LIGHTWEIGHT SMALL ARMS TECHNOLOGIES

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ABSTRACT

From the groundwork laid by the Objective Force Warrior program, the concept of the Soldier as a System was established to create a fully integrated, modular soldier system, based in part on the Future Combat System concept. One of the major reasons for this new way of thinking is that while technology advances and becomes more readily available to ground troops, it results in increasing combat load.

The Lightweight Small Arms Technologies program was established to address this critical issue. The goals of the program prioritize weight reduction over any other characteristic, while balancing the requirements of lethality, reliability, and cost. This presentation focuses on two aspects of the system: lightweight ammunition, and the use of modeling and simulation in the weapon development.

1. INTRODUCTION

The five largest contributors to the Warfighter's load are his weapon, ammunition, protective equipment, communication equipment, and water. The order varies based on the mission and the role of the individual, but the weapon and ammunition are always in the top five.

Established in FY04 as the Lightweight Machine Gun and Ammunition program, the name was changed to Lightweight Small Arms Technologies (LSAT) in FY05 to change the focus of the effort from development of a specific weapon and ammunition system to a suite of technologies that are adaptable and scalable to small arms in general.

To provide a direct comparison with existing systems, the technologies will be demonstrated via a 5.56mm caliber light machine gun. Parallel studies and subsystem demonstrations will address scalability of the technologies- both in caliber and to a family of small arms.

Beginning with a "clean slate", dozens of technologies, applications and concepts were evaluated in a systematic series of trade studies. Again, with weight as the top priority, all of the concepts were then assessed for their ability to provide benefits in the areas of lethality, reliability, and cost, with added factors for training and maintainability. For nine months, two different contractor teams developed their concepts for weapon and ammunition systems that provided the maximum payoff. In February 2005, the AAI Corporation based team was selected to continue for the remainder of the program.

The LSAT program is developing the ammunition and weapon as a system. The AAI concept is based on the parallel development of two ammunition concepts and associated weapons: cased telescoped (CT) and caseless (CL) designs. The weapon design is uniquely configured to fire this ammunition, and incorporates a high level of design and functional commonality between the CT and CL versions. Figure 1 illustrates the key ammunition and weapon technologies being pursued on the LSAT program.

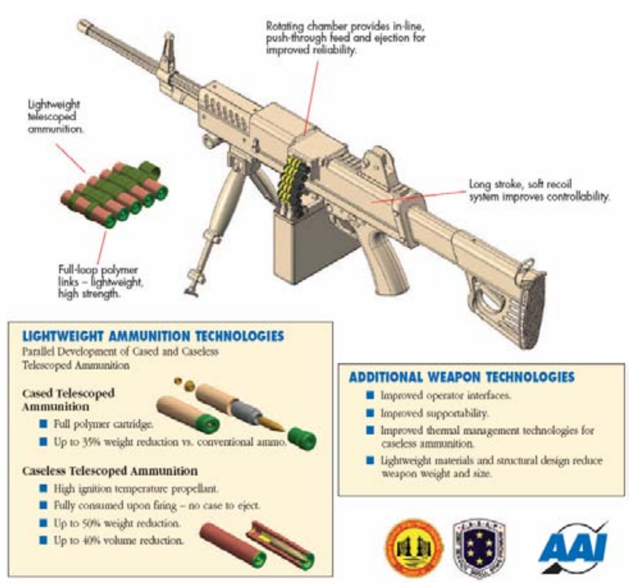

Fig. 1, LSAT Ammunition and Weapon Technology Highlights

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System weight reduction estimates for both systems are illustrated in Figure 2. Both concepts exceed the system weight reduction goal of 38%, with the CL design providing a 50% overall weight reduction.

Fig. 2, LSAT Weight Reduction Exceeds Goal

Phase I of the LSAT program was completed in January 2005. It was a nine-month system design and trade-off effort that used virtual prototyping to develop recommended ammunition and weapon concepts. Phase II is a 28-month prototype fabrication and testing phase currently in progress. Prototype lightweight weapons and ammunition are being assembled and tested to demonstrate concepts and validate design trade-offs. Phase III will encompass all final subsystem and system integration testing.

Once these technologies are successfully demonstrated in Tech Base, the program will transition to a System Development and Demonstration program in PM Soldier Weapons. While there are many milestones that remain before fielding, the program remains focused on increasing the effectiveness and mobility of our ground forces, and reducing the overall logistics footprint of small caliber weapons and ammunition.

This presentation will focus on two key aspects of the LSAT program:

- Lightweight ammunition technologies
- Use of modeling and simulation for weapon development

2. LIGHTWEIGHT AMMUNITION TECHNOLOGIES

The AAI concept is based on a parallel ammunition path. The two ammunition concepts being developed are cased telescoped (CT) and caseless (CL) ammunition (See Figure 3). For demonstration purposes, both cartridges designs have been sized for the current M855/M856 bullet family, and provide equivalent ballistic and lethal characteristics to the current conventional cased ammunition. Both of these ammunition concepts utilize a lightweight, full loop polymer link.

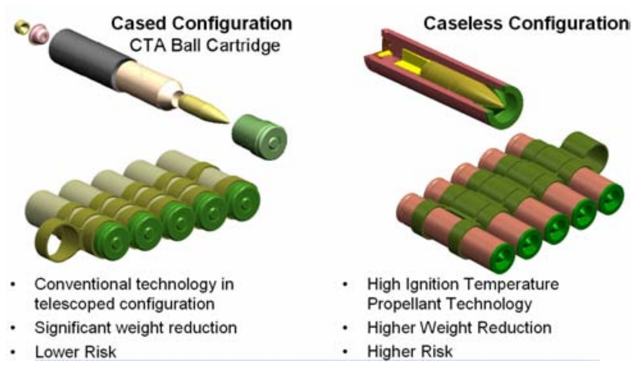

Fig. 3, Cased Telescoped (CT) and Caseless (CL) Ammunition Concepts

2.1 Cased Telescoped Ammunition (CT)

Cased telescoped ammunition is a 100% polymer cylindrical shaped case, inside of which are the projectile (ie, telescoped inward) and the propellant, with a standard mechanical primer located at the base. This approach offers a fairly low technical risk, and provides over 30% weight reduction as compared to standard ammunition.

A spiral development approach is being pursued- Spiral 1 is complete, and entailed development of a cartridge for initial weapon function tests. Spiral 2 is nearing completion, and focuses on material selection, geometry optimization, primer characterization, and propellant finalization. Spiral 3 is a future activity that will focus on production details and further weight optimization.

Highlights of the Spiral 1 & 2 CT ammunition development effort include:

- Over 1,800 rounds have been fired to date.
- Approximately 15 polymer material candidates were tested across a temperature range of -65°F to 145°F to

assess structural integrity and deformation characteristics. A suitable material was identified and has been selected as the baseline (see Figures 4 and 5).

Fig. 4, Molded Case Material Examples

Fig. 5, Example of Failed Case Material vs Successful Material (Fired -65°F)

- Numerous geometry variations were analyzed and tested- including the primer interface, bullet interface, cartridge sealing, and case thickness profile. Particular focus was give to primer initiation characteristics, which in this configuration differ significantly from a conventional brass cartridge case.

- Achieved interior ballistics performance levels equivalent to the M855 baseline (propellant weight, chamber pressure, muzzle velocity).

2.2 Caseless Ammunition (CL)

Like the cased ammunition design, the caseless cartridge also uses a telescoped bullet arrangement. A specialized High Ignition Temperature Propellant (HITP) provides not only the propulsive energy, but also serves as the cartridge structure and exterior surface. Caseless ammunition provides a remarkable 50% weight reduction over the current ammunition.

HITP, which contains HMX as its major constituent, was originally developed by Dynamit Nobel, and demonstrated in the Advanced Combat Rifle (ACR) program in the 1980's. The HITP, along with an external coating, provide sufficient mechanical strength and durability to withstand handling, storage, and transportation, and no additional protection is required. This concept also uses a standard projectile and mechanical primer, but requires the use of a booster, which provides impetus for full ignition of the propellant. HITP is uniquely suited to use for caseless ammunition because it has a cook-off temperature which is significantly higher than standard nitrocellulose based propellant.

The LSAT caseless ammunition development is being undertaken with a significant level of cooperative testing and analysis between the ARDEC Energetic Materials Branch and the AAI team. Within the AAI team, Alliant Techsystems (ATK) has the lead for the caseless ammunition development. To date, the HITP formulation from the ACR program has been successfully replicated by the LSAT Government/contractor team, and is entering the ballistic test phase of the program.

A spiral development approach is being used to develop the LSAT caseless ammunition. Spiral 1 is complete, and consisted of re-establishing and improving the technologies used in the ACR program. Spiral 2 is currently underway, and entails scaling the design to the LSAT configuration.

The Spiral 1 development sequence was as follows:

a) Characterize the chemical, physical, combustion and safety characteristics of both the raw material and completed product for the baseline ACR HITP body as well as the integrated cartridge. Develop chemical and interior ballistics models to match measured characteristics.
b) Develop the HITP material and processing approach, including: identify material sources and/or synthesize, develop propellant mixing and fabrication process, assess safety parameters associated with processing steps, design and build proof-of-concept tooling for fabrication studies.
c) Fabricate HITP and integrated cartridges in the ACR physical configuration- square propellant body containing a 4.92mm bullet. Develop ancillary cartridge components- primer, booster, exterior coating, and projection retention cap.
d) Test the items fabricated in step c) at a component level, including chemical constituents, density, break strength, closed bomb burn rate, ignition, and cook-off. Adjust parameters and refine process as necessary.
e) Test integrated 4.92mm cartridge interior ballistics performance. Adjust parameters and refine process as necessary.

Some highlights of the Spiral 1 caseless ammunition development activities are presented below.

- Over 600 HITP bodies fabricated. Several "Design of Experiment" studies conducted to correlate various chemical and processing parameters with properties of the completed cases.

- HITP fabrication- The original HITP fabrication process used during the ACR program required approximately 14 steps to fabricate the HITP cartridge body after ingredient mixing was complete. For LSAT, this process was reduced to 2 steps, yet produced the same finished product. Figure 6 illustrates a 16-run ¼ Fractional Factorial "Design of Experiment" study performed during the HITP development. Completed HITP propellant bodies are shown in Figure 7. The primer is shown in Figure 8.

Mix #	Factor X	Factor Y		Torque	Hold	Temp	Performance Parameter			
		ID1	ID2				1	2	3	4
1	A	70	8	L	6	70	20.4	15.6	72.95	33.16
2	A	70	8	H	6	40	32.6	23.4	74.29	50.87
3	A	70	12	L	1	40	27.9	20.4	73.39	44.62
4	A	70	12	H	1	70	22.8	17.6	71.82	37.73
5	A	140	8	L	1	40	23.0	17.6	72.58	37.82
6	A	140	8	H	1	70	27.9	20.5	74.25	44.09
7	A	140	12	L	6	70	31.0	22.7	74.06	49.05
8	A	140	12	H	6	40	26.7	20.3	73.10	43.24
9	B	70	8	L	1	70	86.2	49.5	74.67	129.54
10	B	70	8	H	1	40	99.5	56.1	74.75	146.98
11	B	70	12	L	6	40	91.4	46.8	72.67	142.93
12	B	70	12	H	6	70	109.5	57.4	74.92	159.67
13	B	140	8	L	6	40	90.9	47.2	74.39	134.25
14	B	140	8	H	6	70	86.1	48.9	73.16	134.27
15	B	140	12	L	1	70	108.0	54.4	74.70	157.89
16	B	140	12	H	1	40	122.5	62.7	75.13	176.78

Fig. 6, HITP "Design of Experiment" Parameters

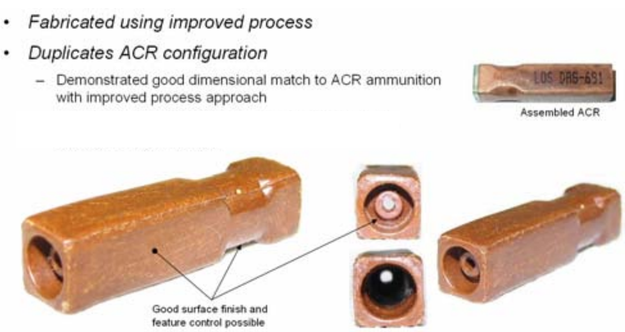

Fig. 7, Completed HITP Bodies (ACR Configuration) Fabricated Using Improved Process

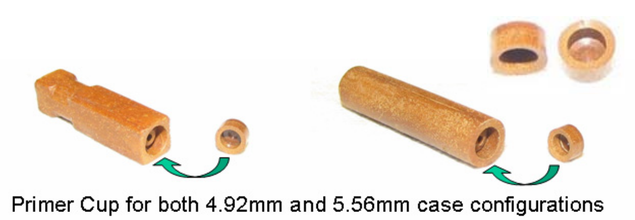

Fig. 8, Completed HITP Primer Cup

- Cook-off- The ability to resist cook-off in a hot weapon is a critical characteristic of caseless ammunition. Characterization of the original ACR caseless ammunition alongside the LSAT replicated ammunition was conducted using the cook-off fixture shown in Figure 9.

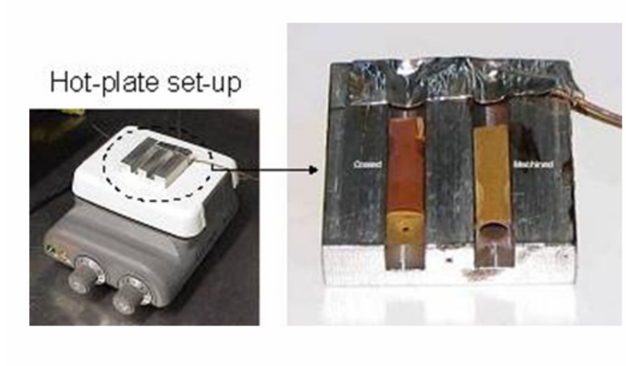

Fig. 9, HITP Cook-off Test Fixture

The results of the cook-off tests are provided in Figure 10. The newly fabricated ammunition demonstrated a close correlation to the original ACR ammunition data, and shows a significant increase in cook-off temperature relative to standard nitrocellulose based propellant.

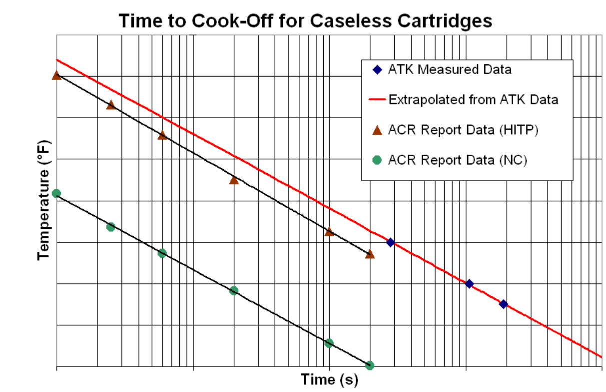

Fig. 10, Replicated HITP Cook-off Test Results Demonstrate Close Correlation to Original Data

- Combustion- HITP combustion characterization tests were conducted using several methods. Initial measurements were obtained using a strand burner, followed by closed bomb measurements using both pressed pellets and entire cases. Specialized fixtures were developed to measure primer and booster combustion properties. The final verification of interior ballistics performance was conducted using the integrated cartridge (4.92mm ACR configuration) in a Mann barrel firing fixture. Figure 11 illustrates burn rate measurements between the original ACR (G11) HITP and material fabricated on the LSAT program. The instrumented integrated cartridge Mann barrel firing fixture is shown in Figure 12.

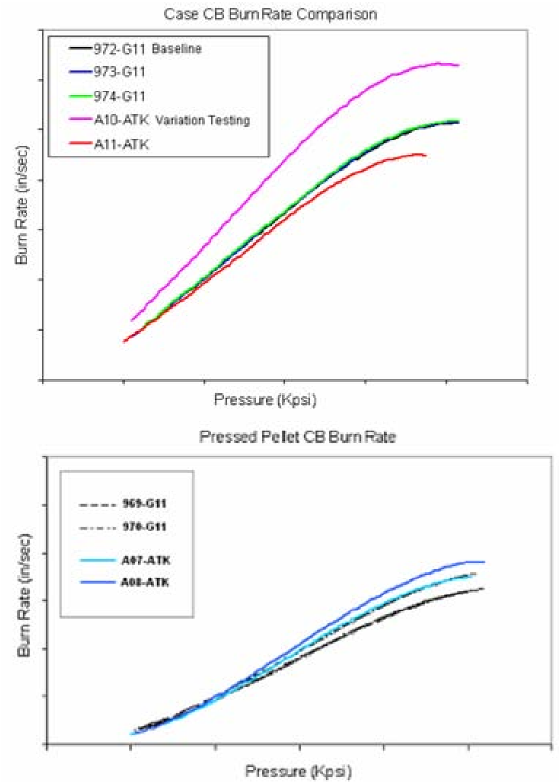

Fig. 11, Closed Bomb Burn Rate Measurements for HITP Fabricated on the LSAT Program Closely Match Performance of the Original ACR (G11) HITP.

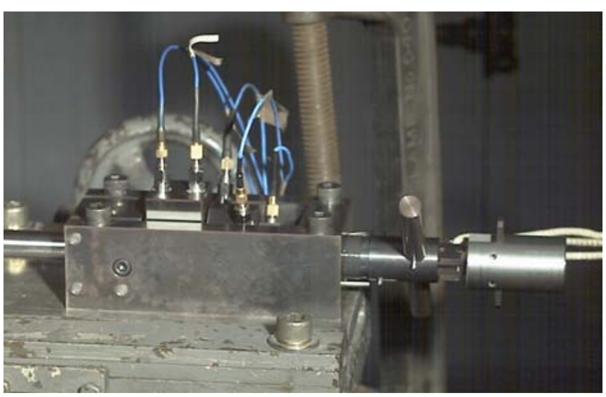

Fig. 12, Spiral 1 Integrated Cartridge Instrumented Firing Fixture (ACR Cartridge Configuration)

Spiral 2 of the caseless ammunition development entails applying the knowledge gained in Spiral 1 to the design and fabrication of 5.56mm configuration. This effort is currently under way, and initial HITP bodies have been produced, as illustrated in Figure 13.

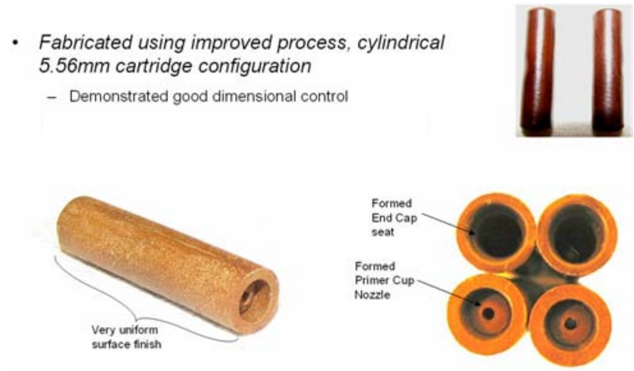

Fig. 13, LSAT 5.56mm HITP Cartridge Bodies

3. WEAPON MODELING AND SIMULATION

In order to fire this uniquely configured ammunition, a new weapon is also being developed. In the early stages of the program, the development of the weapon was performed 100% virtually, and modeling and simulation continues to be a major contributor to the success of the program. The overall weapon design was previously shown in Figure 1. A photograph of CT weapon Serial Number 1 mounted in the test fixture is provided in Figure 14. This weapon has now fired over 1,100 rounds, and has demonstrated successful burst fire, semi-automatic fire, feed from a simulated ammunition canister, and proper function at various orientations.

Fig. 14, CT Weapon SN1 Mounted in Test Fixture

Key weapon operating mechanism design parameters are shown below:

- Propellant gas powered operating system
- Rotating chamber- out of line for feed, in-line to fire
- Straight through ramming/ejection
- Fires from "open chamber" (analogous to "open bolt")
- Long stroke soft-recoil system
- Linked belt feed system
- Both semi-automatic and full automatic firing modes

The weapon action utilizes a rotating chamber which operates in a manner analogous to an "open bolt" system. The chamber rotates in and out of line with the barrel, so the ammunition can be fed straight in from the feed tray. The chamber then rotates into line with the barrel, the weapon fires the ammunition, and the chamber rotates back into the out of line position, where the next round fed in pushes out the empty case. This is all done at approximately 600 rounds per minute, and is only possible because of the cylindrical shape of the ammunition. Both the CT and CL weapons operate in the same manner; however, the CL weapon incorporates an additional chamber sealing mechanism, while the CT weapon relies on the cartridge case to seal the chamber. Consequently, the caseless weapon is slightly heavier than the CT weapon due to additional components required for chamber sealing.

The rotating chamber weapon action provides numerous operating benefits:

- Full positive motion control provides robust operation under harsh conditions.

- Straight push-thru feed system simplifies the feed/extraction process. In particular, no extraction groove is required in the ammunition.
    - For the CT cartridge, elimination of an extraction groove allows the case weight to be minimized by the use of a thin-walled lightweight polymer material. This eliminates one of the most significant technical barriers which historically prevented the use of polymer cased small arms ammunition.
    - For the CL ammunition, lack of an extraction groove eliminates the potential for propellant structural failure during extraction, an issue historically associated with caseless ammunition.
    - Push-thru feeding also allows the use of full circumferential links which have the benefit of enabling a robust link design to be achieved using a lightweight polymer material, providing a 70% weight reduction in the links alone. This also allows either end of the belt to be fed first, whereas current systems can only be fed from one end of the belt.

- Isolation of the chamber from barrel heat.
    - For CT ammunition, the insulating characteristics of the polymer cartridge case and isolation from the barrel combine to keep the maximum chamber temperature well below the softening point of the cartridge material. This eliminates the second significant technology barrier experienced in the application of polymer cases with conventional cartridges.
    - For CL ammunition, use of a separate chamber greatly simplifies the implementation of chamber insulating technologies which historically have been difficult to employ in a conventional chamber arrangement.

Given the unique weapon operating features discussed above, the LSAT weapon cycling dynamics differ considerably from conventional weapon designs. The use of modeling and simulation (M&S) to understand and refine the operating characteristics in advance of hardware fabrication provided a considerable benefit to the program schedule and significantly reduced the number of iterations required once testing began.

Another benefit of the M&S used for weapon development was that it allowed the maximum usage of lightweight materials in low stress areas as indicated by the finite element analysis, resulting in a functioning weapon that weighs 50% less than the current light machine gun.

From a modeling perspective, a gas-driven, belt-fed machine gun qualifies as a challenging mechanical system for analysis. Of special importance to the evaluation of such an engineering problem are the correct modeling of contact effects associated with the camming actions of the weapon mechanisms and also with the passage of the ammunition into the weapon and the ejection of the spent cartridges from it. Effects such as friction and component flexibility can dramatically affect the weapon performance in terms of its cyclic rate of fire, its robustness, and its durability. Starting from 3D Parasolids-based model assemblies, MSC ADAMS and MSC NASTRAN were used to model the LSAT light machine gun demonstrator. Figure 15 depicts the MSC ADAMS kinematic model.

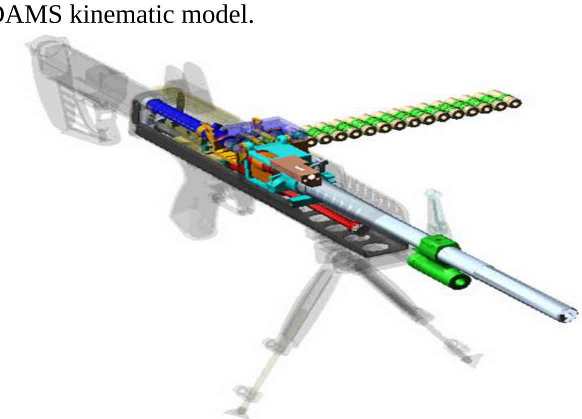

Fig. 15, MSC ADAMS Kinematic Weapon Model

3.1 Modeling Methodology

The weapon kinematic model was developed by team member MSC using their ADAMS dynamic modeling software. All geometry was derived from weapon and ammunition 3D solid models. All functional parts were modeled to their correct size, weight, stiffness, and contacts.

The initial simulation effort focused on verification of geometric clearances and component ranges of motion. Once free movement of the components was established, the focus shifted to simulation of the dynamic operation. This was followed by introducing Finite Element stress analysis modeling via MSC NASTRAN to evaluate the stress and flexure of components while subjected to the dynamic loads.

3.2 Analysis Results and Refinements

Representative initial design studies conducted using ADAMS model were:

- Sensitivity to friction
- Effect of gas pulse profile
- Link stiffness effects- stresses and belt pull
- Belt support options
- Evaluation of stresses and deformations via integration with MSC NASTRAN and LS DYNA

Representative initial design issues and corrective actions identified via the ADAMS model included:

- Feed pawl over-ride: corrected via revised pawls
- Rammer bounce: corrected by adding lock to design
- Chamber bounce: corrected by revising lock design
- Inconsistent ejection: elected to monitor during tests
- Significant belt whip: elected to monitor during tests

Example analysis- The cyclic rate of fire of the weapon is extremely important and is a function of how heavily loaded the weapon is at any point in time. This loading can be affected by the number of rounds belted, the way the rounds are stacked, the state of round/weapon lubrication, instantaneous weapon attitude and/or dynamics, and a host of other factors. MSC ADAMS provided an accurate history of the position and velocity of the operating slide, and the associated forces transmitted to the ammunition belt links during the feed cycle (see Figure 16).

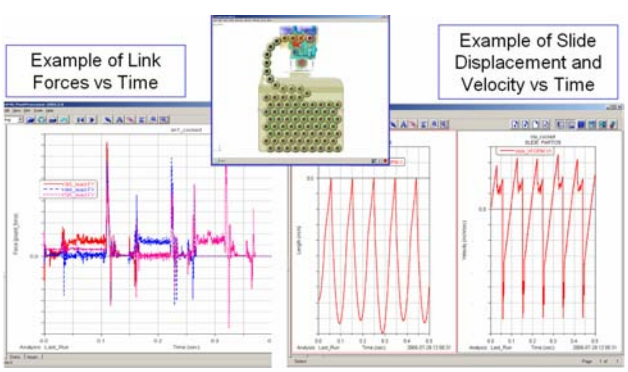

Fig. 16, Weapon Kinematic Output Examples

Once the weapon hardware was fabricated and testing commenced, the ADAMS model was validated against the actual operating characteristics. It was then used to support diagnosis and correction of problems identified during firings.

The ADAMS model proved extremely accurate in simulating the performance of weapon SN1. However, the validity of a few predictions were initially questioned by the design team, and a "wait and see" approach was employed rather than changing the design up front. In nearly every instance, the ADAMS predictions proved to be accurate, and the items in question were subsequently modified based on the ADAMS guidance after testing began.

3.2.1 Model Refinement Example- Ammunition Belt. Figure 17 shows a model loaded with 20 rounds after firing 2 rounds. The rounds and links were macro-generated in a horizontal position and allowed to fall under the effects of gravity and feed mechanism dynamics. Problems soon emerged due to the appearance of violent belt 'slap'.

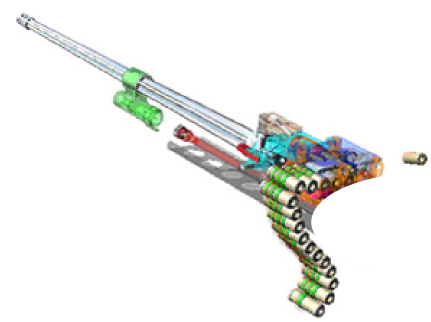

Fig. 17, Belt Feed Dynamics Example

Attempts to increase the round-to-belt CONTACT element stiffness did not solve the problem, resulted in numerical difficulties with the MSC ADAMS integrator, and precluded the setting of the CONTACT stiffness' to effectively model belt link elasticity, which is crucial to the accurate representation of the feed action.

To correct this modeling issue, the ammunition macro was reconfigured to avoid any MSC ADAMS CONTACT forces acting on the links. In the revised configuration, MSC Adams GFORCEs are used in combination with SENSORs to model the belt behavior. The GFORCEs connect each round to its respective link loops, and the SENSORs are employed to key these forces off the first time a reference point on the round passes a reference point on the lower tray. This permits the link, once it is free of the round, to be pushed out of the ejection aperture by the link behind it. This is just one example of the many detailed refinements that went into accurately modeling the weapon performance.

3.2.2 Non-Mechanism-Centric Modeling- An additional consideration in the LSAT M&S effort was developing a holistic modeling approach (to the greatest extent practical). In other words a single model should be capable of answering questions related to any service conditions/performance required of the system. This precludes the time-consuming and costly effort to generate a completely new model for every different loading scenario.

Analyses were conducted to show potential expanded use of the weapon model, including

- Durability Modeling – Impact. A complete assembly model was used to create a single, grouped MSC Adams CONTACT force between the weapon and a hypothetical ground surface. The weapon was 'thrown' horizontally from a height of approximately 3 ft onto a relatively soft surface. Figure 18 gives a superimposed plot of the motion and translational acceleration histories after impact.

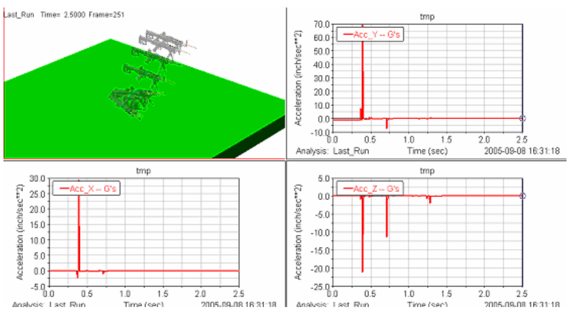

Fig. 18, Acceleration Histories Upon Surface Impact

- Recoil Study- An initial investigation was completed to examine the effect of elastic mount compliance on the functioning of the weapon model. An external shell was added to the mechanism model, which was then connected compliantly to ground at the butt plate and at each bipod foot. The plot in Fig. 19 illustrates the translational displacement histories of the muzzle with respect to ground, thus providing an indication of induced weapon motion during firing.

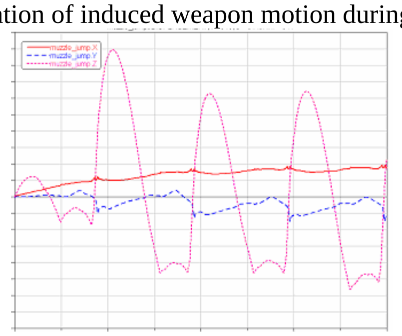
Fig. 19, Predicted Weapon Muzzle Motion During Firing

- Additional non-mechanism-centric simulations performed using this model include lift durability and vehicle mounted rough handling.

CONCLUSIONS

In conclusion, the LSAT program has made significant progress in developing lightweight weapon and ammunition technologies that will increase the effectiveness and mobility of our ground forces, and reduce the overall logistics footprint of small caliber weapons and ammunition.

The two ammunition concepts are being developed on a parallel path: cased telescoped (CT) and caseless (CL). The CT approach offers a fairly low technical risk, and provides over 30% weight reduction as compared to standard ammunition. Successful ammunition function has been demonstrated, and 1,800 rds of this configuration have been tested. Caseless ammunition provides a remarkable 50% weight reduction over the current ammunition, but entails more technical risk. All key fabrication and performance characteristics of the CL ammunition technology have been demonstrated.

The use of modeling and simulation to understand and refine the operating characteristics of the unique LSAT weapon design in advance of hardware fabrication provided a considerable benefit to the program schedule and significantly reduced the number of iterations required once testing began.

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