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Future Ballistics: A Multidisciplinary Approach

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Abstract : Ballistics is the science dealing with the motion of bodies projected through space. Improvement in accuracy in terms of range extension is an important objective for future ballistics via artillery projectile systems. The future challenges facing the continued development and applications of the ballistics sciences are becoming vastly more complex phenomena. While the fundamental laws of science remain unchanged, the added constraints and requirements of modern system design provide substantial challenges to the future ballistician. Quality, Reliability and Safety (QRS) and environmental considerations are of growing importance, performance requirements are increasing, and testing is becoming increasingly prohibitive, both in terms of cost and unacceptable consequences. New design techniques and tools are required which can quickly explore and discriminate between viable and non-viable design options, assessing both safety and performance of a proposed system, prior to having to commit to hardware and conduct expensive tests. In view of above, this paper advocates a modeling, simulation and visualization (MSV)-based approach to system design as a practical aspects of simultaneously realizing higher performing, safer, and more affordable systems, all within a shortened acquisition cycle period and also reduced development cost.

1. Introduction

Ballistics, rooted as it is in the study of motion and indispensable as it has become in the affairs of nations, has held the interest of scientists, engineers, generals, rulers and users. Physicists and mathematicians and others have made fundamental contributions to this science initially, including many of the most significant contributions. The environment in which the ballistics community functions today is challenging as increasing requirements on performance, must be balanced against increasing considerations of quality, reliability, safety, development time and costs, testing restrictions, affordability, and assurance of performance early in the design phase. Defense budgets are generally declining and scientists/engineers are being asked to do more, with less. The combined affects of rapid progress of technology and desire to reduce the cost required to design, test, and produce new munitions make it essential to compress the time allowed for ballisticians to do their work. In addition, as equipment becomes more sophisticated and costly, it becomes less attractive to design by trial and error, let alone conduct vulnerability testing on expensive equipment. Similarly, there are some regimes such as in missile defense, where tests against realistic threats like chemical and biosubmunitions, are simply not possible because of the consequences of the test. The culmination of all of the above considerations is that the end product must be better characterized and understood in terms of its designed performance and response to unintended insults than ever before. And we must accomplish this in a shorter time, at lower cost, with greater safety, higher reliability, smaller size, and increased performance. This is the challenge of ballistics in the coming century.

2. Challenged Multidisciplinary Approaches

The proposed approaches to meet the challenges described above are a combination of physics-based modeling, simulation and visualization, supporting science and validation tests, and diagnostics with sufficient temporal and spatial resolution to measure important and computable parameters. While aspects of these approaches have been under development for more than fifteen years, these approaches are still in their infancy for many ballistics applications.

Both government and commercial modeling and simulation codes are available today, which have demonstrated significant utility for the design of components. These codes are used routinely in the fields of interior, exterior and terminal ballistics, aerodynamics, warhead mechanics, and terminal effects. A more recent application of these codes is in the understanding of mechanical response of larger scale components and assemblies such as a recoil mechanism and its effect on gun barrel motion and projectile muzzle exit. While computer hardware limited the size of problems that could be addressed in the past, continuing advances in both computational capability and parallel code architectures now make large computations possible.

A current technology deficiency in the approaches is the availability of physics-based models to describe the behavior of materials. The models must include a variety of low and high rate loading conditions, including deformation and failure/fracture of structural elements, and as well as subcomponent materials such as energetic materials and electronics. The coupled mechanical and thermal response of both inert and energetic materials must be understood, along with the more challenging problem of the chemical response, both intended and unintentional, of energetic materials. It is important to note that the mechanical, thermal, and chemical response of materials occur simultaneously in real scenarios and so should be modeled in a tightly coupled thermal-mechanical-chemical (TMC) manner. Damage and failure/fracture mechanisms are not well understood even in metals and are of current interest and study. In addition, the computational architecture and resultant capability for combined TMC response is still under development.

For common explosives and propellants (both rocket and gun), the chemical energy release under normal function, i.e., thermal or shock initiation is reasonably well characterized. However, the models tend to be empirical and do not contain the reaction kinetics to properly describe the energy release process in the energetic material under non-ideal initiation conditions typical of accident scenarios. Accordingly, while normal function assuming desired initiation can be empirically modeled to a reasonable extent, our understanding of the physics of ignition and growth of a chemical reaction is insufficient to predict the response of an energetic material to an abnormal stimulus, such as a weak shock, mechanical shear or thermal load. This is an area of current interest and development, the result of which will greatly improve our understanding of the response of munitions in hazardous environments.

Having outlined the deficiencies in current MSV approaches, it is also important to note that current MSV codes are being utilized effectively in the design of warheads and other sub-systems, where the prediction of performance and safety is of paramount importance. These computations involve well-characterized metals and ideal, metal-driving explosives, within regimes where there is much test data and accordingly the calculations have been validated. Various examples are discussed in this paper.

3. Role of Modeling, Simulation and Visualization (MSV)

There are several roles that MSV needs to fulfill. Five specific needs of interest to the ballistician, which MSV can in principle, provide utility. Of these the first one is possible today, the second is possible in some limited cases, while the third, fourth and fifth await development of validated material models and codes. (a) Of primary importance is the performance prediction of a component, such as a warhead penetrating armor plates, propellant combustion, projectile loading and response. This has been the traditional and established usage of MSV. This usage relies on the ability to empirically model material behavior within known ranges of behavior and the results are reasonably predictive. These problems typically can be solved without TMC capabilities. (b) A more advanced usage of MSV is to predict the response of a warhead or rocket motor to a thermal or mechanical insult. If ignition and reaction critical parameters are known, MSV can reasonably predict whether ignition of the energetic material will occur. However, without detailed knowledge and modeling of chemical ignition and reaction kinetics, the degree of violence once a reaction is initiated cannot be predicted. This class of problem tends to require some TMC capability and multiple time scales from microsecond to seconds. Frequently success is possible with outcomes that result in a shock-induced detonation, e.g. Shock to Detonation (SDT) from high-speed fragments or a sympathetic detonation situation. (c) When the reaction kinetics of real energetic formulations are known and implemented into material models in a TMC code, tradeoff analyses can be conducted between performance and safety in rocket motors, and warhead bodies. The ability to conduct these tradeoffs computationally during the design stage of a munition portends large savings in development cost and time. These classes of problems typically involve non-ideal energetic materials and the possibility of sub-detonic response. (d) The advent of MSV as a leading design approach will not eliminate the role of testing, but will reduce the number of tests and influence the design of tests. MSV based analyses can be used to identify performance margins and thereby focus tests to assess performance about the margin. By comparison, without knowledge of design margins, any one test can give information about performance, but many tests are required to establish the margin. (e) A final role for MSV, when a fully validated and integrated MSV tool is available would be to virtually test, and predict, the un-testable. This situation could result from environmental concerns over hazardous materials, the inability to design a test to accurately simulate a regime of interest, or if the value of a target is too great to permit destructive tests. As munitions become more sophisticated and complex, this situation will arise more frequently.

4. Supporting Test and Evaluation (T&E)

For MSV to have real value it must be accompanied by judicious T&E; this includes scientific tests to develop and calibrate material models, as well as highly diagnosed integrated tests to validate a final design. Before confidence in the tools is established the initial number of tests which accompany an aggressive utilization of MSV as a design approach can be substantial and may even exceed the number used in the absence of MSV the first time. However, once validated and established, models need not be revalidated and subsequent design exercises using the same materials in the same parameter space may only require a final "system" validation test resulting in significant cost and schedule savings. In addition, the integrated tests that are conducted can be judiciously planned using models to explore design margins and thereby provide substantially more information than a single test designed to only verify the design point.

5. Diagnostics

The role of T&E as described above is to develop material properties data and to validate candidate designs. This role requires that specific and critical parameters of material behavior be measured with high spatial and temporal resolution, and well posed boundary conditions. Scientific tests to determine material behavior obviously require sophisticated measurements of material behavior (stress, strain, strain rate, temperature, damage) over a range of parameter space that encompasses the complete range the material(s) will experience during actual function. Similarly, the purpose of a design validation test is to compare the function of a hardware design with the MSV predictions and assess the significance of any differences observed between measured data and the predictions. This comparison of test data with calculations requires that specific and critical parameters of function can be measured and with sufficient temporal and spatial resolution to allow a meaningful comparative assessment of any observed differences. While this approach produces much more data than a simple performance test measuring only the key performance parameter, it also provides insight into the understanding of the device function and thus provides insight into the robustness of the design and sensitivity to design and manufacturing tolerances.

6. Benefits and Payoffs of MSV

The overall value of MSV to the ballistician is to achieve better designs in a shorter time and at reduced cost. This benefit arises from several factors. One is the ability to conduct design tradeoffs early in the design cycle. Non-viable design options can be identified and eliminated from consideration prior to committing to hardware. The design optimization cycle time can be greatly reduced when employing MSV rather than fabrication and testing of hardware, resulting in a better design in a shorter time and requiring only validation tests. Finally, significant virtual testing can be conducted which explore and establish design margins. These simulations will provide additional insight into function and performance with increased confidence in a design. Ultimately MSV will allow for the use of sub-scale tests where the MSV will provide robust, non-linear scaling of full-scale system performance. All of these benefits of MSV require a robust MSV toolset, validated over the range of materials and conditions for which they are employed. While this toolset is still under development, some fundamental capability exists today and is already demonstrating real value.

7. Current Examples of MSV Approaches

7.1 *Warhead Validation T&E*

Modeling and simulation has been used for several years in the design of jetting warheads. An essential initial step in that process is the validation of material models and numerical schemes against highly diagnosed experiments. An image from the complete sequence of jet formation images is depicted as an example of a validating experiment for illustrative purposes. The ink grid lines marked on the surface of the copper shaped charge liner serve as spatial references throughout the collapse of the liner and subsequent jet formation and allow a mapping of the time history of the collapse and formation process. These data provide substantially more information than the jet velocity and mass distribution typically obtained with radiography. The additional information is vital to validating the material models and numerical schemes used in the simulation of the liner collapse history and jet formation process, Figure 1.

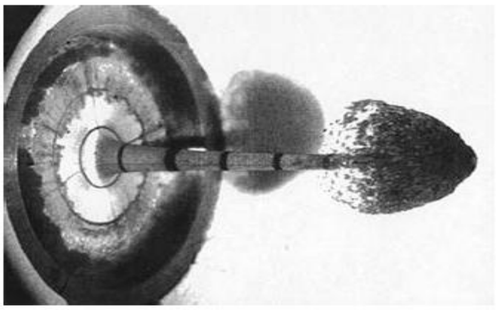

Fig. 1: Image of Shaped Charge Jet

Having a validated MSV tool for a shaped charge design allows computational exploration of alternate configurations of charge design using the same materials under similar loading parameters. Application of these validated models to a design problem has resulted in a computationally developed shaped charge warhead, shown as Figure 2, that exceeded performance requirements, with a 24% less diameter, 41% shorter, and length to diameter ratio of 0.9 compared to the baseline design. At the same time a cost saving and schedule within limits are realized.

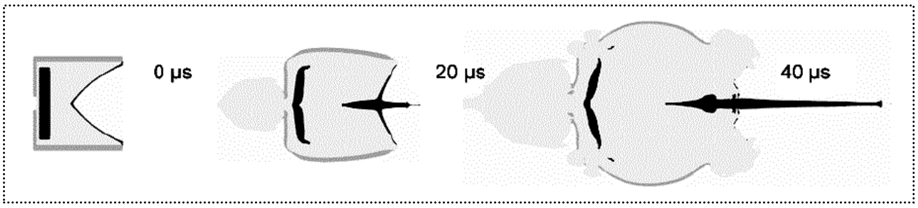

Fig. 2: Simulation of Optimized Shaped Charge Warhead

7.2 *Warhead Fragmentation*

Significant progress has been made in recent years to develop the capability to predict the nature of explosively driven metal case fragmentation. The work of Orzechowski and Goto, has provided a set of well diagnosed “pipe bomb” experiments, post-test fragment characterization, and detailed MSV analysis. The MSV analysis consisted of continuum modeling and direct numerical simulation. The experiments consisted of a number of explosively driven, AerMet 100 steel cylinder fragmentation tests that were extensively diagnosed with flash x-ray, photographic coverage, and multi-point velocimetry. Extensive efforts were also made to soft catch all the fragments with subsequent metallurgical analysis and statistical analysis to obtain mass and size distributions. An initial attempt using standard explicit LaGrangian techniques to “seed” the case mesh with a statically distributed value to a single parameter in the Johnson Cook failure model produced a realistic fragmentation pattern as shown in Figure 3.

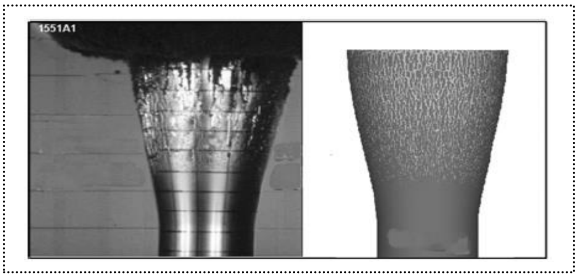

Fig. 3: Comparison of Experimental and Computational
for an Explosively Steel Case

7.3 *Warhead Safety*

Another area where MSV can play a large role is in the assessment of safety of munitions to various mechanical and thermal insults. A standard laboratory scale test for assessing the behavior of a munitions to long duration heating is the slow cook-off test in which a sample of explosive is contained inside of a steel pipe and subject to an external heat flux (on the order of 5°C/hr). While a basic result of the test is the time at which a violent reaction ruptures the steel pipe, it is more important for MSV validation of the material models to compare the evolution of state variables to the many observable parameters. An example of such an instrumented test is illustrated in Figure 4, where in addition to thermal data, mechanical strain of the pipe, time to rupture, and velocity and size of resulting fragments are recorded. The data obtained from instrumented laboratory cook-off tests is used to help validate the thermal and chemical reaction kinetics models for energetic materials. When validated, the models for TMC behavior can be applied to full-scale systems where the tools provide the non-linear scaling laws from the physically based models. This is a difficult goal where progress has been significant, but the goal remains to be achieved. However, the payoff in terms of costs saved from reduced testing can be great. An example where the cost savings is extremely large is with large diameter rocket motors.

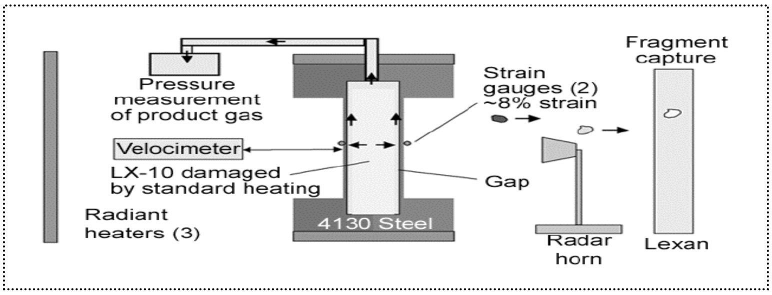

Fig. 4: Slow cookoff test to measure time to rupture, tube expansion, fragment velocity and size

8. Conclusions

A comprehensive MSV approach, including a sophisticated T&E capability accompanied by high-resolution diagnostics, is postulated as the new paradigm for ballisticians to meet the significant design challenges of the future. This approach builds on the rapidly developing hardware and software capabilities in today's computational environment. It also requires a concomitant commitment to a judicious and well-planned T&E program. We believe it is important for ballisticians and their supporting institutions to recognize the MSV based design paradigm and create the software and test infrastructure necessary to support the ballistician in the future.

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