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A Compact Shock Tester Concept Using Velocity Amplification

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Foreword:

The following white paper describes a concept and procedure conceived by Proof Engineering for shock testing of a ballistic missile in which the missile is stationary and the target is in motion. The concept would result in a compact test apparatus and method that does not require pyrotechnics.

1.0 Significance of the issue

Considered an integral part of new weapons development, terminal ballistic performance testing of high speed weapons remains an important issue for weapons designers. During target penetration, projectiles are subjected to tremendous forces developed at the weapon-target interface. The resultant decelerations coupled with oblique impact angles of attack and an interaction with structurally non-uniform target materials leads to a complex multi-axial inertial loading environment. The loading may lead to premature weapon destruction or failure of internal components. Mechanical responses and complex dynamics of munitions and targets are not easily predicted and usually require test validation. Therefore, the capability to replicate terminal ballistics in test environments is critical to successful development of new weapon systems.

Historically, the high G-level and relatively long duration of penetrating impacts required operational or ballistic weapon testing. Apart from the high cost and safety concerns, these tests have had limited repeatability and reproducibility. When a ballistics test is implemented, weapons must be propelled to a distant target by either a rocket motor launcher or an air gun. In doing so, there is a limitation to the number of deployed sensors and instrumentation capabilities of on-board electronics. The development of a new reverse ballistics shock tester is desirable because most research and development test programs can benefit from an increased number of sensors and reduced operational cost associated with a near-stationary test machine.

The challenge of designing a reverse ballistic shock tester lies in the necessity of accelerating a high mass target towards a stationary warhead to a significant speed. In practice it means that a fairly long acceleration distance must be available (for example, Sandia National Laboratory in New Mexico utilizes a 10,000 ft long track). When a target hits a test article, it crushes and effectively generates forces similar to ones observed in operational tests. Most of the target mass does not interact with the projectile but serves as a ballast to ensure that target impact velocity is not significantly reduced due to impact momentum transfer. Normally, since a flying target mass significantly exceeds that of a test article, a large portion of the energy used for target acceleration is lost. Proof Engineering's team has considered an apparent inefficiency of reverse ballistic testing and has conceived a different approach. If a unit under test (UUT) was accelerated by means of a compliant structure whose deformation produced a desired pulse shape and duration, then the forces seen by an UUT would be identical to those in operational or reverse ballistic testing. Such a structure does not need to have a specific mass if it is attached to a test article and receives sufficient energy by other means. The effective shock machine payload would consist of a combined structure and UUT weight, and the required energy would be found from the desired velocity change and the payload. In order to produce a high velocity change in a compact package and without using energetic materials, Proof Engineering proposes to take advantage of impact dynamics and stress wave propagation in solids, which theoretically allows conversion of high mass and low velocity energy into a high velocity of a smaller mass.

1.1 Background

A number of shock test machines are currently in use by the US Air Force. Frequently, air guns are used to apply large accelerations to test articles. Closed muzzle air guns work on a pneumatic principle whereby pressurized gas or air expand to quickly propel a piston (or a sabot) containing a test article. During this event, accelerations ranging from 200,000*g* for small-diameter (2") guns and in excess of 20,000 g for larger (7" diameter) guns [7] may be achieved. The payloads of the larger air guns are reported to reach 30 lbs [3], making them suitable to test larger weapons. A major drawback however, is that closed muzzle air guns are unable to impart off-axis loads, limiting their application to axial only shock environments.

Another type of air gun, known as an open muzzle or an air launcher, actually fires the test vehicle into a nearby target be made from various materials. While off-axis inertial loads of a free flying and target penetrating test article can be reproduced, the problems associated with limited data collection still remain. In addition, air launchers do not scale very well. In order to propel heavier vehicles, their length must continually increase to contain more pressurized gas.

Utilization of a stationary or near-stationary shock machines for ordnance impact testing is more efficient. Tests by means of shock machines are preferable to tests under actual field conditions for various reasons: 1) the nature of the shock makes it more controllable, and the shock can be repeated with reasonable accuracy; 2) the severity of the shock can be selected from practical design considerations; 3) an external data collection system with many channels can be utilized; and 4) natural reduction of operating costs is achieved, allowing a greater number of component developmental tests that otherwise would not be practical.

The challenge of developing a shock machine capable of testing larger weight weapons in single and multi-axial modes is attributed to relatively large velocity change requirements. When test article weights are in the range of 10-50 lbs, the 10,000 g acceleration requirement with impact durations approaching five milliseconds results in a delta V of 1650 fps (~500 m/s). These conditions are difficult to achieve using conventional gravity based drop tower setups even when aided by pneumatic means. For comparison, conventional high-G shock machines can deliver small article accelerations in the required range, but the shock pulse usually lasts only 20-50 μs which is only a fraction of the duration needed to replicate a terminal ballistics event. For this reason, additional means for converting impact energy into a high velocity relatively long duration shock pulse are required.

1.2 Velocity amplifier solution

The pseudo-static test operation in ballistics usually implies that a target impacts the test article. Because the striking target generally must be heavier than the test article, a very significant mass must be accelerated to the required velocities. For example, a 100 lb flying target would likely be needed to approximate an operational environment acting on a 10 lb penetrating weapon. Developing a launcher with such a payload capability would represent a challenging problem from both technical and economic considerations. To avoid the expense of designing and building an unusually large machine and to eliminate the necessity of accelerating a heavy target, a hybrid approach that in part relies on mechanics of a stacked chain of masses is considered. The best known example of such a system is the Newton cradle [Figure 1], named after Sir Isaac Newton, a device that demonstrates conservation of mechanical momentum and energy via a series of swinging spheres. A symmetric Newton cradle consists of spheres of identical weights. If one of the spheres is pulled away and released, it strikes the second sphere and stops, the rest of the chain appears almost at rest while the last sphere is propelled with the speed of the striking ball.

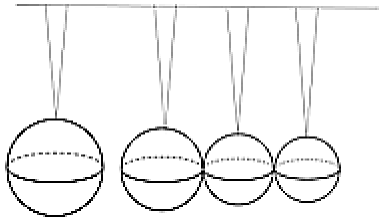


Figure 1 - Asymmetric Newton's cradle

It has been shown [2] that if sphere sizes (i.e. masses) are proportioned in a certain way, the impact velocity can be amplified, and the total velocity gain would be a product of gains that occurs in the collision of each pair. When the first mass is projected by mechanical or pneumatic means, for instance to a velocity of 300 feet per second and then amplified by a series of colliding masses by a factor of five or six, the overall machine size and weight should remain quite reasonable even for larger test articles. Our initial estimates, assuming average impact restitution coefficients of 0.9, suggest that for a 12 lb test article (the last mass in the chain), a stack of four additional masses would be sufficient to produce a rigid body velocity change of 1600 fps. This would require that the first mass be accelerated to 300-350 feet per second (fps) and that the overall weight of intermediate masses total to less than 800 lbs (under 4 cubic feet of volume if the material is steel). Since the test article could be arbitrarily oriented, off-axis accelerations are also possible.

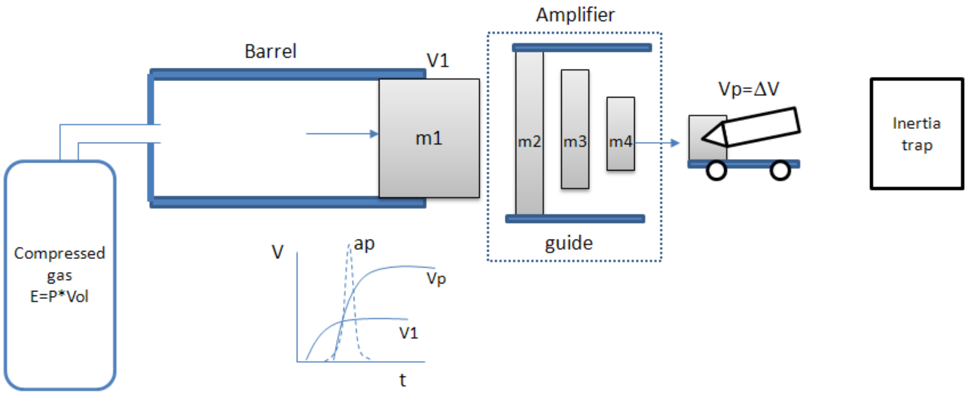


Figure 2 - Proposed system architecture

In the embodiment of (Figure 2), the initial velocity of the first mass in the stack would be achieved pneumatically, requiring a twelve inch diameter, six feet long barrel gun if operating at 2000 psi (note that multistage air compressors with working pressures up to 5000 psi are commercially available and inexpensive). Comparing to a flying target arrangement without a velocity amplifier, one can estimate that presenting a 30 lb target at 1600 fps to a 12 lb stationary test vehicle would require an air gun approximately 90 ft long if operating at the same working pressure. With the above consideration, the expected small footprint of a proposed hybrid system becomes increasingly attractive. The velocity amplifier system also appears readily scalable to a target payload of at least 50 lbs without going outside of customary equipment dimensions and industry standard pressures. However, at heavier payloads, increased launcher pressures may result in more cost effective systems. In this case, the compressed air may be readily replaced by nitrogen gas to avoid the risk of potential auto-ignition of hydrocarbons (i.e. mineral oils) often contained in compressed air.

1.3 Generation of Shock Profiles

Another important consideration in designing a terminal ballistics impact tester is generation of shock profiles and interface forces similar to operating field conditions. While shock shape and duration can be managed by traditional shock programmer devices (i.e. deformable media), purposely developed test fixtures are needed to replicate confinement pressures and off-axis motion effects. In the field, when a projectile penetrates a material such as concrete, the nose portion becomes embedded in the media (Figure 3) resulting in high pressures that may lead to a circumferential buckling of the weapon shell. Also, when penetration resistance force deviates considerably from the weapon's axis of symmetry, a side inertia load develops and causes a bending mode tail motion sometimes referred to as a tail-slap. Additionally, the weapon's unconfined length varies with time (Figure 3a) which makes natural frequencies and mode shapes of the weapon change at different stages of the target penetration event.

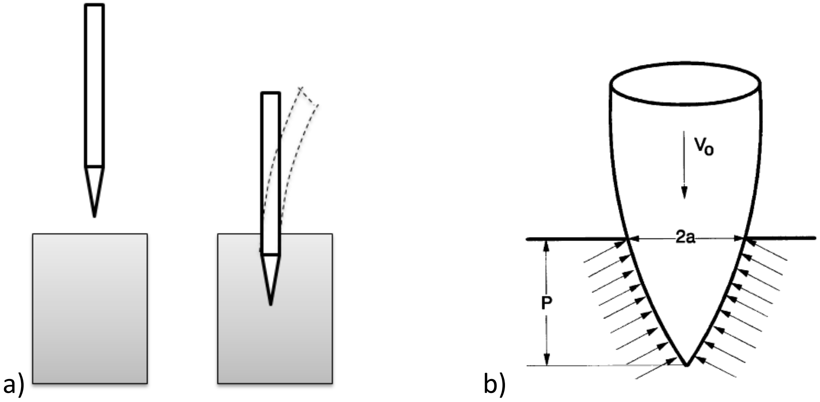


Figure 3 - Forces and deflections of projectile penetrating a target: a) Tail slap bending b) Confinement pressures [ref 8]

To our knowledge, there is no existing method to replicate the described dynamic environment in laboratory conditions. A potential solution is to simulate the described phenomena on a test stand by impacting a test article through a purposely designed fixture consisting of a split cone with adjustable stiffness (later described in more detail in Task 2 of Section 3.0). This simple approach would allow tuning the level of confinement to approximate the effects of different target materials, and a tail-slap like bending would be initiated by positioning the fixture and test article at a predefined angle relative to the striking mass velocity vector. The sliding "fixed" boundary condition would be implemented by relative motion between the fixture and projectile during the impact while the desired shock profile would simultaneously be generated. The feasibility of generating twisting/shearing moments by the same relative motion would also be investigated, however a reliable design for such an approach may prove difficult. If projectile spin rates are found to have a significant influence on the overall dynamic response, spinning the test article itself prior to the impact may be an acceptable solution.

3.0 Development Steps

This section divides the development effort into specific tasks which are described in detail below. The scope aims to determine feasibility of achieving desirable shock characteristics using the proposed system architecture.

1 - Modeling of operational multi-axis loading

In order to establish target bending and shear moments for performance verification of the new test machine, one must quantify the munition operational forces and moments occurring during impact. Each weapon has a critical yaw angle at which its bending mode is excited during impact; yaw is defined here as the angle between the projectile's axis and its velocity vector. If the projectile is spinning on entry, there should also be a relationship between the spin rate and amount of flexural deformation. Lastly, quantification of stress seen by the projectile's structure must depend on the duration of impact. Given the complicated physics of the projectile penetration event, the most effective way to obtain the necessary insight is through numerical modeling. For the Phase I effort we propose to utilize a simplified numerical simulation approach based on a Forrestal concrete penetration model [1]. The model allows direct prediction of the penetration force in the tunneling region (Figure 6) and is described as:

$$F = \pi a^2 (S f_c' + N \rho V^2) \qquad \text{Eq. 1}$$

where a is the projectile radius, S a constant dependent on unconfined concrete strength f'_c, N is a function of head geometry and V is projectile velocity.

A numerical explicit LS-Dyna model may be developed and consists of a simplified elastic and uniformly distributed mass projectile that would be given an initial velocity of 1600 fps. The axial resisting force is computed from Eq. 1 as a boundary condition. The projectile would travel through a rigid hollow cylinder representing a tunnel that restrains the penetrated portion of the projectile's radial motion. A frictional resisting torque is introduced simply as a product of force and projectile half-radius multiplied by a friction coefficient in the region of 0.4. Projectile geometric and inertial properties reference provided design details of the subscale system mentioned previously.

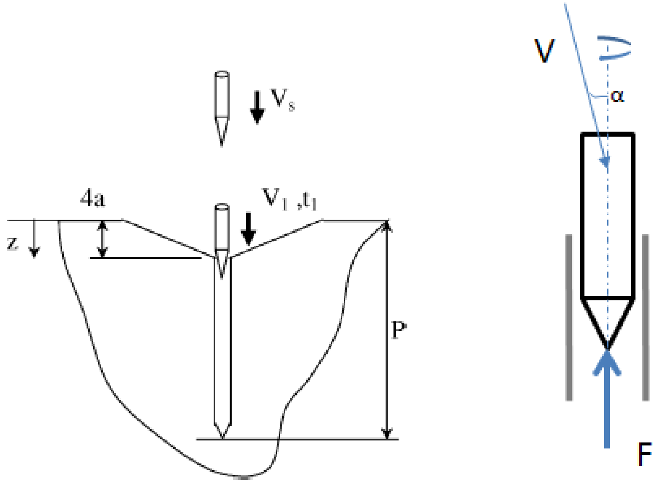


Figure 4 - Penetration geometry for Forrestal model [ref 1] and corresponding simplified FE model

Also in Task 1, a series of screening simulations would be performed. These consist of a 2-level design of experiments (doe) with factors being the yaw angle, concrete strength, projectile spin rate and impact velocity. If using a fractional doe design, eight simulations would provide a linear regression equation for the tail flexural deflection as a function of spin, angle of attack, deceleration and initial impact velocity. This information would be useful in design of the test article holding fixtures. Of particular interest here is the estimate of sensitivities of the projectile bending deflection to the spin rate. Modeling would help determine if the presence of torsion inertial loading must be included or omitted altogether in testing. Another consideration is the apparent dynamic stress amplification factor as a function of force duration (or initial velocity). Addressing it allows determination of the minimum impact duration necessary to represent a particular structural damage. Although the obtained results would not be general due to limited considered parameter ranges and a single projectile geometry, they should provide sufficient design information to develop a test solution for the provided test article specification. The task output data is essential for selecting a representative test configuration that may be used in the following effort.

2 - Modeling multi-axis loading during impact testing

In task 2, by modeling the impact of a stationary, off-axis projectile and flying, steel mass (Figure 6), multi-axis loading is replicated. Included in this effort, is the design of the projectile-holding and pulse-shaping fixture which draws upon Task 1 simulation results. Due to the need for converting a relatively fast metal-to-metal impact to a millisecond scale event, a non-elastic energy conversion with associated losses must be considered at this stage. Unless acceleration pulse shaping provisions are employed in the design, the impact of a flying mass would result in a several microseconds long, high magnitude shock profile, instead of the desired 5 milliseconds long event.

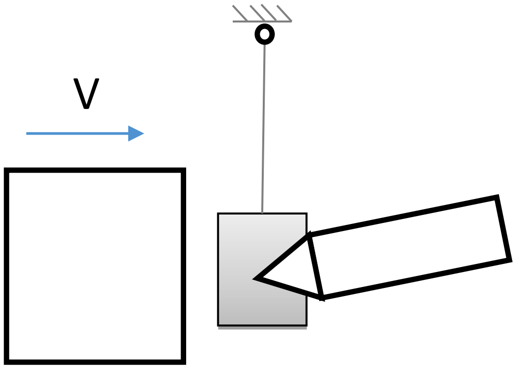
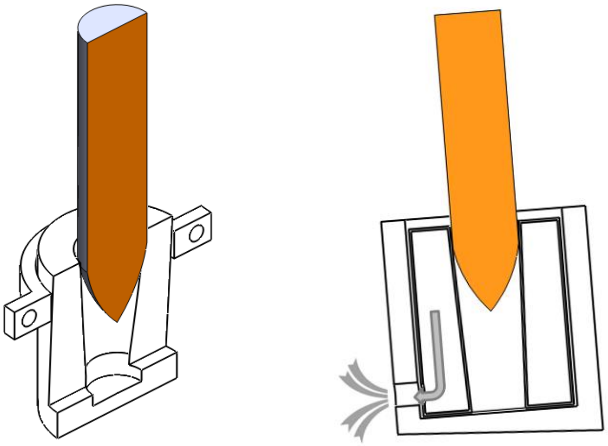


Figure 5 - FE model for fixture design

An acceptable fixture design would allow adjusting of the confinement pressure to the nose part while still allowing relative fixture-projectile motion. In a sense, the fixture not only acts as a shock profile shaper but would also provide a moving boundary condition that we believe is critical in tail-slap motion initiation. While pulse shapers are usually designed by experimental trials of different materials, we think that the needed kinematic boundary component required here makes numerical modeling a preferable design tool

Two initial fixture design concepts are presented in Figure 8. The concept in Figure 8a is essentially a split cylinder with a diminishing internal diameter and adjustable radial stiffness by means of an external clamp ring; the second concept has an internal donut-shaped cavity filled with a viscous fluid (figure 8b). This fluid may be discharged at a predetermined rate based on a built-in orifice size and operates on a dashpot principle. The design intent of both concepts is to replicate confinement pressures on the projectile shell while providing a sliding, "fixed" boundary to the non-penetrated portion of the projectile.



a) b)

Figure 6 -Confinement fixture initial concepts

The finite element model would include elastic-plastic material properties. Material strain rate effects are accounted for using a Cowper- Symonds model that scales the static material yield stress with a predefined exponential parameter. The necessary material parameters are adapted from literature. Each concept is subjected to a short duration velocity change and its design parameters and materials adjusted until the desired performance is achieved. Performance is understood as either a five millisecond long, 10,000 g acceleration from the topic solicitation, or accelerations recovered in Task 1 for the specified test article. Because of the non-linear nature of the system's response, the process would involve a number of iterations.

Each of the design concepts would be judged by three parameters: fixture mass, shock profile shaping, and moving boundary replicating ability. Energy losses and apparent restitution coefficients should also be quantified and presented. Ultimately, the lowest weight design with an acceptable performance is desired; its mass combined with the mass of the test article would then define the impulse and energy requirements for the shock tester.

3 – Five mass velocity amplifier design

The dynamic behavior of an ideal maximum gain velocity amplifier is described [2] as

$$G_n = \frac{(1+e)^n}{\left(1+R^{\frac{1}{n-1}}\right)^{n-1}} - 1 \qquad \text{Eq. 2}$$

where *Gn* is the overall gain, *e* is the restitution coefficient, R is the ratio of smallest and largest masses in the chain and n is the number of masses.

The rigid body dynamics formulation in Eq. 2 predicts that velocity increase by a factor of five is possible with four or five masses in the system assuming a restitution coefficient of 0.9. At first glance this makes the velocity amplifier design appear trivial; however, the amplifier theory is based on simplified dynamics and is not sufficient to describe the instantaneous forces occurring during pair-wise amplifier mass collisions. Even a fully elastic impact (i.e. no material yielding) does not automatically result in a restitution coefficient of unity because shock loading excites numerous vibration modes in real materials. The energy that is converted to standing vibration waves would eventually be dissipated and lost by material internal damping. Thus, the impact would not be "elastic" in a rigid body dynamics sense. Consequently, if stresses on contacting interfaces exceed the colliding materials' yield stresses, a localized plastic flow would lead to further energy losses. For these reasons, the feasibility of transferring impact energy based on a fairly high required restitution coefficient should be investigated.

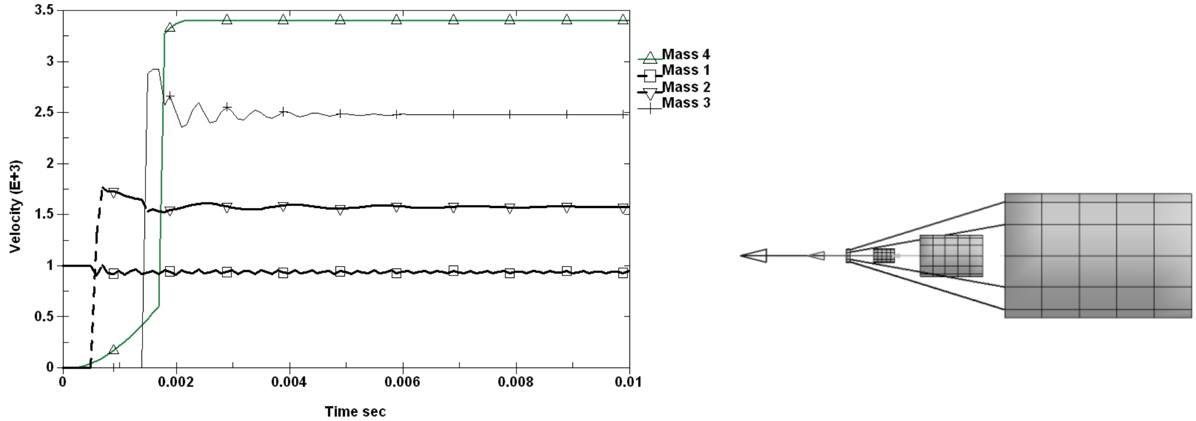


Figure 7 - Mass chain velocity amplification by finite element analysis

To illustrate the argument, Proof Engineering performed a simple analysis using arbitrary but diminishing sized cylindrical rods, elastic-plastic materials with properties of steel, and contacts with 10% damping (Figure 9). Clearly, the resultant restitution coefficients (found as ratios of two body velocity differences before and after collision) are on the order of 0.5. The overall velocity amplification of 3.5 was achieved only after connecting the first and the last body with soft springs, otherwise velocity gain was under 3.0. The simulation underscores a non-optimized behavior of kinetic energy transfer, characterized by the time a stress wave travels through the body.

To optimize the performance (and thus reduce weight) of the amplifier system, it is necessary to match the stiffness of contact interfaces and natural frequencies of contacting bodies for maximization of elastic compression and rebound. It has been reported [5] that maximum kinetic energy transfer occurs only when the impact pulse duration is equal to a fraction (i.e. ¼, ½, 1.0) of the natural period of the impacted part. If this statement is indeed true, the impacting bodies of the mass stack would only need to be dynamically tuned to the same lowest natural frequency. In doing so, velocity amplification would be maximized without any regard to interface stiffness other than material yielding limits. With this in mind, a trade-off study may be performed in terms of occupied volume by modeling a stack of masses in the shape of a) cylinders, where natural frequency is inversely proportional to the square of length, and b) thick plates (whose natural frequency is a function of thickness and side length) under impact. Throughout the study, underlying shock and vibration theory principles [3] used in designing vibration shock absorbers would be utilized. Internal structural damping is assumed as 2% of critical and the potential plastic deformation would be captured through use of elastic-plastic material models. Using arrangements of two colliding bodies with identical and differing natural frequencies, apparent restitution coefficient's dependency on the bodies' natural frequency ratios would be shown. With this information, the velocity amplifier weight stack may be optimized to the required impact loading, making sure that stresses remain below the yield point at impact contact interfaces. Note that fairly conservative estimates for amplifier performance are assumed; an effective restitution coefficient in the 0.75-0.80 range would still result in a reasonably compact velocity amplification system. In the exercise described, stresses would be obtained using a dynamic explicit analysis (LS-Dyna code). The design would be documented in CAD software and necessary design features such as linear bearing guides integrated. The outcome of this task would be a preliminary design of the amplifier system which would serve as a critical component for the system scalability evaluation. The design would be sufficiently mature to manufacture a scaled physical proof-of-concept prototype to be tested in Task 6.

4 - Design of a launcher

Task 4 would include preliminary design of a single stage compressed gas gun launcher used to accelerate the largest first mass in the velocity amplifier stack. The main advantage of this type of launcher is its relative simplicity, reliability, and ability to adjust the launch velocity by gas pressure regulation. Also, this concept is a non-pyrotechnic launcher therefore avoiding extensive development and safety certification. In general, the intention is to use the smallest air gun capable of launching the required payloads.

The suggested design approach would generally follow the development process as outlined in D.G. Wise's Universal Air Gun Launcher System [4]. In this report, a four feet long, 10 inch diameter gun with an external gas storage tank is developed to launch payloads weighing up to 40 lbs with velocities of up to 400 fps. The suggested system requires similar launch speeds but much heavier payloads which in turn requires increases in barrel diameter, barrel length and operating pressures. In order to develop a compact system, trade-off studies using barrel length, diameter, storage volume, and gas pressure as design variables to minimize the system weight may be performed. The payload is determined a priority by results of the previous tasks. Barrel and storage tank thicknesses and material requirements may be calculated using ASME Pressure Vessel Code guidelines. Concurrently, expanding gas pressure calculations may be performed using adiabatic expansion thermodynamics; the gas transported from the storage tank would be determined by a standard choked orifice air flow approach. Mass acceleration would be computed as pressure multiplied by barrel area and divided by mass, while the launch velocity calculated by integrating mass accelerations over the barrel length. A numerical simulation of the launch may also be performed in LS-Dyna (ALE formulation) for design verification. The resulting optimized system would be then documented using CAD software.

5 - System integration and scalability study

To determine scalability of the compact shock tester, a thorough understanding of the relationship between various test payloads and resultant machine parameters is required. In this study, the system may be considered scalable if it is able to accommodate increases in payloads and/or shock acceleration pulses with simple changes of geometry, weight and operating parameters. At the same time, the underlying technology and architecture should be maintained. Scalability may be limited by physics, material capabilities, or the commercial availability of certain components.

This effort would include development of a system level mathematical model allowing determination of main component dimensions for various test payloads. The model would utilize standard engineering calculations to determine machine parameters from the required velocity changes, shock durations, and test article masses. Structural, thermodynamic, and Newtonian dynamics formulae would be used to determine optimal configurations of the launcher, compressed gas storage, and the velocity amplifier unit. Operating loads and stresses acting on machine components would then be evaluated, followed

by calculation of test system parameters necessary for accommodation of 10, 50 and 100 lbs test payloads under identical shock acceleration pulses.
Following these exercises, sub-system level CAD models developed earlier would be integrated and a set of top level engineering drawings of the machine would be generated.

12.0 References

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