BOAT3D Tech Notes 2010

A. Some comparisons of BOAT3D results with recent research published in the literature

In the *Technical Paper for BOAT3D* published on our web site in 2008 the basic concepts of BOAT3D are outlined. The equations for force of the water on the boat are not presented as derived from more basic physical concepts; they are simply a set of assumptions based on previous work (much of which goes deeper into the physical concepts) and logical adjustments based on observation of how the mathematical model compares with experiment. Comparisons are presented with tank-test data and other boat data to show that BOAT3D works for a wide range of cases.

In recent as well as 1990's and earlier literature theoretical and experimental results are presented for prismatic boat sections plunging directly downward into water. It is useful to test the BOAT3D equations against these results because then one does not have to deal with the large amount of geometric and other detail in the actual BOAT3D program. (The detail involves the conversion to a coordinate system moving along with a pitching and lunging non-prismatic boat.)

There are primarily two cases, first, a boat section being driven downward through the surface at constant speed, and second, a boat section being dropped in free fall until it hits the water surface and is slowed, stopped, and bobs upward again. The constant-speed case has been studied theoretically and the drop test case has been studied theoretically and experimentally. The constant-speed case is related to modeling a boat traveling along on smooth water, and the drop test is relevant for investigating slamming in rough water, where the boat is thrust upward, sometimes completely clear of the water, and falls back.

When BOAT3D is used to estimate the motion of a boat in moderate waves, it is estimating cases varying somewhere between smooth travel and slamming.

As discussed in the Technical Paper, the added mass concept is used with BOAT3D. If a theoretical or computational method is entirely independent of the added mass concept, and yet the BOAT3D equations give results in agreement with it, this lends support to the BOAT3D methodology. Support is also of course lent by any agreement with experimental results.

In the *Technical Paper for BOAT3D* the equation for the upward dynamic force on a boat segment assumed in BOAT3D is stated as

$$F_d = \Delta x \, (m' \, d\Delta v/dt + \Delta v \; dm'/dt) \qquad (1a)$$

if dm'/dt is equal or greater than zero and

$$F_d = \Delta x \;\, m' \, d\Delta v/dt \qquad (1b)$$

if dm'/dt is less than zero.

Here Δx is the length of the boat segment, m' is the added mass per segment length, and Δv is the difference in vertical velocity between the boat segment and the water level. For calm, stationary water Δv is just the vertical velocity of the boat segment; in all cases Δv is the rate at which the boat segment is being inserted into the water. For BOAT3D and a particular boat cross-section, there is a simplifying assumption that m' is a function only of the depth the segment is inserted into the water, and m' always increases with depth.

A bouyancy force, connected with a damping force, is also assumed:

$$F_b = \rho \, g \Delta x \, A \, (1 + k \, \Delta v) \qquad (2)$$

where A is the cross-sectional area submerged below the undisturbed water level, ρ is the density of water, and g is acceleration due to gravity. k is an "artificial damping coefficient". $F_d + F_b$ gives the total upward force resisting the downward motion of the prismatic boat section of length Δx plunging into the water. These equations are the basis for BOAT3D and can be used directly for the prismatic boat section dropping vertically downward, whereas in the actual BOAT3D program which models a non-prismatic boat moving forward, pitching, etc., they must be transformed and have many geometrical factors, etc, applied. In the results which were computed with these equations the values of m', A, and k for a particular boat cross-section were supplied directly (through a data file) from the actual BOAT3D program (and through the interpolation routine taken from BOAT3D) and the simulation of a drop test was done with our DMSolver general-purpose simulation system.

Relatively recent publications involving entry of prismatic sections vertically into water include Vorus (1996, theoretical), Kim et al (1997, experimental and use of the theory of Vorus), Yettou et al (2006, experimental and comparison with older theories), Lewis et al (2007, CFD computer simulation and comparison with Yettou et al), and Lewis et al (2010, experimental).

In his Figure 14 Vorus (1996) presents theoretical results for force coefficient for 3 differently-shaped boat sections entering the water at constant speed. In 2008 BOAT3D results were compared with these results and some adjustments made to BOAT3D parameters. Those BOAT3D results are shown again in Figure 1 below (see the 2008 report by Singleton for more details):

In 2008 BOAT3D results were not compared with Vorus' results for a boat section striking the water and slowed by the forces after impact. This is now done in figures 2 and 3 for forces: The definitions for force coefficient (C_f), dimensionless time (τ), and mass coefficient (C_M) in the Vorus (1996) paper were used to convert the BOAT3D/DMSolver results. The sudden step down in force that the plots show happens when the chines become wet, i.e. when the "spray root" reaches the chines. After chine wetting the force estimated by the BOAT3D/DMSolver computation tends to be somewhat higher than the Vorus theoretical prediction.

Figure 1 BOAT3D Added-mass Force-per-unit-length Coefficient VS Dimensionless Time
Constant velocity case

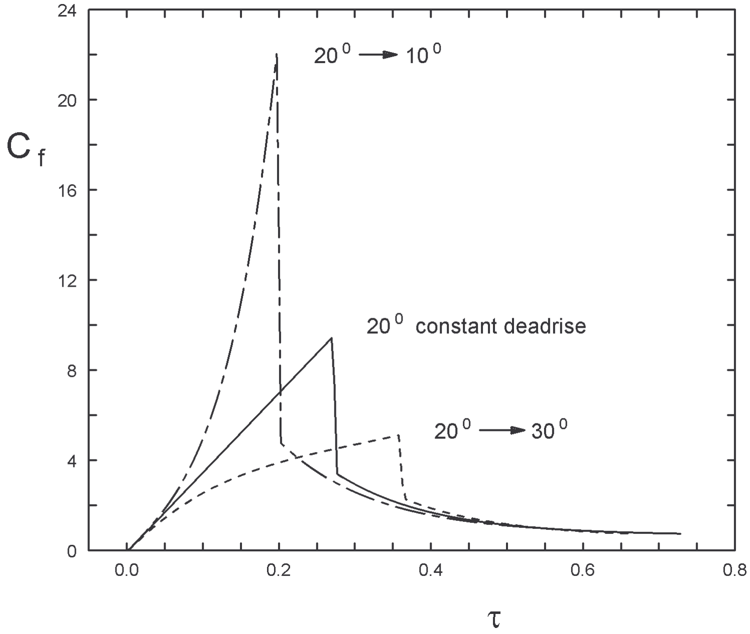


Figure 2 --- Comparison of force coefficients from BOAT3D/DMSolver and Vorus' analytical results for a 20-degree deadrise prismatic wedge in free-fall impact with water, case for $C_M = 0.3$.

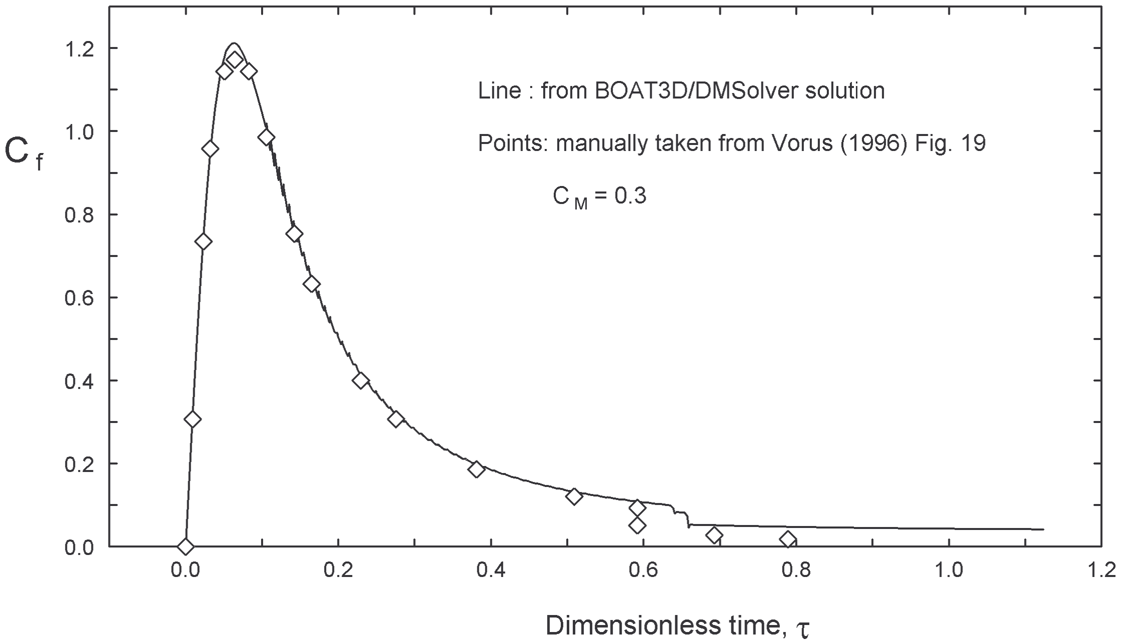
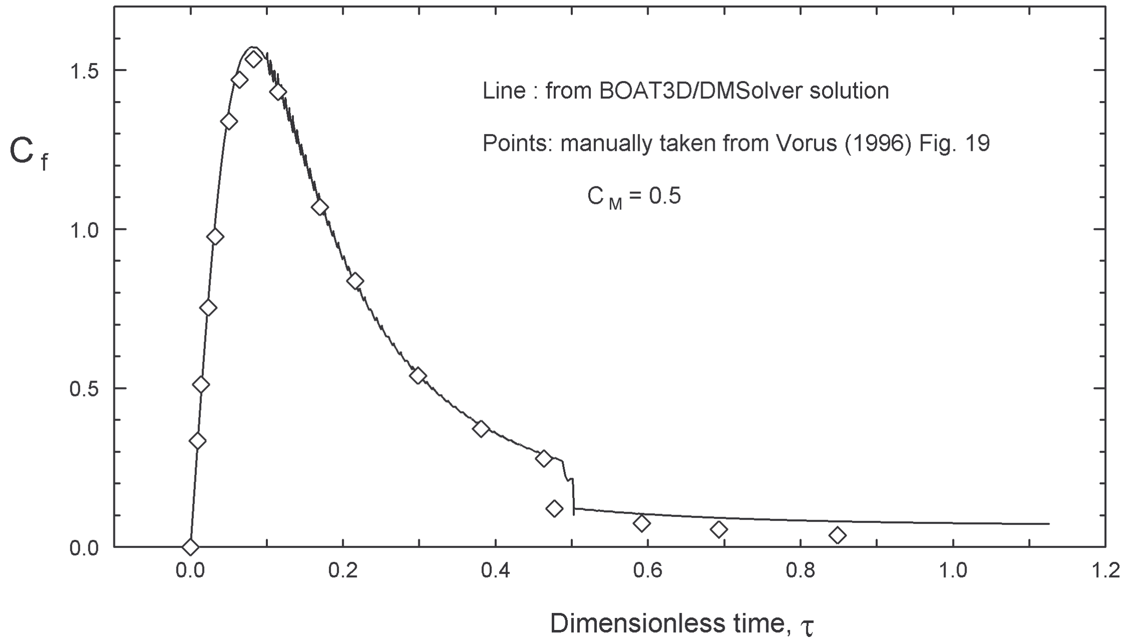


Figure 3 --- Comparison of force coefficients from BOAT3D/DMSolver and Vorus' analytical results for a 20-degree deadrise prismatic wedge in free-fall impact with water, case for $C_M = 0.5$



Vorus also presents plots of dimensionless velocity (relative to the velocity at τ = 0 when the keel first touches the water), and the equivalent BOAT3D/DMSolver values can be computed for comparison:

Figure 4 --- Comparison of BOAT3D/DMSolver results for a 20-degree deadrise prismatic wedge in free-fall impact with water, case for $C_M = 0.3$ (same case as Figure 2 above).

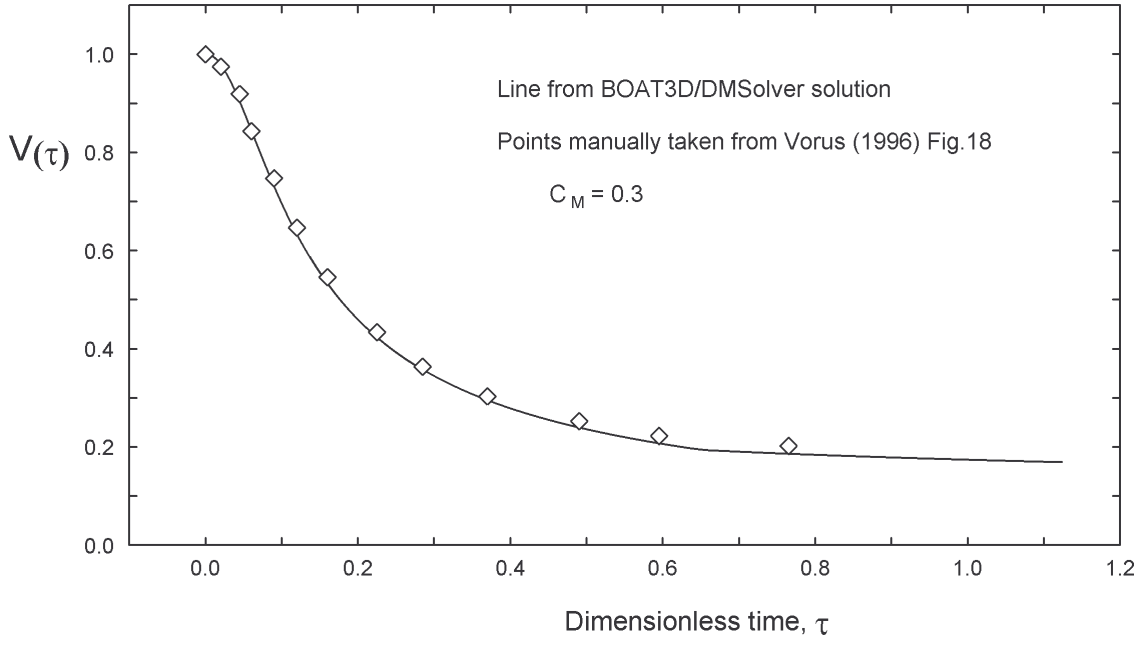
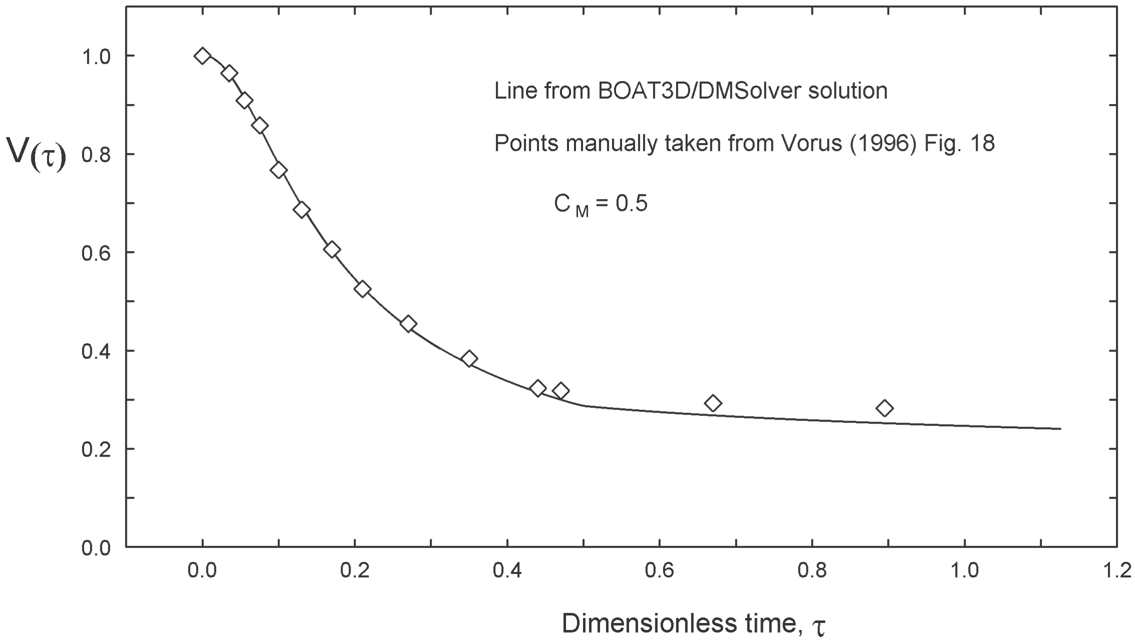


Figure 5 --- Comparison of BOAT3D/DMSolver results for a 20-degree deadrise prismatic wedge in free-fall impact with water, case for $C_M = 0.5$ (same case as Figure 3 above).



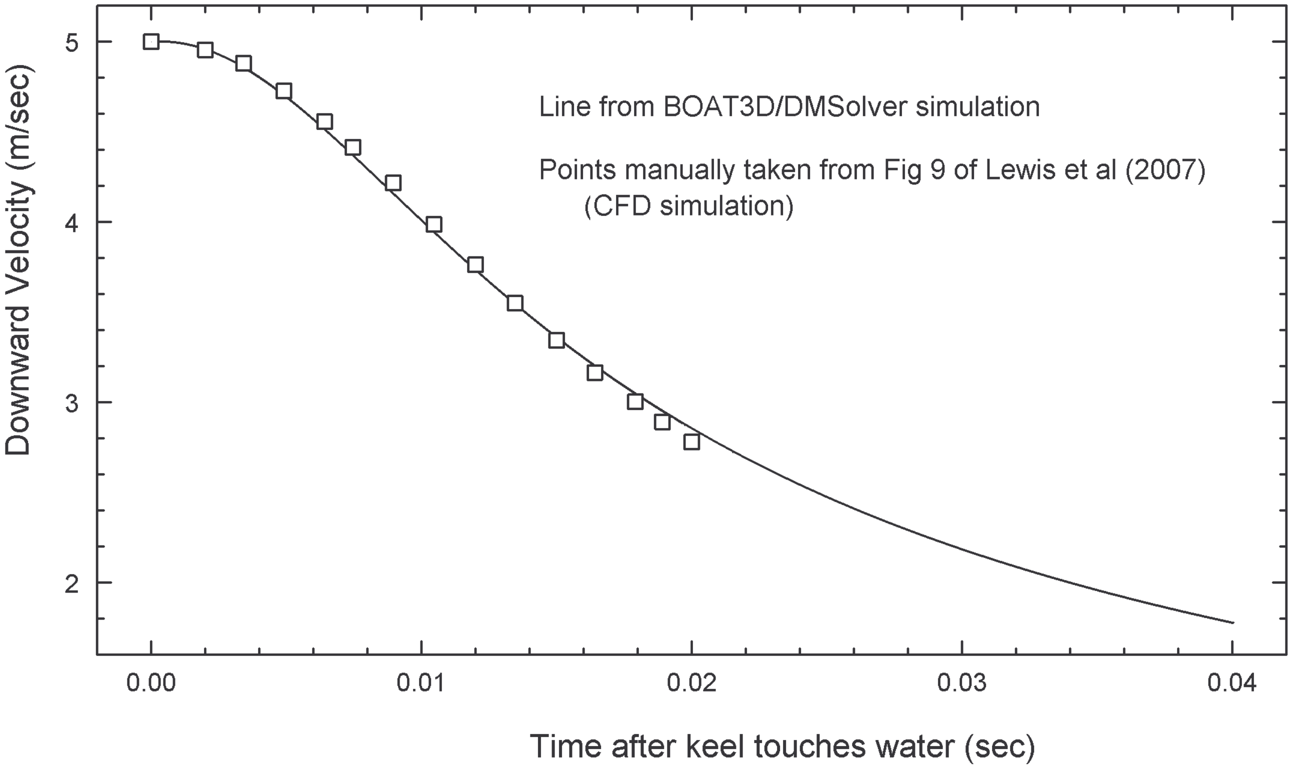
As with figures 2 and 3 the BOAT3D/DMSolver results are closest to the theoretical results by Vorus before the chines become wet, and deviate a bit more after. Thus the simpler BOAT3D mathematical model shows agreement with the more complex one of Vorus.

For figures 2 through 6 the reader should note that the points on the graphs were obtained by manually measuring points on the original authors' curves with a scale, and so there are errors which could occur in this process, and the choice of point spacing is somewhat arbitrary.

The other detailed physical/mathematical model compared with BOAT3D in this paper is the CFD analysis with a computational mesh surrounding a 25-degree-deadrise wedge by Lewis et al (2007). Figure 6 shows the simulated drop off of velocity after the wedge touches the water. The Lewis et al computation was not carried out all the way to a chines-wet state.

Figure 6

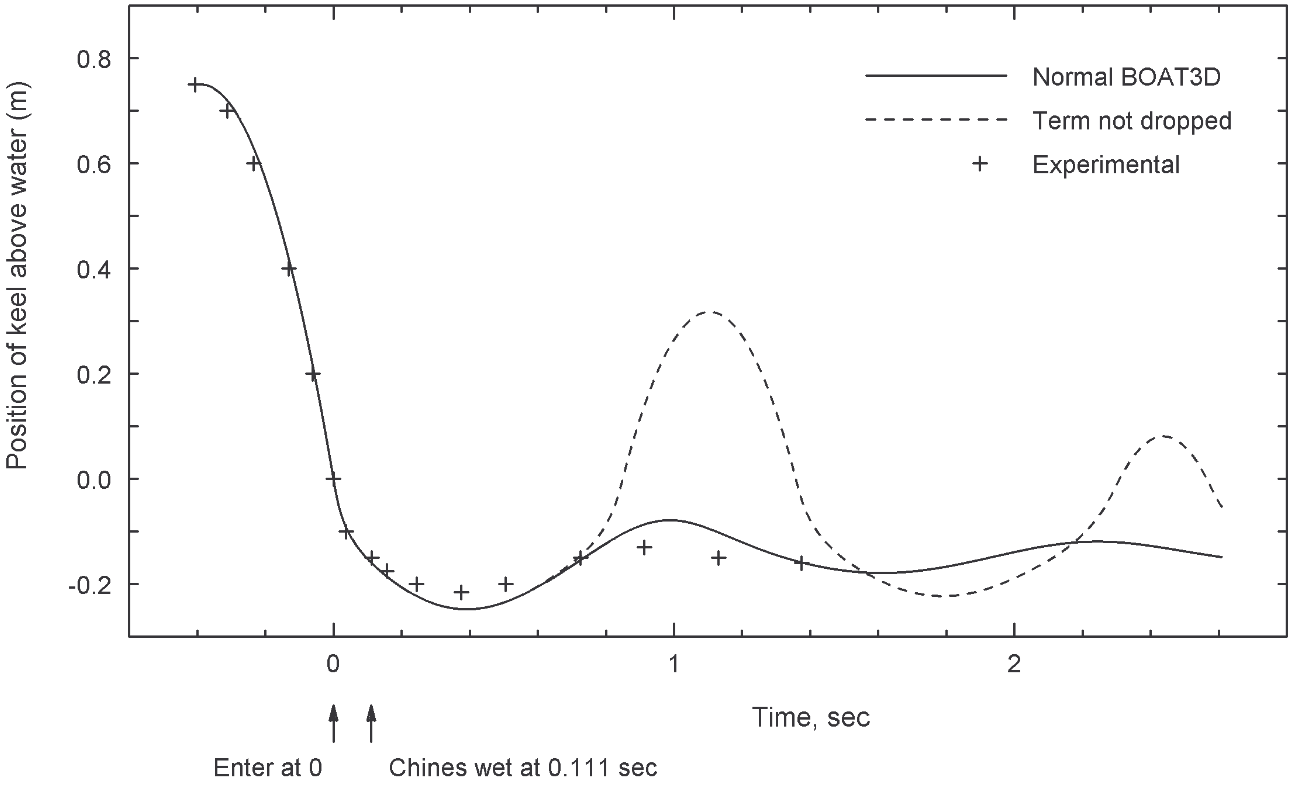
Comparison of BOAT3D/DMSolver results for a 25-degree deadrise wedge impacting water with a CFD simulation of the same system



Experimental accelerations for impacting prismatic boat sections have been presented by Kim et al (1997), Yettou et al (2006), and Lewis et al (2010) (and also earlier experimenters not mentioned here). It would support BOAT3D if experimental forces or accelerations could be compared with its results, as well as mathematically-modelled values as in figures 2 and 3. However, this is difficult to do because the experimental results for accelerations are very noisy, including those generated by accelerometers as well as by numerical differentiation of motion data. For this paper no attempt has been made to extract acceleration data from the rather complex and noisy graphs in the literature. In the Kim et al (1997) paper, in their Figure 5, acceleration by Vorus' method has been compared with experiment. Given that the BOAT3D method generally agrees closely with Vorus' method, a similar result is likely to occur if we were to attempt a reproduction of the Kim et al graph with BOAT3D simulated acceleration added.

However, an interesting comparison can be made with position data as shown in Figure 7.

Figure 7 --- Position above the water surface, BOAT3D/DMSolver compared with experimental data of Lewis et al (2010) for a boat segment with 25 degrees deadrise in free fall into water.



The important time range which has been discussed above where growth of added mass produces a large dynamic force is from time=0 to time=0.111 sec, a very small region on the graph in which the BOAT3D/DMSolver result and the experimental result are close together. Before this time range is the free-fall range, in which the curves should be the same exact parabolas. After this range the chines are wet and there are differences between the BOAT3D and experimental values --- there is more damping of up-and-down movement in the experimental case. There could be many reasons for this difference. However, note that with wet chines there is not an exact correspondence between experiment and BOAT3D simulation because in the experiment the boat section is a triangular wedge and water might flow back over the top of the wedge, whereas the simulation is for a boat with vertical sides rising from the chines and having more bouyancy the further the chines are submerged.

The dashed line is for a case where equation (1a) is assumed to always apply, and the program does not switch to equation (1b) when the boat is rising out of the water and added mass is decreasing. With this method, which has not been used in the BOAT3D program since 2008, the momentum of "shed added mass" is returned to the boat, and it is propelled out of the water. If it were not for the "artificial damping" term in the equations, it would bounce back to its original height. As was stated in the 2008 documentation, a derivation from more basic physical principles has not been done to justify dropping the "shed added mass", but the simulation results are much more realistic when this is done.

It should be noted that the Yettou et al and Lewis et al experiments named above also produced results for pressures at the surface of the impacting wedge. The pressure vs time recordings are generally smoother than acceleration traces. These are very important research contributions but cannot be compared with BOAT3D because its simpler model does not produce pressure profile predictions. It only allows a prediction of average pressure.

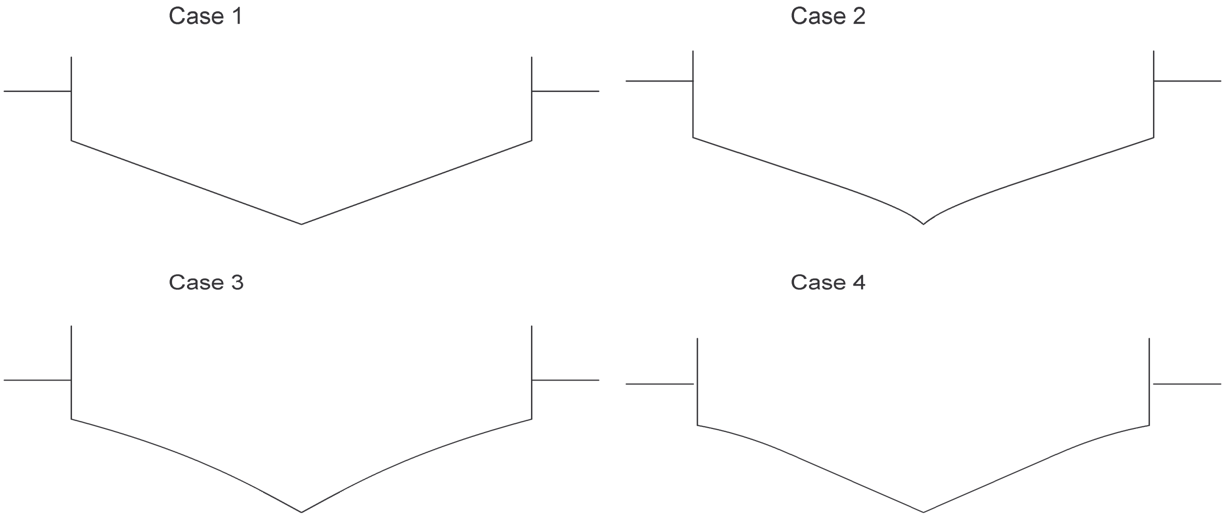
B. BOAT3D estimations by drop-test when the boat configuration is not "straight-vee"

A "straight-vee" configuration is when the boat cross-section has a straight line from keel to chine. In the experimental drop tests mentioned above the prismatic boat sections dropped were always wedge-shaped, i.e. straight-vee, except in one case in the Kim et al (1997) paper for which "lifting strakes" were added to the wedge.

In the 2008 paper (Singleton, 2008) the approximate method that BOAT3D uses to estimate how deviation from a straight-vee configuration affects dynamic forces was described, and Figure 1 above was first presented then to show how the BOAT3D method approximately agrees with Vorus (1996) for the deviations from straight-vee investigated. Drop test simulation provides an interesting direct look at the results of the BOAT3D method without additional confusing factors involved when a regular simulation of a moving boat is done.

In this paper results for boat configurations shown in Figure 8 are presented.

Figure 8 Drop test configurations --- the horizontal lines show the static water lines



Case 1 is straight-vee. Cases 2 and 4 have straight portions. In Case 2 this is near the chines and in 4 it is near the keel. In Case 3 there is a cubic polynomial with concave curvature continuously from keel to chine. Deadrise angle degrees associated with these shapes are as follows:

	Overall (keel to chine)	Tangent at keel	Tangent at chine
Case 1	20	20	20
Case 2	20.7	41.9	18.35
Case 3	25.0	32.1	16.9
Case 4	23.9	26.6	12.35

These deadrises were chosen to generate nearly identical forces in steady planing of a prismatic hull, so according to BOAT3D estimation, prismatic boats with these shapes would have approximately the same performance characteristics for smooth-water planing. The drop test simulations were done to estimate how they would differ in slamming situations.

A conventional parameter for drop test analysis is how far the boat segment drops from the starting rest point to where the keel touches the water, but since there are different shapes in this analysis the dropping distance has been taken as the distance from the starting point to where it would be in static floating equilibrium. The masses and beams of the test sections are assumed identical in each case.

Figures 9 through 12 show the results for acceleration. The acceleration is initially -1 g just as the keel touches the water, because the boat segment is in free fall. In cases 1, 2, and 3 it rises to a peak as the fall is slowed, and after decreasing for a while, suddenly drops to low values as the chines become wet. In Case 4 there is always a peak right at the end where the chines become wet. The reader will note some numerical noise in the DMSolver results. Just as acceleration is difficult to measure in an experiment, small computational fluctuations are amplified so it is difficult to simulate.

Figure 9 Simulated acceleration in g's for boat segments dropped from 0.45 beam lengths above the static equilibrium point

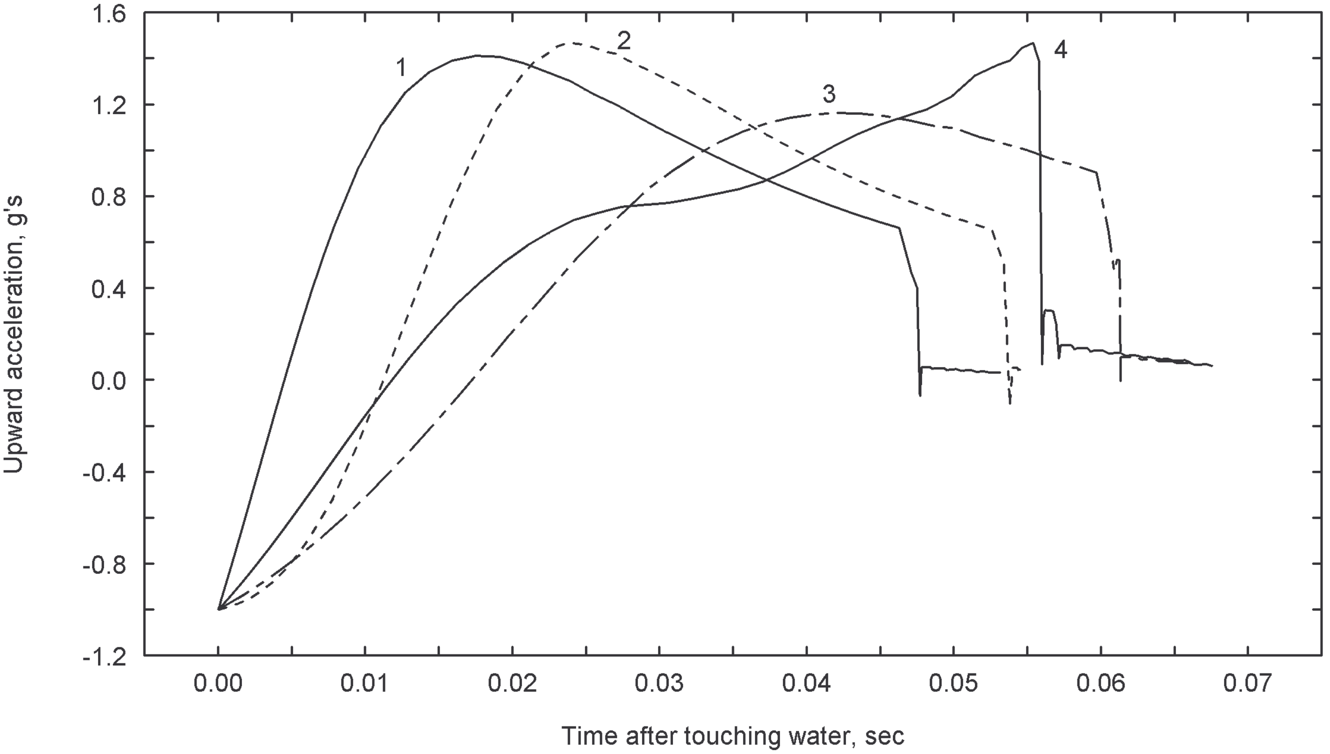


Figure 10 Simulated acceleration in g's for boat segments dropped from 0.64 beam lengths above the static equilibrium point

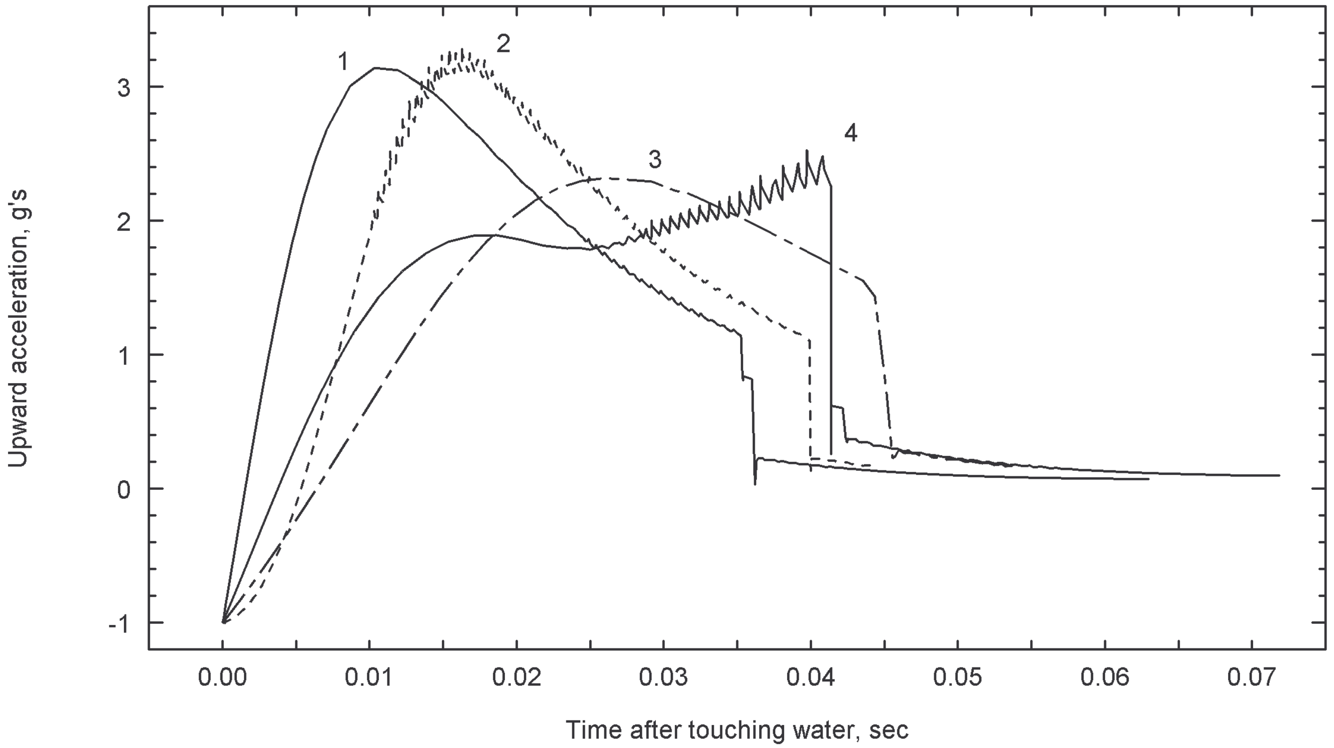


Figure 11 Simulated acceleration in g's for boat segments dropped from 0.94 beam lengths above the static equilibrium point

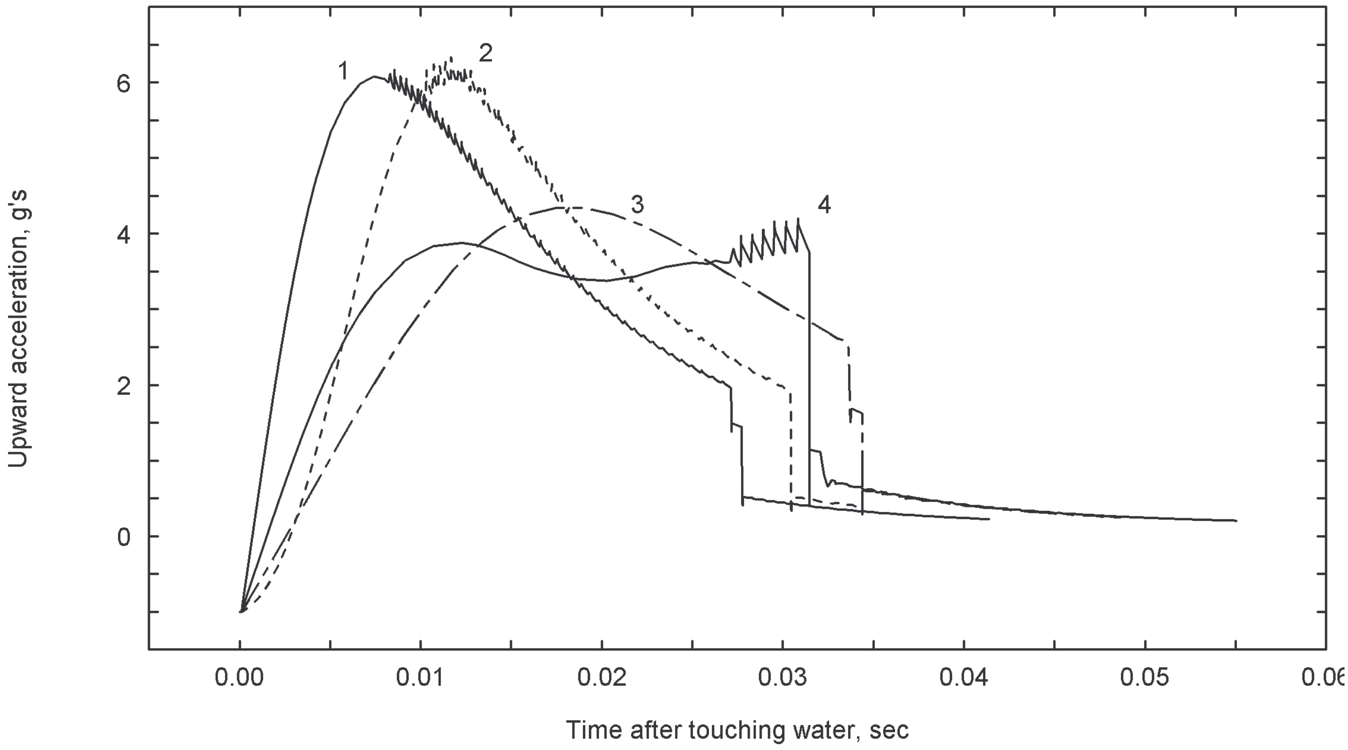
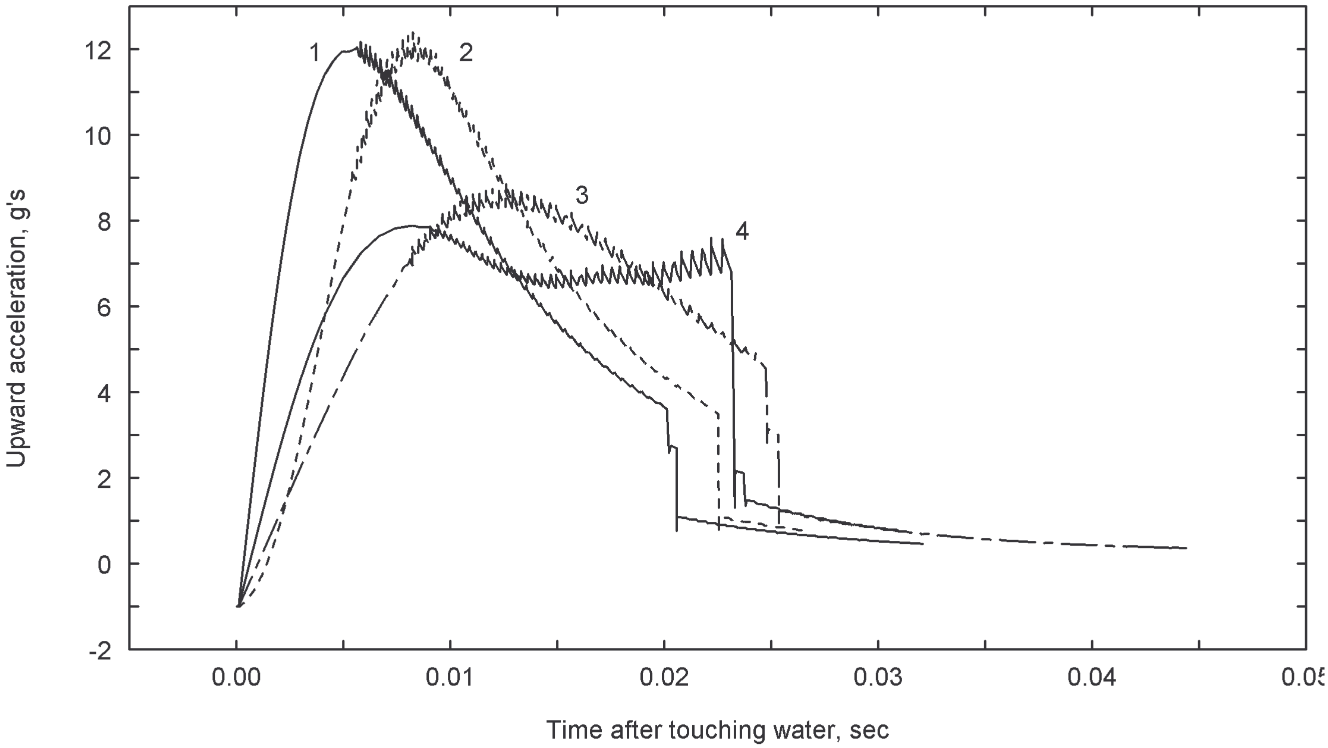


Figure 12 Simulated acceleration in g's for boat segments dropped from 1.55 beam lengths above the static equilibrium point



In comparison to the straight-vee Case 1, Case 2 simply delays the acceleration peak slightly and does not reduce its height. In the very concave case (Case 3) the acceleration peak is reduced considerably, but Case 4, with lower deadrise at the chines, is very effective at flattening the peak, except in the lowest drop test run, for which all accelerations are relatively low.

In both cases 3 and 4 the estimated acceleration peak due to severe slamming is reduced considerably compared with the straight-vee case. However, one might be concerned about the behavior of a very concave boat (Case 3) if slamming occurred while the boat was in a heeled state and the concavity led to very high dynamic forces. On the other hand, the shape used in Case 4 is not very different from that of numerous boat designs with "lifting strakes", etc., at the chines, so Case 4 appears to indicate a practical approach to slamming force reduction.

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