actually has a large quadratic and cubic component, the equivalent linear damping is a strong function of roll angle.

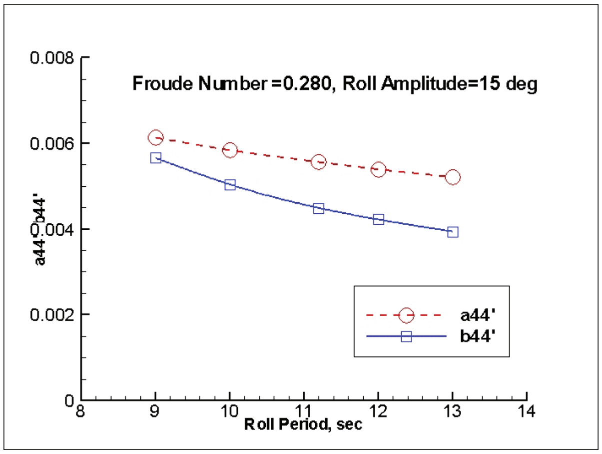

Fig. 4: Variation in Bilge Keel Parameters with Roll Period (full scale)

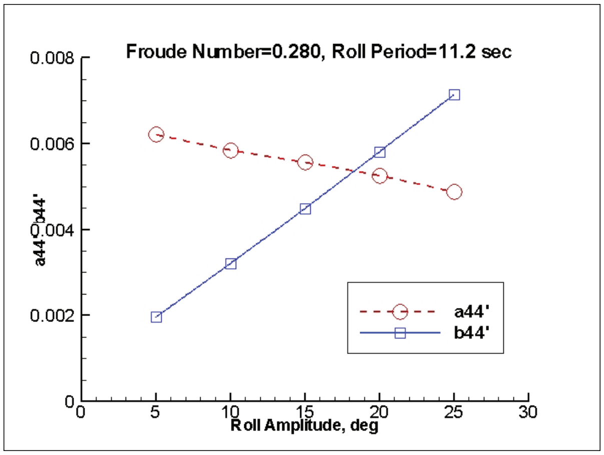

Fig. 5: Variation of Bilge Keel Parameters with Maximum Roll Angle (full scale)

CONCLUSIONS

Some example calculations from a new time-domain bilge keel force model have been presented and an attempt has been made to compare the results from this model with existing experimental and CFD results for DTMB Model 5415. Some encouraging agreement with existing experimental and CFD data has been obtained even with approximate calculations of the bilge keel inflow, but questions about the bilge keel force behavior, especially possible scale effects near a Froude number of 0.07, require further investigation. The interpretation of bilge keel added mass effects in the context of roll experiments where the roll axis passes through the center of gravity (regardless of added mass effects) also requires a re-examination.

ACKNOWLEDGEMENTS

The development of the bilge keel model referred to in this paper was done initially with support from NAVSEA SE/TA funds (James Webster, Program Manager) and later support from ONR (Dr. Pat Purtell, Program Manager). Dr. William Belknap and Dr. Arthur Reed at NSWCCD were the technical monitors for the development of this bilge keel model. Simmy Willemann and Brian Petersen of APS assisted with the calculations shown in this paper. The opinions expressed here are those of the author.

REFERENCES

Belknap, W.F. and Reed, A.M. (2010), "TEMPEST – New Computationally Efficient Dynamic Stability Prediction Tool", 11th International Ship Stability Workshop, Wageningen, June 2010.

Bollay, W. (1936), "A New Theory for Wings of Small Aspect Ratio", Caltech Ph.D. thesis, Pasadena, CA, 1936.

Greeley, D.S. and Petersen, B.J (2010a), "Efficient Time-Domain Comptation of Bilge Keel Forces", 28th ONR Symposium on Naval Hydrodynamics, Pasadena, CA, September 2010.

Greeley, D.S. and Pertersen, B.J.(2010b), "TEMPEST Level III Bilge Keel Force Model Theory", Applied Physical Sciences Report, September 2010.

Hess, J.L. (1972), "Calculation of Potential Flow About Arbitrary Three-Dimensional Lifting Bodies", McDonnell-Douglas Report No. MDC J5679-01, October 1972.

Himeno, Y. (1981), "Prediction of Ship Roll Damping – State of the Art", University of Michigan Department of Naval Architecture and Marine Engineering Report No. 239, September 1981.

Irvine, M., Atsavapranee, P., Carneal, J. *et al* (2006), "Comparisons of Free Roll Decay Tests for Model DTMB 5415/2340/5512, and Investigation of Lateral Hydrodynamic Loads on Bilge Keels", 26th ONR Symposium on Naval Hydrodynamics, Rome, Italy, September 17-22, 2006.

Miller, R.W., Bassler, C.C., Atsavapranee, P. and Gorski, J.J., (2008), "Viscous Roll Predictions for Naval Surface Ships Appended with Bilge Keels using RANS", 27th Symposium on Naval Hydrodynamics, Seoul, Korea, 5-10 October 2008.

Newman, J.N. (1977), Marine Hydrodynamics, MIT Press.

Sarpkaya, T. and O'Keefe, J.L. (1996), "Oscillating Flow About Two and Three Dimensional Bilge Keels", Journal of Offshore Mechanics and Arctic Engineering, Vol. 118, February 1996.