Simulated Ship Shock Tests/Trials?

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Submarine Shock Tests and surface ship Shock Trials are vital components of ship test and evaluation (T&E), and of Live Fire Test and Evaluation (LFT&E) requirements. Ship Shock Tests/Trials, surrogate and component tests, the Total Ship Survivability Trial (TSST), and associated analyses and simulations are key components of any alternative to full-up, system-level testing using munitions likely to be encountered in combat. Ship Shock Tests/Trials, although conducted under conditions more benign than realistic threat conditions, provide insight into platform vulnerabilities with respect to underwater proximity bursts, and produce significant decision-making data for corrective actions.

The cost of conducting a ship Shock Test/Trial and the tremendous advances in simulation capabilities are driving the question: “Can simulations be substituted for ship Shock Tests/Trials?” Unfortunately, current simulation capabilities still seem insufficient to provide decision-making data of equal utility to ship Shock Tests/Trials. Simulations hold the potential, however, to provide complementary decision-making data of greater value than ship Shock Tests/Trials alone. Simulation capabilities must therefore continue to be advanced.

This paper contrasts the relative, overall utilities of ship Shock Tests/Trials and simulations. A list of advantages for both tests and simulations is presented, with strong arguments in favor of a combination of both approaches.
INTRODUCTION

The U.S. Department of Defense is accelerating the development and adoption of modeling and simulation (M&S) capabilities in order to reduce weapon system acquisition costs. As with other technologies, M&S must pass through the traditional phases of research, development, test, and evaluation (RDT&E) to obtain an acceptable product. Although some program offices would like to replace some tests with simulations, the rush toward application of this developing technology must be carefully considered. Toward that end, this paper addresses the advantages and disadvantages of adopting simulations as a supplement to, and potential replacement for, ship Shock Tests/Trials; however, it does not address an optimal cost/benefit mix of testing and simulation.
Test and Evaluation of Ships

Ship survivability depends on susceptibility, vulnerability, and recoverability. Although closely related to vulnerability, susceptibility falls within the realm of Operational Test and Evaluation (OT&E). Vulnerability and recoverability (including organizational-level reparability) are part of Live Fire Test and Evaluation (LFT&E).

Live Fire Test and Evaluation legislation requires full-up system-level testing under realistic threat conditions (i.e., representative of combat conditions, not just design conditions), unless suitable alternatives are approved for reasons of cost and practicality. The assumption is made that platforms will be subjected to realistic weapon effects in combat, and not simply be able to avoid such conditions.

The ship Shock Test/Trial surrogate and component tests, the Total Ship Survivability Trial (TSST), and associated analyses and simulations are key components of any alternative to full-up system-level testing using munitions likely to be expected in combat. A Shock Test/Trial is typically performed on the lead ship of a new class of submarines/surface ships. The Navy has mandated a Shock Trial for first ship of every shock-hardened class of surface ships in OPNAVINST 9072.2. No similar mandate exists for submarines, although the "Live Fire Test and Evaluation of U.S. Navy Ships Process Description" states that surface ship Shock Trials will be performed and submarine Shock Tests may be performed. Testing of the lead ship, as opposed to a follow ship, better enables LFT&E to fulfill its role in correcting design deficiencies early on.

Shock Tests/Trials address design requirements by testing to a significant fraction of the design level. A combination of requirements is integrated into the design of surface ships and submarines. These requirements may take into account specific weapons effects or specific vulnerability reduction design features. Unfortunately, design requirements

1 “Shock Test” is usually applied to submarines, while “Shock Trial” is usually applied to surface ships. For brevity, "ship Shock Tests/Trials" will be employed to denote surface ship Shock Trials and submarine Shock Tests.
for some weapons effects may be omitted, or the design levels actually selected may be less than levels that will be experienced in combat. Nevertheless, while ship Shock Tests/Trials are conducted under conditions more benign than realistic threat conditions, or even full design conditions, they do provide significant insight into platform vulnerabilities with respect to underwater proximity bursts.

In a Shock Test/Trial, a submarine or surface ship is subjected to a series of underwater explosion (UNDEX) shocks generated by large explosive charges at large standoff distances off the beam of the ship. These conditions provide a nearly uniform, side-on shock environment that is somewhat characteristic of distant nuclear underwater explosions, but that is far less representative of realistic threat encounters with conventional proximity burst weapons. Realistically, the shock environment would be expected to vary from bow to stern, and typically would reach levels locally in excess of the shock design level. Furthermore, Shock Test/Trial conditions effectively eliminate the “whipping” (flexural) response of the ship resulting from the nearby oscillations of the underwater explosion bubble. Due to cost and crew safety, it is only in surrogate tests (tests of platforms similar in size and construction) where the underwater explosion environment, and the resulting structural responses, are representative of expected threat encounters. The series of UNDEX events in a Shock Test/Trial begins at a relatively low shock level, and progresses in severity to a level determined by the Navy to be safe for the ship’s crew. The final test of the series is accepted as partial fulfillment of the Live Fire Test and Evaluation requirements. The current standard for the final test of the series has been two-thirds of the design keel shock factor (DKSF) for surface ships, and one-half of the operability shock factor (SFO) for submarines.

In addition to the UNDEX event, a surface ship Shock Trial includes scenarios to exercise the combat system, and a “fight through” period during which the crew attempts to reconfigure or restore equipment and systems inactivated as a result of the UNDEX event. These exercises are not conducted for submarines, largely because of nuclear safety concerns.

Ship Shock Tests/Trials are performed with a crew on board, and are not intended to damage equipment. Realistic testing of a surface ship or submarine would require removal of the ship’s crew during the test for safety reasons, and would require costly repairs of the ship’s structure and equipment after the test. Realistic testing would therefore eliminate the benefits of having the ship's crew on board to experience the effects of underwater explosions. In addition to system (including equipment) performance, LFT&E focuses on the equipment/crew interface when systems are damaged - does the ship design allow the crew to reconfigure systems, isolate damage, etc? Having the crew on-board, even at lower shock levels, adds to the realism that the LFT&E legislation requires, and provides an invaluable training experience, albeit for only one crew from a hands-on perspective.

Component Shock Qualification

For surface ships in accordance with OPNAVINST 9072.2 [1], and for submarines in accordance with individual ship specifications, all mission-critical components must pass a shock qualification process in which the components are subjected to a shock environment nominally consistent with the ship’s full DKSF or SFO. Many of the components are qualified by component shock tests according to MIL-S-901D [3], some are qualified by extension (being similar to equipment previously shock qualified), and others are qualified by analysis. The intent of the component shock qualification process is to verify that mission-critical equipment is able to withstand a generic shock environment somewhat representative of nuclear or conventional weapons effects; it is a cost-effective risk reduction effort, not a guarantee of component survivability.

In assessing the robustness of simulations for Shock Test/Trial supplementation (or potential replacement), several shortcomings of the component shock qualification process must be addressed:

- Since a particular equipment can be installed in dozens of locations onboard a ship, and installed onboard many classes of ships, the component shock test environment is designed to be generic. The environment is not customized to the equipment’s installation onboard ship because testing to all potential operating conditions (e.g., underwater explosion environments) is prohibitive. Even characterizing a “worst case” environment is difficult or impossible. The shock environment to which a component is shock qualified therefore does
Component shock test on a Floating Shock Platform (courtesy of Hi Test Laboratories)

not equate to that experienced in a ship Shock Test/Trial. Sometimes the component's local environment in a Shock Test/Trial is more severe than that to which it was qualified, even though the ship's global shock environment is below DKSF or SFO; a common example is the difference in frequency content between the component shock qualification and Shock Test/Trial environments. In qualifying equipments for various ship types, the process is generally very successful; however, there are significant exceptions that can avoid detection until the Shock Test/Trial. It is common for some equipment failures to occur during Shock Tests/Trials, although the ships are tested at well below the threshold (nominal shock environment) at which any individual equipment failures are expected. Indeed, one of the justifications for full ship shock testing is that failures do occur and that the causes of failures can be and have been corrected, even though no specific pieces of equipment have been predicted to fail. This alone demonstrates that shock testing of individual components is not an adequate substitute for a Shock Test/Trial (testing all components assembled). Furthermore, extensive pre-test preparations assure that unexpected failures are minimized in a Shock Test/Trial; in its absence, more serious equipment and system vulnerabilities can be expected.

- Since MIL-S-901D does not require that a test be instrumented, component tests are usually not instrumented unless tested on board a test vehicle like the Floating Shock Platform (FSP) or Submarine Shock Test Vehicle (SSTV). Comparison to actual shipboard shock environment is difficult without knowing the shock test environment. In addition, components are not tested to failure, except for inadvertent failures. Thus, component failure modes are typically not characterized.

- Though components might be energized and lubricating fluids might be flowing, component inputs and outputs in the forms of mechanical loads and electrical/fiber optic information transfers are typically not duplicated. Simulated shipboard connections are required for equipment, but extensive use of dummy masses is allowed. Actual shipboard failures during shock trials have shown that these simulations are not always realistic. With few exceptions, the ship Shock Test/Trial is the only test in which components operate together as an integrated system to perform the intended system functions; invariably, surprises occur.

- Due to the limited number of actual tests, component shock test results are not statistically significant.

Simulation Applicability

Decision-making data are usually generated through some combination of testing and computer simulation, with the role of each determined by its inherent limitations. If accuracy estimates are available for both types of data, and if these kinds of data were truly independent, the relative value of testing and computer simulation can be assessed. In fact, computer simulation data are dependent on test data for validation and calibration.

The general need for testing is based on the fact that analysis methods and computer models remain insufficient to fully characterize the situation under investigation. The desire to reduce dependence on empirical test data, and for increased fidelity and insight into response mechanisms, is driving the development and application of physics-based simulation tools (vice “empirically-based” simulation tools). Unfortunately, the physical basis of a simulation tool is usually a trade-off between desired utility (sufficient to allow required insight) and allowable expense. The wide range of length and time scales inherent in ship and equipment responses typically requires resources that exceed those available for Shock Test/Trial simulation. The spatial and temporal discretizations employed in physics-based models define the minimum length and time scales of the responses that can be captured. The minimum time scales appropriate for capturing structural responses range from microseconds and milliseconds, typical of shock response, up to hundreds of milliseconds and seconds, if only the whipping response of the hull is investigated.

High fidelity, full ship structural response simulations demand a far broader range of length scales than is affordable with current computational resources. The circuit boards, switches, cables, and pipes in complex mechanical, electrical, and electronic equipments contribute significantly to the structural damping evident in ship response to underwater explosions. It is this coupling of the equipment responses with other ship responses that makes the prediction of full ship structural responses in general, and equipment failure modes specifically, so challenging.

Given limited computational resources, sub-scale responses are typically approximated through empirical or computational assumptions and approximations. Examples of empirical approximations for sub-scale responses include structural damping, constitutive models (which typically do not account for the myriad of phenomena activated in
material deformations), “smearing” of stiffener properties into orthotropic plate elements, and lumped masses. Artificial viscosity to eliminate the discontinuities of shock waves is also a computational approximation for a sub-scale phenomenon. Although sub-scale response approximations enhance a model's computational efficiency, they generally impose significant limitations to a model's ranges of applicability.

Sub-scale response approximations also limit a model's predictive capabilities to the average effects of those sub-scale responses. In fact, it is the sub-scale geometric uncertainties and variabilities that drive the unpredicted behaviors prevalent in system responses. Current-generation "deterministic" physics-based simulations require complete specification of initial conditions – usually not entirely known, especially if one is predicting the response of a ship as built, rather than as designed.

Simulation of ship responses to realistic threat encounter conditions, as represented in surrogate tests and historical incidents, presents additional challenges, since damage is expected that does not occur under Shock Test/Trial conditions.

Simulations generally do not provide the same data as tests. Ship Shock Test/Trial instrumentation, for example, usually provides velocities, accelerations, and strains at various points throughout the structure, and pressures at various points external to the structure. In addition, the resulting equipment failures are observed and logged. Physics-based simulations, on the other hand, can potentially monitor any relevant quantity at any location. Simulations of ship Shock Tests/Trials, however, generally do not predict the coupling of global ship responses with local equipment responses, including failures. Due to the wide range of length and time scales, the fully coupled problem would require enormous computational resources. Also, since equipment response (including failure) modes are rarely characterized, the component shock qualification process does not yet support the needs for validating such advanced simulation capabilities.

The cost of conducting a Shock Test/Trial is driving the question: “Can simulations be substituted for ship Shock Tests/Trials?” To be able to answer this question, the relative merits of tests and simulations must be identified and quantified. More specifically, the value of data obtainable only through Shock Tests/Trials, the value of data obtainable only through simulation (without culminating Shock Tests/Trials), and the inaccuracies in both test and simulated data must be quantified.
There are various reasons for pursuing simulations in support of Shock Tests/Trials:

- **Test Data Supplementation and Extrapolation.** Physics-based simulations can provide insight into system performance that is difficult or impossible to measure in ship Shock Tests/Trials. This insight can contribute to early improvements in design and employment. For example:
  - Given the limited production runs and high unit cost of ships and submarines, realistic test articles are not available for testing early in an acquisition program. In the absence of full-system test data, simulations must provide the decision-making data when design inputs are most valuable. The practice of simulating full-ship UNDEX response early in an acquisition program is implemented for submarines more than for surface ships.
  - Shock Test/Trial conditions are generally more benign than full design conditions and realistic combat conditions. Simulation therefore becomes the tool to extrapolate Shock Test/Trial results to realistic threat conditions, though this has yet to be accomplished for a surface ship or submarine LFT&E program. Credibility of the extrapolation is established through successful prediction and replication of Shock Test/Trial data and surrogate test data.
  - For various reasons, significant configuration differences can exist between each platform within a surface ship or submarine class. For example, significant “grooming” efforts prepare a ship to perform well in a Shock Test/Trial; these efforts are not always duplicated for other ships of the class. The outfitting of ships for different missions and equipment upgrades during the production run and throughout the life span of each ship also account for differences. In the absence of testing these differences, simulation allows shock analysis (a “virtual Shock Test/Trial”) of every ship as built, and as modified over its lifetime (except for undocumented changes), ensuring that the effects of these modifications are quantified.
  - Simulations potentially allow rough exploration of the “edge of the envelope” of a ship’s UNDEX vulnerabilities through extrapolation from tests. Approximately characterizing performance degradation is particularly
useful in recognizing that the current class of ships will not be the last system developed to accomplish the mission. The edge of the envelope information is useful to the follow-on class as a measure of improvement.

- **Environmental Concerns.** Simulations have the potential to reduce reliance on underwater explosions. Before testing, significant resources are expended in ship Shock Tests/Trials (and surrogate tests) in preparing environmental impact statements, monitoring sea mammal activities, and demonstrating to environmental groups that Shock Test/Trial planning and execution is environmentally acceptable. During a Shock Test/Trial, extensive and costly mitigation efforts are conducted to safeguard the environment. Such expenditures would not be required if simulations could replace ship Shock Tests/Trials.

- **Regulation.** Pre-test predictions are a requirement for every Live Fire Test. Technically, the regulation does not require the prediction to be based on a computer model or simulation. If the test is conducted at shock levels below the design level, an implicit prediction is that no equipment failures will occur that could affect the ship’s combat mission. Nonetheless, if a computer model or simulation will be used in the evaluation of ship vulnerabilities, it should be used also to predict the results of the Shock Test/Trial.

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 Shock Trial of U.S.S. YORKTOWN (CG 48) (courtesy of U.S. Navy)

**REPLACE SHIP SHOCK TESTS/TRIALS WITH SIMULATIONS?**

Although there are various reasons for pursuing computational simulation in support of ship Shock Test/Trials, significant obstacles remain in the quest to replace Shock Tests/Trials with computational simulations:

- **Immaturity of Simulation Capabilities.** Simulations have yet to demonstrate the capability to predict accurately the mechanical and electrical failures (and non-failures) of extremely complex systems like ships when subjected to
shock environments. For example, pre-test predictions of surface ship mast motions have been historically inaccurate. The quality of decision-making data produced by a ship Shock Test/Trial (e.g., the undeniable evidence of failed equipment) therefore exceeds that of current-generation simulations. A "virtual Shock Test/Trial" does not yet provide the credible incentive to repair potentially damaged equipment. Nor is it credible enough to provide the validation basis for model extrapolation to realistic threat encounter conditions. Successful prediction and replication of Shock Test/Trial and surrogate test data in tandem are the mechanism for establishing credibility of the extrapolation.

- **Lack of Verification, Validation & Accreditation.** The Department of Defense is requiring the rapid adoption of formally accredited simulation tools in support of weapon system acquisitions. However, UNDEX simulation tools have yet to be formally accredited to supplement, let alone replace, ship Shock Tests/Trials. Furthermore, the test basis on which to validate simulation tools is not established, since equipment failure modes are not characterized as part of the shock qualification process.

- **Lack of Quantified Data Accuracy.** In general, the accuracy of Shock Test/Trial data and simulation data are not rigorously quantified. Decision-makers tend to be more comfortable with the test data due to the relative maturity of UNDEX experimental methods. Over the course of decades of UNDEX testing, a qualitative, if not quantitative, understanding of test data accuracy has been established. The distrust of computational data is due, in large part, to the fact that the validity of physics-based simulation results is a strong function of analyst expertise. The accuracy of both forms of data need to be rigorously quantified to formally weigh their relative merits.

- **Lack of Quantified Uncertainties.** Current generation physics-based simulations can account for only deterministic phenomena, yet it is such things as the small scale variabilities and quality assurance deficiencies that produce the equipment failures common in ship Shock Tests/Trials. The fact that computational resources remain insufficient to accommodate the breadth of length scales required to account for small-scale phenomena in a full ship simulation only magnifies this problem.
SUMMARY

The response of a surface ship or submarine to an underwater explosion is an extremely complex event. This fact is responsible for the intense interest and need for computational simulations, and for the continuing difficulties in simulating this response adequately.

Simulation capabilities have advanced to the state where they are integral and vital components of the research, development, test, and evaluation process, and are being considered as substitutes for such complex tests as surface ship Shock Trials and submarine Shock Tests. In their emerging role as complements to test data in LFT&E, physics-based simulations may soon have roughly equivalent value to ship Shock Tests/Trials. In particular, simulations can potentially address the Live Fire Test and Evaluation requirement for evaluation of underwater shock responses more representative of actual combat than a Shock Test/Trial. Several factors, however, have so far precluded the adoption of simulations as replacements for ship Shock Tests/Trials. As summarized in Table 1, these factors include the fact that current computational resources remain insufficient to predict the UNDEX response of the integrated system (both global ship responses and local equipment failures). Other factors include the lack of data accuracy quantification and formally accredited simulation tools.

In order to consider simulations as substitutes for ship Shock Tests/Trials, simulations must accurately predict not only the ship shock environment experienced by shipboard equipment, but also the responses (including failure) of that equipment. This is an issue since equipment response modes (including failure) are not characterized as part of their qualification process. The component shock qualification process does not yet support the needs of modeling and simulation.

Table 1. Ship Shock Tests/Trials vs. Simulations

<table>
<thead>
<tr>
<th>Ship Shock Tests/Trials</th>
<th>Simulated Ship UNDEX Response</th>
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</thead>
<tbody>
<tr>
<td>Evaluate platform under sub-design conditions</td>
<td>Potential to evaluate platform under realistic threat encounter conditions</td>
</tr>
<tr>
<td>Test of integrated system</td>
<td>Simplified representation of integrated system</td>
</tr>
<tr>
<td>Limited influence in ship design</td>
<td>Influence design early in acquisition cycle</td>
</tr>
<tr>
<td>Limited data obtainable</td>
<td>Extensive data sets obtainable</td>
</tr>
<tr>
<td>Unexpected equipment failures common</td>
<td>Equipment failure prediction not demonstrated</td>
</tr>
<tr>
<td>Uncover &quot;as built&quot; vulnerabilities</td>
<td>Simulate &quot;as designed&quot; conditions</td>
</tr>
<tr>
<td>Data accuracy not formally quantified</td>
<td>Data accuracy not formally quantified; strong function of analyst expertise</td>
</tr>
<tr>
<td>Representation of ship class is questionable</td>
<td>Potential to evaluate individual platforms</td>
</tr>
<tr>
<td>Inside performance &quot;envelope&quot;</td>
<td>Explore performance &quot;edge of the envelope&quot;</td>
</tr>
<tr>
<td>Formally accredited data acquisition methodology</td>
<td>Lack of formally accredited data acquisition tools</td>
</tr>
<tr>
<td>Maturing methodology</td>
<td>Developing methodology</td>
</tr>
<tr>
<td>Significant resources expended to demonstrate minimal environmental impact</td>
<td>No environmental impact</td>
</tr>
<tr>
<td>Partial fulfillment of LFT&amp;E Legislation</td>
<td>Not currently accepted as Shock Test/Trial replacement</td>
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</table>
RECOMMENDATIONS

Test and evaluation resources should be expended on a combination of testing and simulation that generates the best overall decision-making data. The cost/benefit ratio, though beyond the scope of this paper, should be quantified.

Physics-based UNDEX vulnerability simulations should be employed in the acquisition cycle for:
1) Early design assessments for surface ships as for submarines,
2) Pre-test predictions both prior to and during the Shock Test/Trial,
3) Extrapolation of Shock Test/Trial results to DKSF/SFO conditions and realistic threat encounter conditions through validation on surrogate tests, and
4) Analyses of differences in each ship of a class, once the model is calibrated to Shock Test/Trial results.

Given the computational resources required for generating simulated Shock Test/Trial data of value potentially equivalent to tests, shock testing of the first of every new class (or major product improvement) of surface ships and submarines should continue. If advanced simulation capabilities are to fulfill their role in enhancing the Live Fire Test & Evaluation process for ships, test procedures must evolve to better support simulation tool validation. Of primary value would be a shock qualification process that characterizes component failure modes.

Given their enormous potential value, simulation capabilities should continue to be developed aggressively, and priorities should be established in which validation and accreditation play a central role. Other priorities should include formal quantification of test and simulation data accuracy and uncertainty. Tests needed to validate advanced simulation capabilities should be identified - such validations should be targeted initially at acquisition programs for major ship upgrades like the current DDG Flight IIA, where Shock Test/Trial data for a similar ship are available.

An inter-program effort supporting the entire Shock Test/Trial community should be initiated, responsive to all surface ship and submarine acquisition programs on matters relating to both testing and simulation, and able to drive research and development efforts. Such a coherent organization would be better equipped to take advantage of programs already underway that significantly enhance the ability to simulate complex phenomena similar to Shock Tests/Trials. These programs include:

- The U.S. Department of Energy’s Accelerated Strategic Computing Initiative (ASCI) [8], which is accelerating the development of supercomputing capabilities, including the development of scaleable software and hardware, and is addressing validation and the quantification of simulation uncertainties.

- The U.S. Department of Defense’s High Performance Computing Modernization Program (HPCMP) [9], currently being expanded to include the requirements of the DoD’s test and evaluation community.

Finally, a convergence of design threat and expected threat through implementation of operationally-oriented vulnerability requirements [10,11] should be considered in support of "simulation-based acquisition."

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REFERENCES


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