The Creation of a Fully Functional Virtual Prototype of an Automatic Weapon using MSC Adams

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Abstract

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 Parasolids-based model assemblies, this paper describes the use of MSC Adams and MSC Nastran to model an experimental light machine gun.

Background

Figure 1 below gives a general view of the weapon under consideration. It is a hand-held, gas-operated, automatic weapon designed to fire cased, telescoped ammunition (ref. fig. 2) from a free belt or from a canister . The belt links differ from those seen with most current ammunition belts for automatic weapons in that they are plastic and of the 'disintegrating' variety. A typical link is shown in figure 3.

Fig. 1 Light-Weight Machine Gun

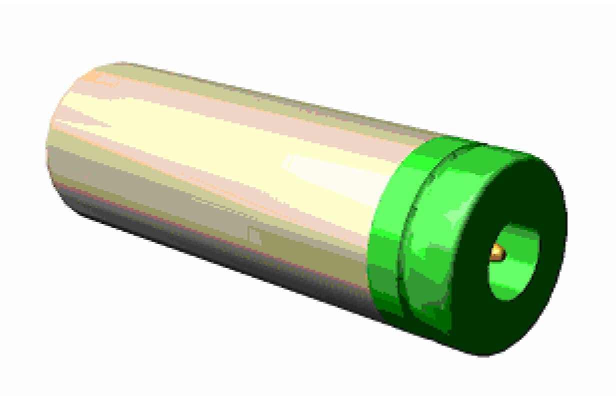

Fig. 2 Cased. Telescoped Ammunition Round (Typical)

Fig. 3 Ammunition Link (/typical)

The weapon is operated by tapping propellant gas from behind the projectile and using it to drive a piston, The piston is connected to a slide which drives a rotary feed cam and a linear rammer. The firing chamber is cycled by slide-mounted drivers engaging cam grooves on the bottom of the chamber carrier. Unique to the design is the use of the round being chambered to eject the spent casing of the preceding round.

Modeling Methodology

In keeping with the prudent *"crawl – walk – run"* philosophy of modeling, a stepped approach to the modeling was employed. Starting with a complete, Parasolids model assembly with every, individual component in its proper place in the assembly, the model was reduced to the essential parts necessary for the functioning of the virtual prototype model. The fundamental steps are enumerated below:

1) remove all non-essential parts
2) combine any parts which, when in the assembly, form non-articulating sub-assemblies
3) define constraints connections where contact effects are not important
4) define CONTACT elements wherever they are necessary for the correct interaction of parts
5) create (temporary) motion constraints to move the system and confirm its correct behavior
6) add visco-elastic elements (springs, bushings, buffers, dampers, etc) and verify their correct performance under constrained (e.g., kinematic) cycling.
7) verify the mass properties of the system components
8) replace the kinematic motion control with the force-based (i.e., kinetic) driving elements defined for the weapon
9) if repeated elements are present. use Adams/View macros to generate them using copy/move/rename command sequences

10) if test data is available, validate and tune the model where technically defensible to approach the known performance behavior.

Some Special Problems

Fig, 4 below shows the primary action of the weapon system, representative of the system as initially bench-tested, loaded with 10 rounds of ammunition.

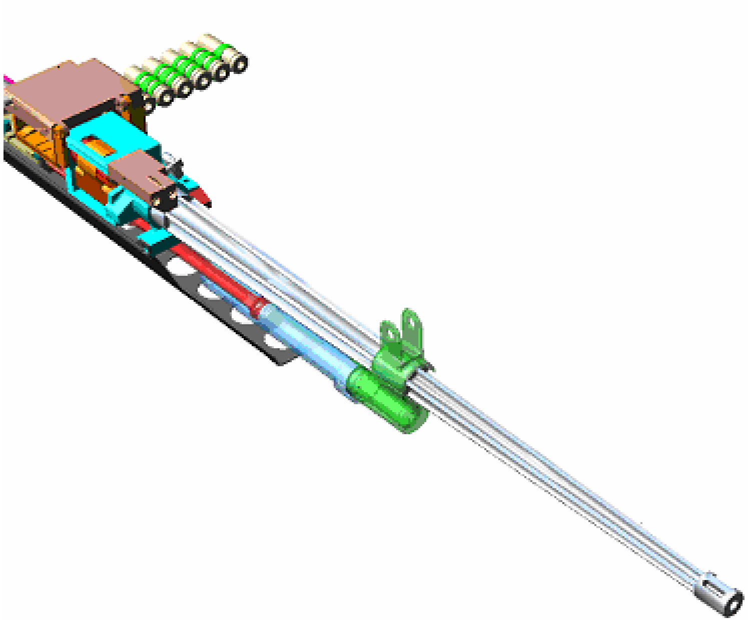

Fig. 4 Minimal System Model

Gas Piston Force Implementation

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. Regardless of these effects, the weapon must 'fire' correctly. Thus, even if the gas pulse is assumed identical for each round fired, the weapon can only fire when the firing pin contacts the cartridge primer, and the cycling rate will be a function of the weapon state at any point in time. MSC Adams SENVALl entities were used to sense when the firing pin reached the primer position, at which point a gas pressure pulse was triggered *each time the primer position was reached*. Refer to fig, 5 below for a typical gas pulse (input as an Adams/Spline).

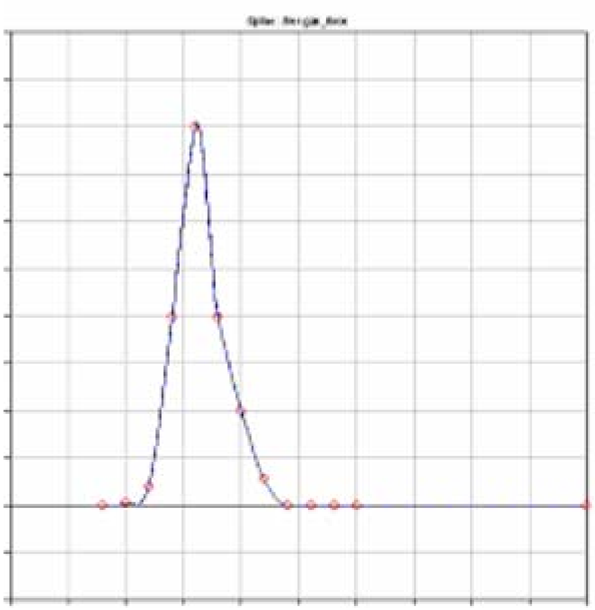

Fig. 5 Preliminary Model – Simplified for Cyclic Gas Piston Force Development

Figure 6 gives an idea of the force uniformity (vertical scale) and the time uniformity (horizontal scale) achievable with the weapon systems model. This plot was generated

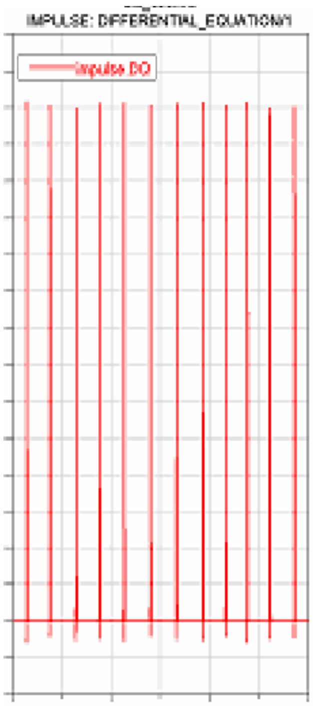

Fig. 6 Typical Pulse pattern During Automatic Fire

from a model loaded with 20 rounds and having the last round in the belt vertically supported at the feed aperture level.

Alternate Belt Modeling – Link CONTACTs Exchanged for GFORCEs

Fig. 7 shows a model f\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'. The free end of the belt would tend to exhibit 'crack-the-whip'-like behavior resulting in belt disintegration. On other occasions, the belt would wrap around the weapon action and 'stall' the feed drive. Under further analysis it was discovered that the belt disintegration problem persisted whenever more than 6-7 rounds were specified, with the violent contact of the rounds with lips of the feed aperture also causing spontaneous belt disintegration. The disintegration occurred any time a solid part was over-penetrated by another. This usually took the form of one of the loops of the belt link being pulled completely inside a round. 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 stiffnesses to effectively model belt link elasticity, which is crucial to the accurate representation of the feed action.

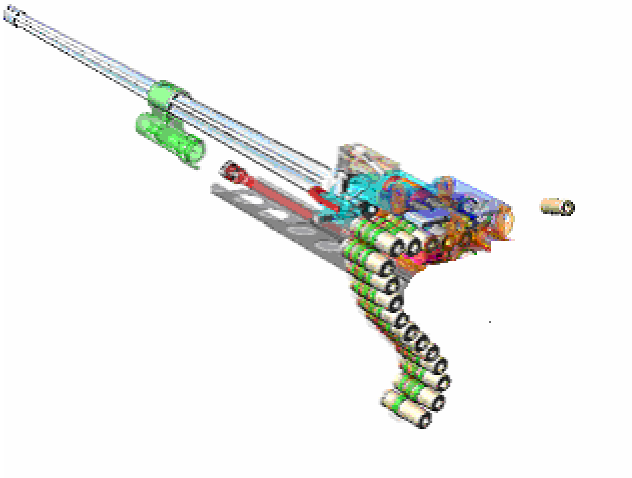

Fig 7 Model Exhibiting Belt 'Slap'

The decision was made to completely re-configure the ammunition macro 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.

Ammunition Canister Modeling – Inconsistent Round Geometry

The violent belt dynamics cited above pointed out how complex (and important) the belt behavior is to the system performance and led to questions about the weapon performance when feeding canistered rounds. Figure 8 shows the weapon with a canister partially filled with 30 rounds. Further modifications to the ammunition macro were required to properly stack the rounds, and, after the first 20 rounds, rigid constraints were used to connect subsequent rounds to the links.

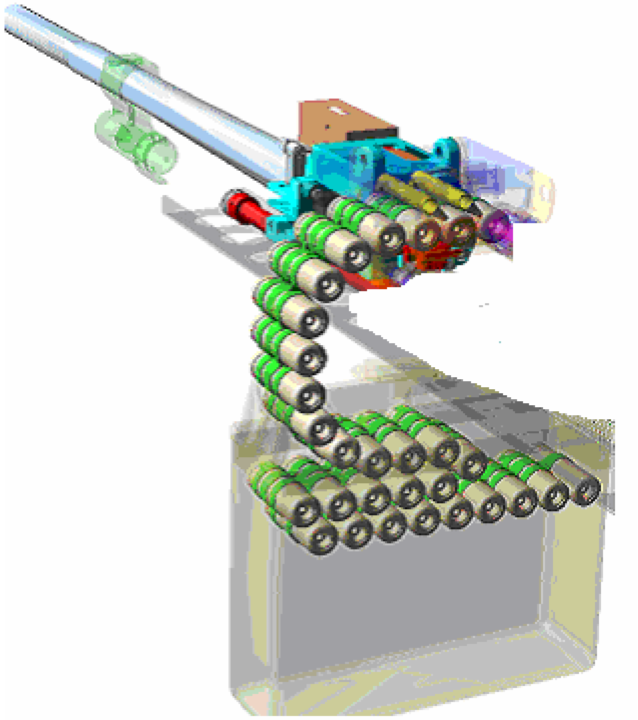

Fig 8 Weapon with Ammunition Canister and 30 Rounds

Non-Mechanism-Centric Modeling

It is the opinion of the author that a virtual prototype model should, if practical, be holistic. 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 necessity of generating a completely new model for every different loading scenario. With this in mind, a series of quick analyses were performed to show potential expanded use of the weapon model.

Ballistic Modeling

In order to more completely predict recoil effects, a quick study was made to determine the practicality of including projectile effects in the weapon model. MSC ADAMS GFORCEs were used to model both the cartridge/projectile and barrel projectile forces. An additional, aerodynamic drag force, using a very high drag coefficient was applied to each bullet as it cleared the muzzle to prevent the potentially high bullet displacements from impacting the analysis numerics. Fig. 9 shows the weapon with 3 rounds expended and a fourth moving down the bore.

Fig. 9 Weapon with Ballistic Modeling

No attempt was made to synchronize the piston actuation to the projectile position with respect to the gas port, although inclusion of this effect is certainly possible. The effect of bore rifling was accomplished by referencing each bullet twist to the total barrel twist relative to a MARKER located at the start of the bore. This corresponded to multiple full turns along the full length of the barrel and resulted in very high angular velocities for the bullets as they exited the muzzle. These high rotational velocities slowed the computational speed of the analysis appreciably. While this modeling was proved feasibly, further effort was dropped to concentrate on the weapon mechanism behavior.

Durability Modeling -- Impact

An initial investigation was completed to examine the possibility of using the MSC Adams virtual prototype model to perform durability investigations such as those described in document **AD/A136 335 U.S. ARMY TEST AND EVALUATION**

COMMAND TEST OPERATIONS PROCEDURE “AUTOMATIC WEAPONS, MACHINEGUNS, HAND AND SHOULDER WEAPONS”. A complete assembly model available was used to create a *single*, grouped MSC Adams CONTACT force between the weapon and a hypothetical ground surface (see fig. 10 below).

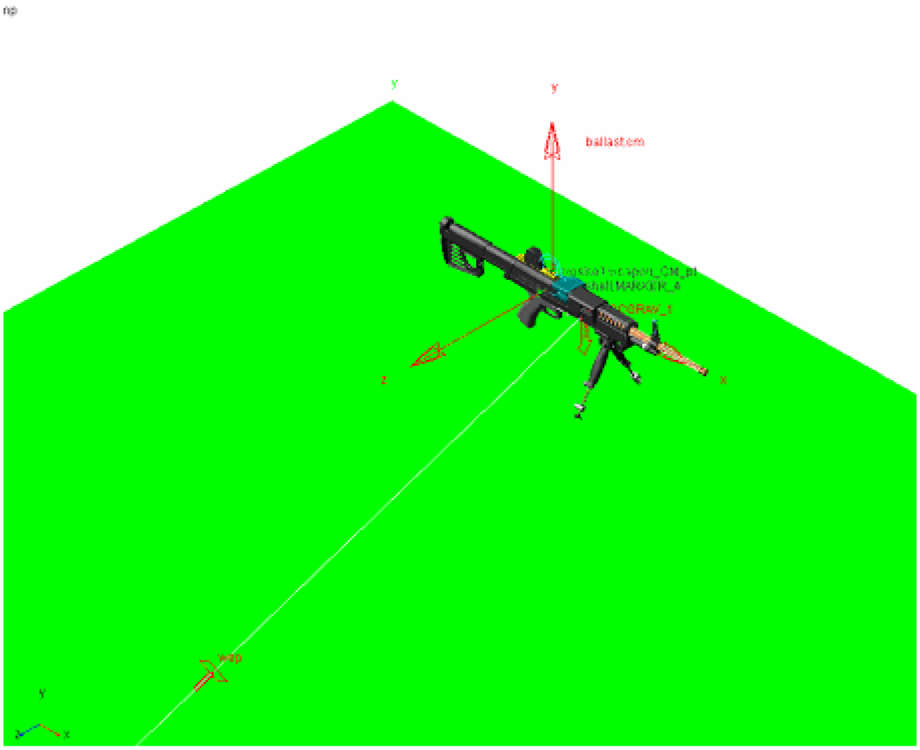

Fig. 10 Weapon Drop Test -- Simplified

Internal parts, not capable of ground contact and almost all pins, clips, buttons, etc were stripped from the assembly, after which all remaining parts were merged into a single component. This contact force references all the solids associated with the external surface of the weapon.

The weapon was ‘thrown’ horizontally (+Z-direction) to the right at a velocity of 6 ft/sec from a height of approximately 3 feet (+Y-direction) onto a relatively soft surface. No angular velocities are imparted to the weapon during the throw. Since the weapon was thrown ‘flat’, it contacted the bipod legs first, then the bottom of the butt. Its momentum caused it to continue over laterally into its right side. It rolled sufficiently that both bipod legs project upward at one point, after which it settled back onto its right side.

Figure 11 below gives a superimposed plot of the motion and translational acceleration histories in G’s.

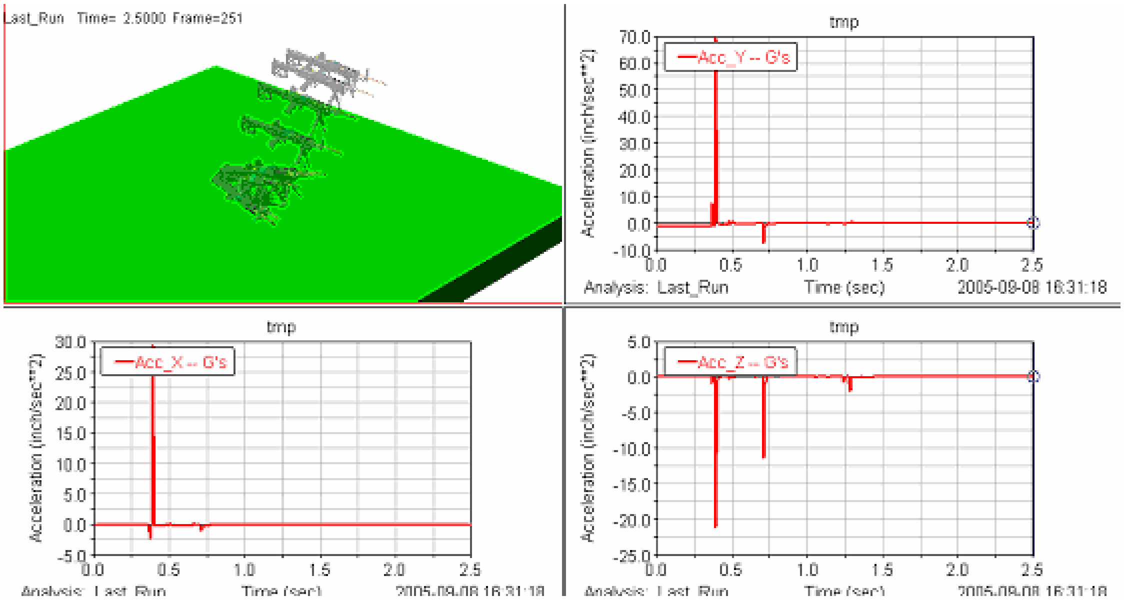

Fig. 11 Drop Simulation History

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Durability Modeling -- Lift

A cursory investigation was completed to illustrate the application of an MSC Adams FLEX_BODY to the issue of weapon durability. Fig 12 below shows the assembled model

Fig. 12 Infantryman Lift Model

comprised of a (rigid) infantryman possessing a weight of 250 lbs, standing on the approximate center of the weapon with his right foot (only). The structural model is a *very* simplistic, FEA-generated, flexible model of the weapon generated from 33 nodes and 20 elements (shells and beams). It should be pointed out that the solution process is almost indifferent to the size of the FEA model used to generate the flexible body, and the model could posses hundreds of thousands or even millions of node and the process would still be numerically efficient.

The weapon was compliantly supported at the butt and muzzle and, starting from a static equilibrium, the weapon was smoothly, but rapidly moved 20 inches vertically in ½ second. The accelerations were sufficient to throw the foot load clear of the weapon, after which it re-impacted.

The FLEX body was generated with modal stress contours as well as the default deformation sets, and fig. 13 shows the von Mises stress state of the structure at 0.9 sec. into the simulation

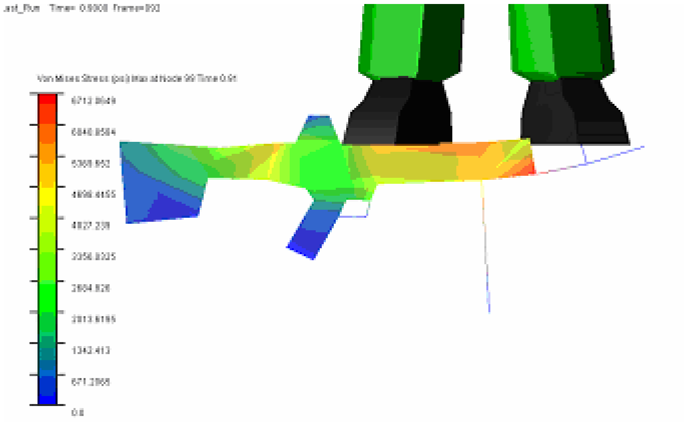

Fig. 13 Von Mises Stress and (Exaggerated) Deformations at Simulation Time 0.9 Sec

Figure 14 gives the history of the boot contact force on the weapon

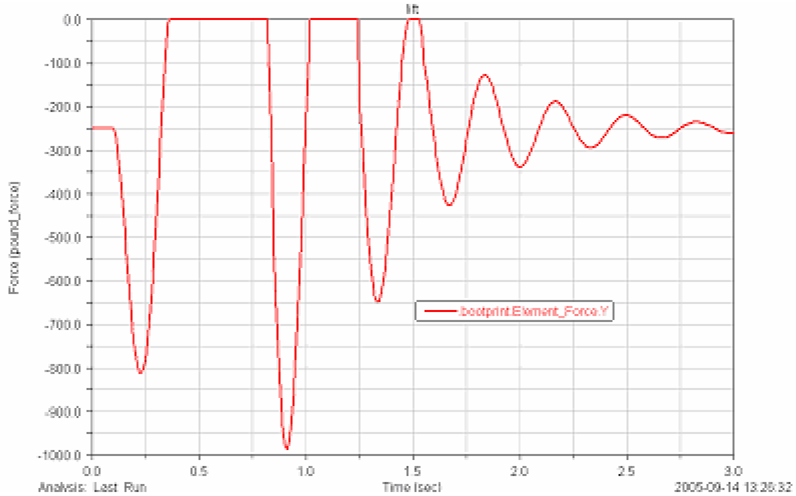

Fig. 14 Boot Force on Weapon

Rough Handling Simulation

An initial investigation was completed to examine the effect of vehicle motion on the weapon when mounted on a vehicle. A complete weapon assembly model was attached on a pole secured to the roof of a simplified “Hummvee” vehicle, which was then subjected to reasonable, but arbitrary, (harmonic) motion along and about all 3 axes. The weapon was permitted to gimbal relative to the vehicle through +/- 10 degrees in roll (X-rotation), +/- 30 degrees in yaw (Y-rotation), and +20/-30 degrees in pitch (Z-rotation). Arbitrary but reasonable stiffness values were employed in the gimbal stops. The model is shown below inn fig. 39 at 2+ simulation seconds.

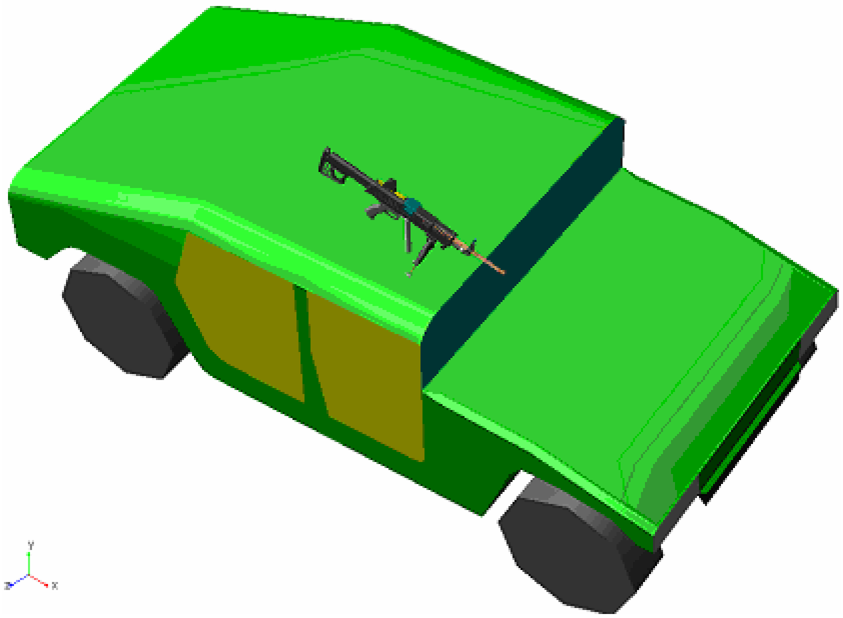

Fig. 15 Vehicle Mounted Weapon -- Preliminary

The plots below in fig. 16 give the translational acceleration histories of the weapon mass center (blue curves) with respect to ground in part orientation and the translational acceleration histories of the vehicle (red curves) vehicle, also with respect to ground.

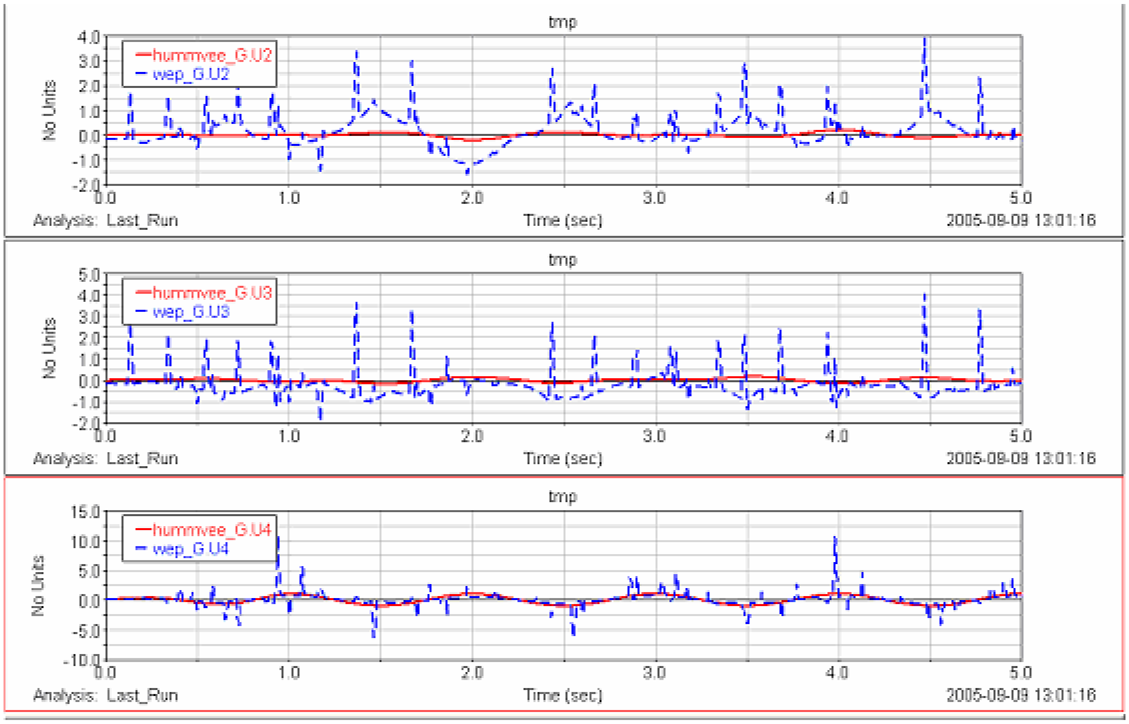

Fig. 16 Translational Acceleration Histories –Weapon and Vehicle

It should be noted that the acceleration of gravity is not included in these traces, although it could be. Because of the imposed pitching motion on the vehicle, the weapon Z-accelerations appear to be the most severe..

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 butt plate attachment was intentionally made very soft, as was the lateral support on the right bipod foot. The vertical bipod supports were stiffer by a factor of 10. Five (5) rounds were loaded for this simulation.

The plots below (fig. 17) give the translational displacement histories of the muzzle with respect to ground in ground orientation.

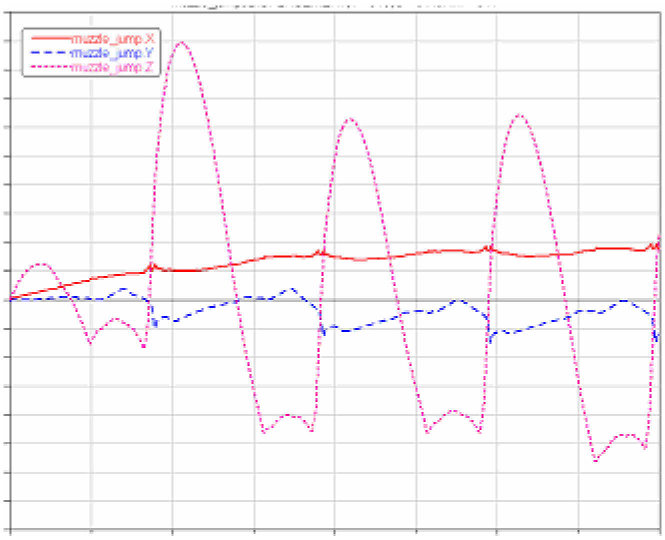

Fig. 17 Muzzle Translational Displacement History

Fig. 18 gives the bushing forces reacted at the weapon butt plate.

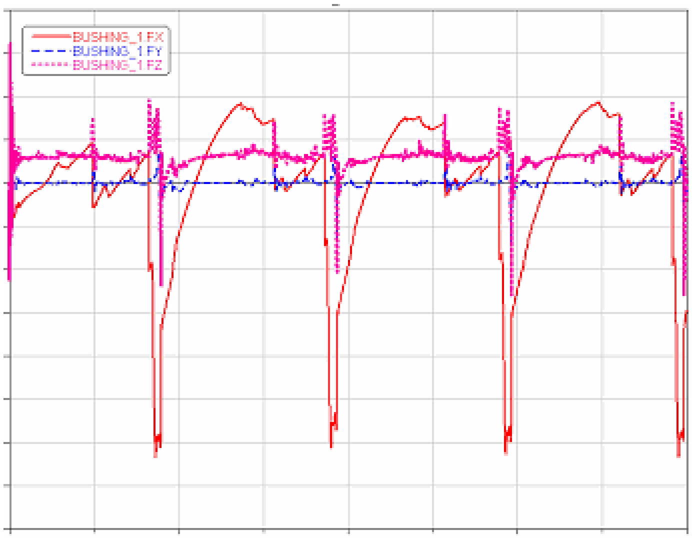

Fig 18 Butt Plate Reaction Forces – Assumed Stiffnesses

Animations showed that the weapon exhibited a slight tendency to 'walk' forward when firing at full automatic.

Flexible Component Conversion

The modeling previously described bas been, principally, motion oriented. Structural loads determined from such a model are usually approximate, at best. The CONTACT elements themselves, while using sophisticated algorithms to determine the parts contact geometry, employ highly simplified algorithms to calculate the forces resulting from the contact. Sophisticated, Hertzian-type force analyses are not currently part of the CONTACT element capability. However, enhancement of the model to include (linear) elastic structural effects is possible with the employment of MSC Adams FLEX_BODY elements derived from full-blown finite element (FEA) models. This carries with it the disadvantage that the sophisticated CONTACT element modeling must be replaced by user (pre-)defined, multiple distributed, contact forces. In effect, the user must know ahead of time what contacts can take place. This can result in a significant increase in model size, especially if two, flexible bodies are in continuous, sliding contact. Against this disadvantage, the importance of the specified contact force parameters, which are usually only rough estimates, is reduced, since the structural compliance of the element is usually much softer than the contact compliance. This is analogous to the effective, combined stiffness of two springs with greatly differing stiffness constants in series being dominated by the softer spring. Again, precise, Hertzian effects are difficult or impossible to include. However, the stresses computed in the flexible structure remote from the immediate contact point should be very useful.

Initial conversion to flexibility was limited to those articulating components experiencing appreciable interaction forces. Chosen were:

1) rammer
2) slide
3) cross feed cam
4) chamber carrier

Using the same Parasolids elements from the assembly model, MSC Patran was used to meshh the subject components into solid (TET4) elements for the subsequent generation of MSC Adams FLEX_BODYs in MSC Nastran.

Interestingly, initial flexible analysis resulted in an increase in the weapon cyclic rate of fire when compared with same model using rigid components. It is conjectured that this is attributable less system energy being lost as heat due to contact element damping.

Trigger Group

Not included in the modeling cited above was the integration of a complete trigger mechanism into the model. The mechanism included all associated moving parts and elastic element. The ‘selector lever could be set to, ‘SAFE’, ‘SEMI-AUTOMATIC’, or ‘FULL-AUTOMATIC’. Through a series of cams, levers, and locks using, again, MSC Adams CONTACT elements, the sear/slide interaction was controlled.

After verifying the correct mechanical behavior of the trigger group, is was usually eliminated from the full weapon model, since it resulted in an appreciable increase in model solution time, due to all the trigger group elements being in constant, excited contact.

Discussion

The primary key to the modeling success experienced so far has been the CONTACT element in MSC Adams. Because of its tremendous utility, it is now possible to have a mechanism model such as the one described here functioning in a matter of hours. Without this capability, such modeling would require days or weeks, if it were even possible at all. Similarly, the great utility and power of the MSC Adams FLEX_BODY element greatly simplifies the modeling of complex behavior. Also, all of the simulations cited here were executed using the latest, C++ solver in MSC Adams. It has proven to be robust and time efficient.

It would be worthwhile to cite at this point the initial contributions the MSC Adams modeling has brought to this design effort. In summary:

1) Confirmation that the weapon physics are basically correct as designed. The weapon should function at or near the intended cyclic rate and should possess sufficient power to meet ammunition feed requirements.
2) Initial inconsistencies in the element geometry were hi-lighted when the assembled MSC Adams model would not pass the intended ammunition through the weapon. This was use to correct the geometry before the prototype parts were submitted for fabrication.
3) Initial MSC Adams analysis indicated that the pawls in the ammunition feed tray were not correctly positioned to retain the ammunition belt in the weapon when cycling. The design was modified prior to parts fabrication.
4) Initial MSC Adams analysis pointed out the need to add a spring-loaded lock between the rammer and its guide to keep the weapon properly configured.
5) Detailed information has been generated concerning the variation of dynamic link loads along the ammunition belt.
6) Initial studies have been done on the effect of round/mechanism lubricity on the weapon performance.
7) Strength problems have been identified and/or confirmed at 3 different locations in the weapon.

Conclusions

The ability to create a complete, functioning, mechanism model (e.g., a ‘virtual prototype’) of a belt-fed, automatic weapon has been demonstrated. Initial expansion of the model fidelity to include structural flexibility has likewise been shown. It remains to complete the conversion of the mechanism model to a full, *structural*, mechanism model.

Acknowledgements

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