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# UPDATED PHYSICS-BASED SIMULATION MODEL CORRELATION OF A CANNON CONCEPT TECHNOLOGY DEMONSTRATOR WITH UNSTABILIZED TEST FIRING

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**ABSTRACT**

*The cannon Concept Technology Demonstrator is a U.S. military proof of concept 155 mm self-propelled howitzer platform. It demonstrated fully automated ammunition handling, weapon stabilization, and mobility in a 24-ton test platform. The next generation Concept Technology Demonstrator served as a transfer mechanism of capabilities from a heavyweight howitzer platform to a notional future lightweight self-propelled howitzer. Simulation model data of the demonstration platform vehicle response during weapon firing was contrasted with the initial notional lightweight system's firing stability analysis. The results of this comparison stimulated an updated correlation effort. This correlation effort utilized test firings without chassis stabilizing spades to reveal physics-based simulation model fidelity requirements for future programs. Observations of simulation and system performance were used to define a systematic approach to simulation model fidelity improvements and enhancements. The resulting simulation model was shown to correlate strongly and robustly with the Concept Technology Demonstrator across multiple scenarios. The lessons learned from this updated correlation effort established new modeling standards for future cannon firing stability efforts.*

## INTRODUCTION

The Cannon CTD (Concept Technology Demonstrator) is a proof of concept platform that demonstrated firing stability in a 24-ton mobility platform for the U.S. military [1]. The CTD platform, shown in Figure 1, integrated a 38-caliber, 155 mm cannon with a hybrid-electric track platform to fire more than 2,000 rounds during its testing. The platform demonstrated firing scenarios of single round, multiple rounds, rate of fire, and MRSI (multiple round simultaneous impact) with fully automated ammunition handling from the 24-round magazine to the laser ignited weapon. This testing was used to define operational scenarios and determine system configuration in a lighter weight platform in anticipation of future cannon firing stability efforts. The CTD served as a technology and capability bridge from a previous heavyweight self-propelled howitzer to future cannon firing stability efforts.

The CTD ammunition handling and weapon stabilization technologies were transferred from the prior self-propelled howitzer program. The fully automated ammunition handling transfers the projectile and propellant from magazines to a loader arm for ramming into the gun tube. The CTD accommodates standard 155 mm howitzer rounds

**Figure 1:** CTD Firing and Mobility Platform

and the MACS (Modular Artillery Charge System) propellant in combinations from zone 1 to 5. The radial zone is determined by propellant type and number of charges. The weapon stabilization technology was developed during the prior 60-ton program where rate of fire and accuracy requirements necessitated stabilization of the weapon during firing response and on-board ammunition handling disturbances [2]. The stabilization goal was to maintain inertial pointing of the weapon during the vehicle response to disturbances. This effort, initially applied in elevation, was extended to traverse in subsequent studies [3]. The stabilization result is that the weapon's elevation and traverse were partially decoupled from the vehicle response.

Firing sensitivity increased as a trend of decreasing the system mass was executed from program to program. This trend started with the transition of the prior 60-ton program to a 40-ton system, and then subsequently a lighter weight 20-ton system. The CTD provided a 24-ton platform to evaluate firing stability, the system response to weapon firing, and technologies to improve firing stability. These technologies included hydro-pneumatic suspension units, stabilizing spades, active weapon stabilization, and an optimized muzzle brake. These allowed the firing sensitivity to be investigated from the source of the firing impulse to the response of the vehicle system. The firing impulse was mitigated with changes in zone (charge) and improvements in muzzle brake efficiency. The vehicle response was diminished with the suspension units and/or the stabilizing spades. The suspension units provided adjustable dampening for the attenuation of the vehicle response. The stabilizing spades, when deployed, provided a reaction point for stabilized firing. When the spades were not deployed, the vehicle response was called unstabilized, with unstabilized referring to the absence of the stabilizing spades, not a lack of system stability.

System stability assessment was one of the first goals of the CTD firing testing. This assessment was performed with combinations of firing scenarios to assess the vehicle response and potential crew environment. The firing scenarios included stabilized and unstabilized to assess the necessity of the spades for the lighter weight platform. These scenarios are initially simulated to predict the vehicle response to these firing impulses. During firing stability testing, the vehicle responses are collected as test data and then compared to the simulation data. The correlation between the simulated and the actual indicates the suitability of extracting loading conditions from simulated firing scenarios and the ability to extrapolate to other untested scenarios, where other operating environments are not easily replicated in test. An initial correlation effort was performed where the simulation model was tuned to the test data [4]. That correlation effort indicated the ability to successfully adjust the available model parameters to the test data. The correlation effort was revisited in an effort to identify the model fidelity requirements necessary to achieve robust test data correlation. The approach and results of that model fidelity enhancement and correlation effort is revealed here.

This correlation effort focused on identifying what design data was critical for simulating firing stability and overall system performance. A review of the prior correlation effort was performed and a prioritized list of model enhancements and updates was developed to be incrementally and systematically applied to the simulation model. The prioritized list was established based on the assessed reliability of the proposed changes. Priority was given to changes that could be substantiated in the list. Changes that were less understood were put-off until more relevant updates were made. Periodic reviews of the model correlation were performed during the effort to verify suitability of the changes. This paper initially describes the simulation model, follows with the firing test rounds selected for correlation, and then outlines the updates and enhancements to the simulation model.

## MODEL DESCRIPTION

The firing stability system model consists of the integration of a physical sub-model and a control sub-model in different modeling packages. The physical system is modeled in the DADS (Dynamic Analysis and Design System) software from LMS International. The control system is modeled in MATLAB from The Mathworks. These two systems interact during coupled simulations by passing state information between the sub-models. The state of the physical system is passed as sensed information to the control system, which in turn provides forces and torques to the physical model to articulate the weapon. This close coupling of the systems permits the models to respond to each other and allows the system interaction to be understood before hardware is available. This opportunity is a beneficial step in the maturation from concept to hardware, as the weapon control algorithm used in simulations is proven incrementally to become the hardware control system. The ability of the physical sub-model to represent the actual system becomes instrumental in the development of the pointing control system. A short description of each sub-model follows.

The physical system model consists of five rigid-bodies connected by various joints, springs and dampers. The bodies represent the chassis, turret, elevating mass, left and right spades. The elevating mass models the combined gun mount and weapon, and is articulated relative to the turret. The gun firing impulse is applied through the gun mount to the trunnion as the total recoil force time history. This applied force is reacted through the chain of bodies from the gun mount to the turret and chassis. The elevation drives exert force between the elevating mass and the turret, to elevate/depress the weapon and also stabilize the weapon during the firing response. The turret traverses to slew the weapon relative to the chassis. The chassis is supported by left and right track super-elements and spades, when they are deployed. The track super-elements are used to model the roadarms, roadwheels, and track interaction with the soil model [5]. Each track consists of six independent roadwheel-roadarm pairs to support the vehicle. The spades are deployed to provide additional stability to the chassis by establishing a more direct path for transferring the firing impulse to the ground. The firing stability model permits the spades to be deployed or retracted to evaluate stabilized or un-stabilized weapon firing.

The GPCS (Gun Pointing Control System) model orients the weapon by applying torque and forces to the joints between the gun mount, turret, and chassis. The GPCS accomplishes this by utilizing system commands and sensor input to determine the necessary force output to achieve the system goals of inertial stabilization and weapon articulation. As the servomotors of the physical system establish a performance envelope that naturally limits the force and speed articulating the weapon, the control system is intentionally designed to function within this envelope. The GPCS model in this incarnation includes not only the control laws necessary for articulation, but also models of the electric motors and brakes, models of the sensor systems and their discrete/continuous sampling, and the flow logic governing the control states. This modeling detail provides a means to evaluate weapon accuracy and stabilization, and tune system performance in a simulated environment prior to hardware availability. As the system progresses towards hardware, this control system is matured and surrogate model components are replaced with physical hardware during follow-on phases of emulation with hardware in the loop. Eventually, the control system is embedded into the system hardware for the final system.

## STABILITY TEST ROUNDS

Three test shots were selected from the CTD firing stability test phase for the correlation effort. These shots each represented a high, medium, and low quadrant gun elevation, with zero relative traverse of the turret. The zero traverse indicates that the weapon was aligned with the centerline of the vehicle during the shots. The combination of different elevations provide a mixture of pitch and heave responses to the chassis and suspension. These shots were fired without the use of chassis stabilizing spades, and consequently are referred to as unstabilized. Each round was propelled with two increments of MAC propellant to yield a zone 2 firing. The zone 2 firing without spades is sufficient to substantially recoil the weapon and consequently react the vehicle. The characteristic pitch response of the chassis is shown in the left plot of Figure 2 for each of the elevations. The responses are normalized to the peak pitch response of the lower elevation test round, which is the largest pitch response. The weapon relative elevation displacement response for the chassis is shown in the right plot. The relative elevation change is normalized with the same scale as the pitch responses.

The response during these particular test shots is significant in that inertial stabilization was interrupted during the firing. The interruption was due to an anomalous sensor signal. The GPCS entered a safety mode so that errant torque commands would not be sent to the drive motors, which could excite a response mode of the system inadvertently. This mode does not represent normal functioning of the weapon control system, but is a safety mode of the system. This mode is necessary in development testing, where safety is critical.

The unintentional entry of this mode on these particular shots is of tremendous benefit to this correlation. As one of the goals of the GPCS is inertial stabilization, the weapon response becomes fully coupled with the vehicle response

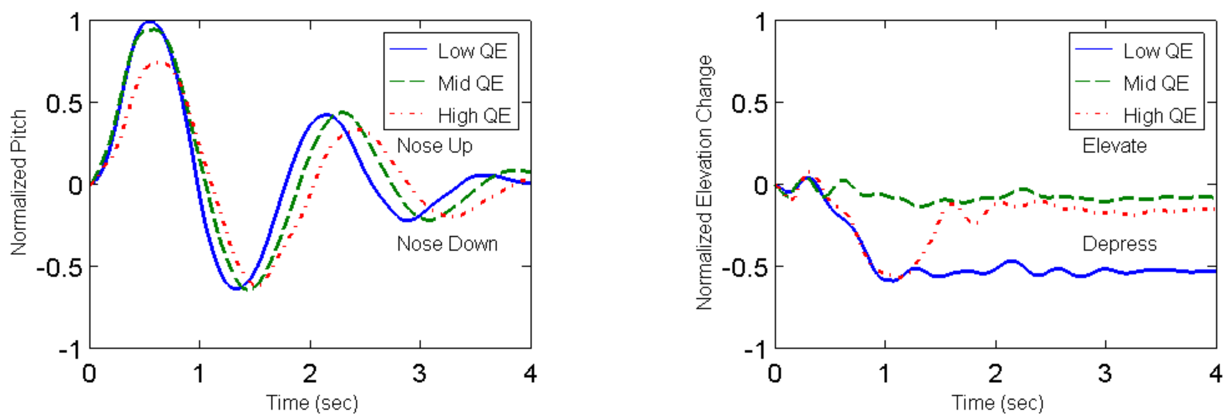


**Figure 2:** Test Normalized Pitch and Elevation Change

when this safety mode is engaged. Since this mode was entered early, these particular shots practically represent the response of the physical system model solely. This was fortunate to this correlation since the effort could be focused on the physical system model solely, without the additional complexity of the coupled GPCS-physical system response.

## CORRELATION APPROACH

The correlation approach for this effort involved updates to the physical system model and an incremental evaluation of those changes. This incremental approach permitted each change to be valued for its improvement to correlation. This was an important step in the approach as firing stability modeling would potentially increase in complexity, and the benefits of the additional burden needed to be identified for future efforts. The effect of each incremental change is not shown here for the sake of brevity, however a summary of the significant changes is discussed in the final correlation.

The physical system modeling enhancements and updates can be grouped into three primary categories, recoil dynamics, suspension dynamics, and power train compliance. The recoil dynamics relate to changes made to the modeling of the weapon stimulus. Changes to the suspension dynamics involve modeling of roadarm performance. The power train compliance deals with the interaction of the driveline sprockets and the chassis. The recoil dynamics are described in the following section, which is followed by the suspension and power train changes.

### *Recoil Dynamics*

The recoil dynamics were substantially changed from previous efforts. Prior modeling of the recoil dynamics was performed separately, where the total recoil force time-history output was generated in a recoil simulation model. The output was then applied to the firing stability model as an input to the gun mount. A normalized force time-history is shown in Figure 3. This sequential method presumes that the recoil dynamics only influences the physical system dynamics through the input force and that the recoil response does not influence the vehicle response significantly. When one examines the characteristic rise rate of the recoil buffing force in Figure 3 and contrasts it to a typical vehicle response curve, such as Figure 2, an assumption that the recoil frequency response is separate from that of the physical system model seems reasonable. The typical rise rate is on the order of milliseconds and the vehicle pitch response is in the hundreds of milliseconds, consequently, the perceived disparity in responses. This separation of responses suggests further discussion, which starts with the recoil system modeling, and finishes with the coupling of the recoil system model with the physical system dynamics.

The separation approach using the force time history output from a recoil simulation to stimulate the vehicle

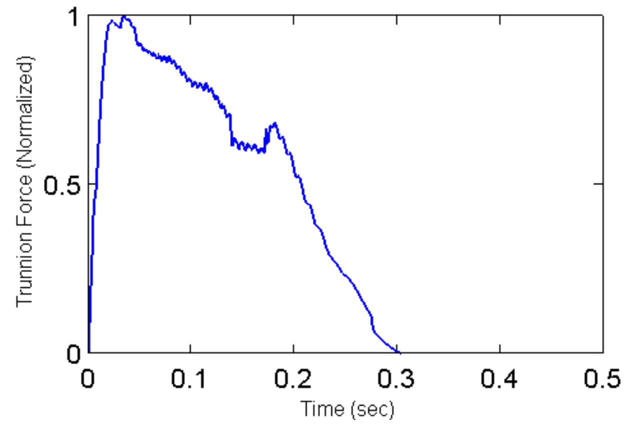

**Figure 3:** Typical Buffing Force

model presumes that the recoil system only defines a single force on the vehicle. This force is applied to the trunnion on the weapon axis in a predefined profile. The profile is developed from a recoil simulation in which the ballistics forces are applied to single mass degree of freedom model, which includes the recoil system model of hydraulic buffing and recuperation. This simulation of the recoiling mass is typically performed at one elevation and then the total recoil force time history in the recoiling direction is extracted and applied to the vehicle system model. Calculations of the force impulse are typically performed to characterize the input to the vehicle. This characterization is minimally performed across firing zones and maximally performed across a spectrum of zones and elevations.

The effect of including the recoil system model was examined prior to the test data correlation by contrasting the recoiling model response with a non-recoiling response. The non-recoiling model used the trunnion force from a stationary firing simulation, as was the method of prior firing stability simulations. This required the performance of a stationary firing simulation to extract the trunnion force time-history, which was performed at a mid QE (Quadrant Elevation) with the gun mount body fixed to ground on the physical system model. To this end, the physical system model was reconfigured for this study so that the comparisons were not colored by the use of different models. The weapon system was separated into recoiling and non-recoiling components, with the recoil system serving between these parts. This weapon separated physical system model became the recoiling system model. The non-recoiling simulation fixed the gun tube to the gun mount in the in-battery position and utilized the trunnion force.

Simulations were performed in both the recoiling and non-recoiling system models and the chassis pitch results were extracted, which are shown in Figure 4 for the mid elevation case. The chassis pitch response is underestimated with the

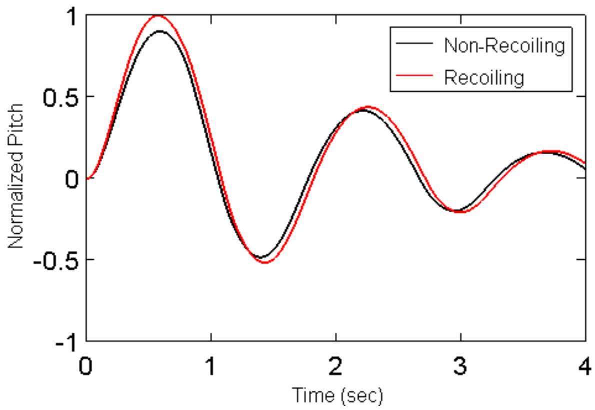


**Figure 4:** Model Recoiling Effects Mid QE

non-recoiling model and the applied trunnion force when compared to the recoiling model and the coupled response. The converse occurs with the chassis heave response, which is an over-response for the non-recoiling model as compared to the recoiling model. This is primarily due to the failure to capture the changes in the collective vehicle inertia and the sprung center of gravity as the recoil/counter-recoil motion occurs with the weapon cycle. As the weapon recoils, the collective pitch inertia is reduced and the chassis pitch response is increased. This recoiled position results in stored energy that is released during counter-recoil and transferred to the chassis counter-pitch response. This is further accented by the weapon recoil effect on the collective sprung center of gravity, which shifts rearward with weapon recoil and returns during counter-recoil. The effect of the recoil system coupling on the physical system is evident in the increased chassis pitch response and the coupling effect on the recoil system is observed next.

The coupling of the recoil system model and the physical system model influences the recoil response as well. This is illustrated with a configuration of the recoil coupled system model to form a stationary recoil model. The stationary

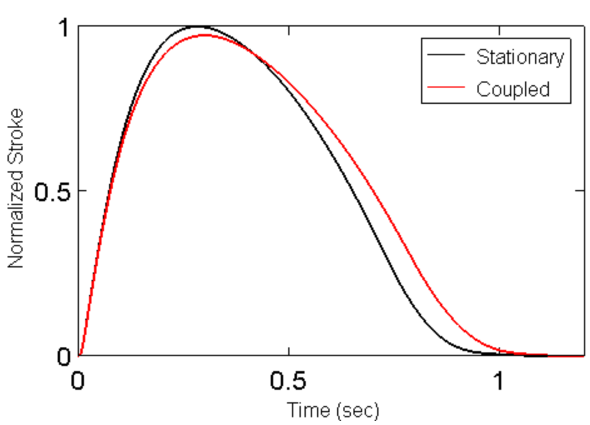


**Figure 5:** Recoil Stroke Effects Mid QE

recoil model is configured with the gun mount fixed to ground. This permits comparisons to be made without coloring the results unduly. The comparisons of the stationary recoil model and the coupled system model can be seen in Figure 5 for the mid elevation case. Since this is a comparison of the effect to the recoil system, only recoil performance is examined in the plots. The peak recoil stroke length is higher for the stationary model, with the recoil cycle time being longer for the coupled system model. The physical system model's tracked suspension dynamics serves as a secondary suspension to the recoil system. The effect of that additional suspension shortens the relative recoil stroke length and lengthens the recoil cycle time. The net result is that the recoil/counter-recoil cycle is extended due to the coupling with the vehicle and that the maximum recoil distance is reduced.

The coupling of the recoil system model with the physical system model affects the performance of both systems. This was shown by comparisons between coupled and decoupled system models. In each case the performance of each system changed when coupled. This coupled performance resulted in increased pitch response to the chassis, decreased stroke in the recoil system, and increased recoil cycle time. These effects could not be observed in the decoupled models where the results of the recoil model fed into the physical system model sequentially.

### *Suspension Dynamics*

Roadarm suspension units, drive sprockets, and their interaction with the band tracks govern the CTD suspension dynamics. The characteristics of each of these components were changed from the prior design estimates to the actual performance of the individual components. These changes required an evolution in the modeling to accommodate the performance characteristics in some instances. Descriptions of the changes and enhancements for the suspension units and track-drive interaction follow.

The CTD vehicle is supported by InArm® Hydrogas® suspension units connected to a band track [6]. These external suspension units provide spring and damping force in a compact space within the roadarm. The pneumatic springs have two chambers. The pneumatic chambers can be charged to a vast combination of pressures within design limits providing support to a wide range of weight classes. The separate chambers permit part of the roadarm travel to be supported by a single chamber's pneumatic compression and the remaining travel is supported by both chambers' pneumatic compression. The CTD's suspension setup, illustrated with the two spring curves shown in Figure 6, was such that the secondary pneumatic chamber was set to engage just into jounce travel to provide a reduced spring rate into full jounce. The increased spring rate in the vicinity of the design travel provides supplemental stability beneficial for a lightweight self-propelled howitzer. The two

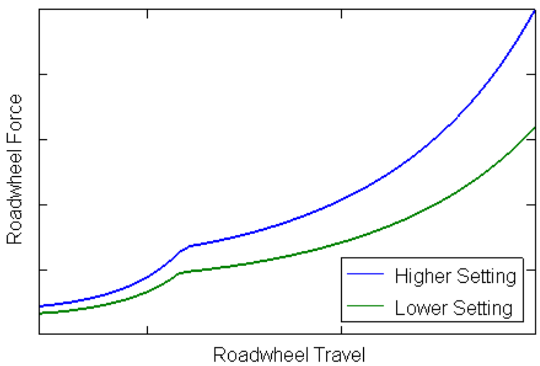


**Figure 6:** Spring Curves

curves illustrated in the figure provided a logistically simple solution to the infinite possibilities to charge the suspension units. The CTD weight and center of gravity permitted the first three roadarm stations to use the lower spring curve and the higher setting to be applied to the last three stations. The CTD simulation model was updated to these spring curves and the settled static attitude of the chassis was very close to the design intent in pitch, roll, and heave.

The CTD suspension units can be adjusted to provide different levels of damping. This adjustment provides continuous levels from a minimum level to a maximum level. When the adjustment is made towards the minimum level it results in damping more suitable for mobility. Conversely, the maximum level is more suitable for firing stability. This adjustment is performed manually for each unit. The damping on the CTD platform was not set to the maximum level for the firing stability, but was set one-third of the way from maximum. This damper setting was interpolated from the vendor supplied maximum, nominal, and minimum provided curves. This was the initial change in the damper modeling and was a necessary step in the evolution to the next level of damper modeling.

The next step in modeling of the suspension unit damping was a significant change from a single damping curve to a damping surface. Whereas the typical damper is a function of velocity only, the internal mechanics of the suspension units result in damping that is dependent upon position and

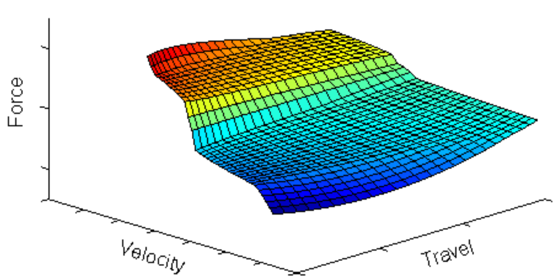


**Figure 7:** Damping Surface

velocity. A damping surface is illustrated in Figure 7 with respect to roadwheel travel and velocity. As the suspension units are exercised, the damping force traces a circuitous route on the surface for each roadarm. Similar to the spring curves, the damping surface is implemented with torque as a function of roadarm angle and velocity. It is shown here with force and travel as a matter of convenience. The implementation of the damping surface was performed with control elements in DADS since the standard track super-element does not support damping surfaces.

### *Power Train Compliance*

The final change in the suspension modeling was the incorporation of track drive sprocket compliance. This modeling addition was based on observation of close-up video of the CTD firing response. It was observed that the drive sprocket was rotating during the firing response. This rotation was not due to an unrestrained drive system, but was presumed to be the compliance between the sprocket and the brake system, which included the final drive gear system. Rotation of the track drive sprocket is performed in a DADS model through direct kinematic constraint or dynamic drive torque specification. This drive sprocket interaction is typically executed to achieve mobility across terrain. In this instance of firing stability, torque from a spring and damper system representing the final drive compliance dynamically responded to the drive sprockets' rotation. The rotation of the drive sprocket occurred from the track tension differences between the top span to the idler and the descending span to the first roadwheel.

The track tension of the DADS track super-element presented a potential method for including the drivetrain compliance. An approach using the track tension would utilize an equivalent spring-in-series calculation and mask the sprocket rotation into the track tension displacement. Consequently the rotation of the sprocket relative to the brake would be lost. This may be viewed as an acceptable loss in modeling; however there are other consequences of this approach. The spring-in-series softening of the track tension permits an increased breathing response of the track spans. This leads to additional roadarm displacements that result in excessive system damping and potentially additional chassis heave, pitch, and potentially roll response from actual. This approach was avoided, as the CTD band track is significantly stiffer than the relative stiffness of the drivetrain compliance. The separation of the track stiffness and the drivetrain compliance provided the correct level of modeling to achieve the final correlation.

## FINAL CORRELATION

The simulation model updates and enhancements were incrementally evaluated during the correlation effort. The mid quadrant elevation test firing case served as the reference to measure correlation improvements during the

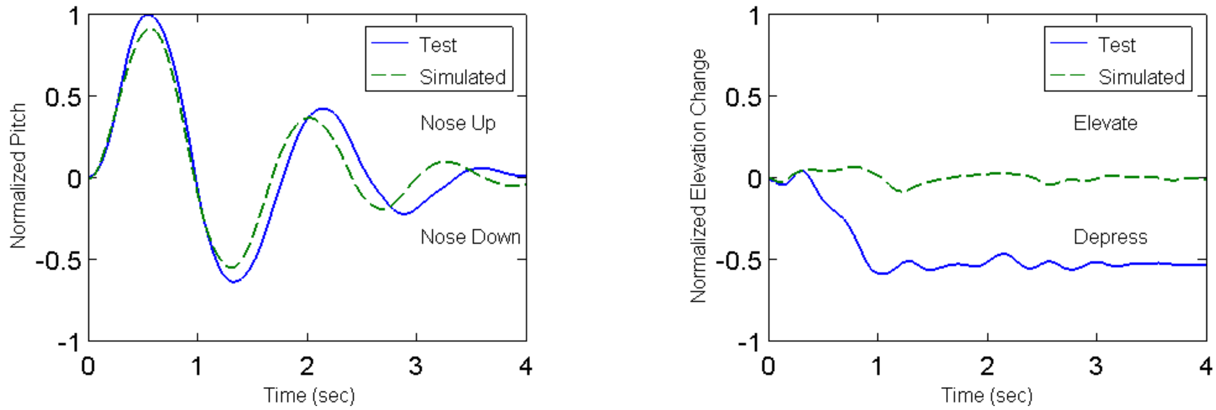


**Figure 8:** Low QE Pitch and Elevation Correlation

effort. When the mid QE correlation was deemed sufficiently close, comparisons between the simulation model and other test cases were made. These other cases were high and low QE test firings at the same firing zone. The only simulation model change between each of these test cases was the specification of the initial weapon elevation. The culmination of the simulation model updates and enhancements is presented here as the final correlation results.

The low quadrant elevation correlation results are shown in the plots of Figure 8. The chassis pitch response is shown on the left. The pitch response is normalized to the peak of the initial setback of the chassis. This scale factor is used consistently in each correlation plot for the different elevation cases. The low QE test shot results in the most significant pitch response of the three elevation cases. The initial timing of the simulation peak response and the test response are very similar. Subsequent simulation peaks exhibit a slight shift in peak pitch responses. This shift in peak pitch response can be explained with the weapon elevation change plot shown in the right plot of the figure. The simulation weapon relative elevation angle change tracks very closely to that of the test initially. As the chassis reaches peak pitch setback, the weapon is depressed in the test firing case. This momentary decoupling of the weapon elevation inertia results in an increase in the peak pitch in the test case that is not replicated in the simulation response. During the set-forward of the chassis pitch response, the elevation drive brakes engage and couple the weapon inertia to the chassis inertia once again. This coupling occurs as both the weapon and chassis are pitching forward at nearly the same rate. The chassis pitch correlation would have likely been closer if the weapon were fully coupled with the chassis during the entire test event.

The mid quadrant elevation correlation results are shown in Figure 9. The chassis pitch angle has strong correlation between the simulation model and the test event. The continuous coupling, shown in the right plot, between the elevating mass and the chassis promotes this strong correlation. The peak chassis pitch angle of the simulation is slightly higher than that of the test, and the subsequent peak to peak displacement is very similar between the simulation and the test. The simulation suspension damping is very similar to that of the test and aligns closely until low velocity

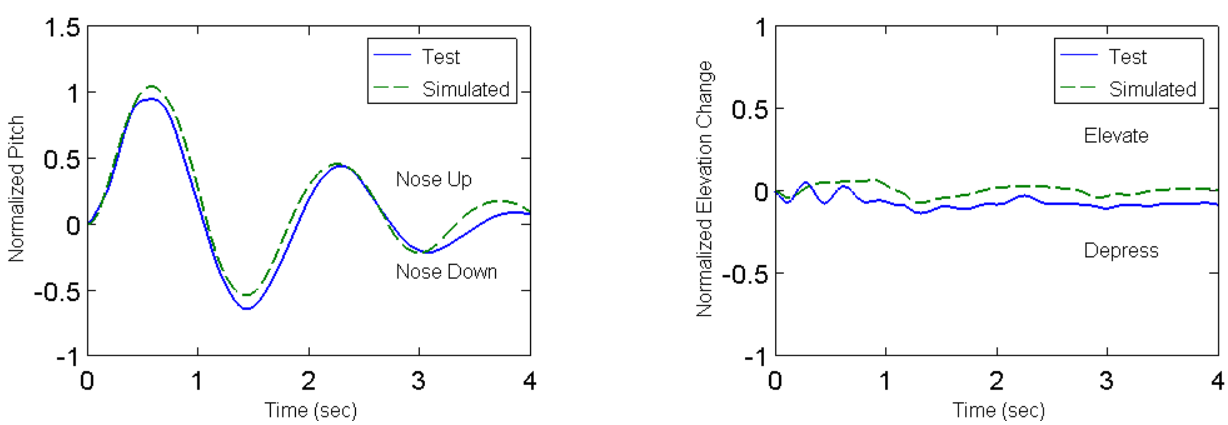


**Figure 9:** Mid QE Pitch and Elevation Correlation

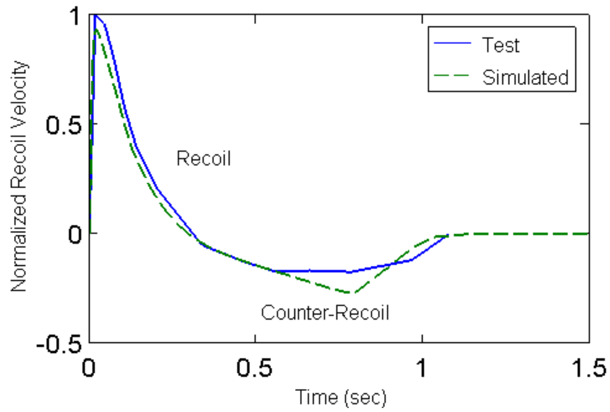


**Figure 10:** Mid QE Recoil Velocity Correlation

frictional effects of the test platform become prevalent.

An additional aspect of correlation was available for the mid QE test case. Video analysis permitted the weapon relative recoil velocity to be studied. This was compared with the simulation model recoil velocity. The comparison of the velocities is shown in Figure 10. The velocity profile and timing is very similar during the recoiling phase of the cycle. The counter-recoil velocity profiles exhibit more significant differences. The overall timing of the recoil cycles are very close. This correlation assessment of the simulation recoil velocity to test is not taken immediately as error, as the video analysis method is not as accurate as the other test data acquisition methods used in this correlation effort.

The high quadrant elevation correlation plots are shown in Figure 11. The pitch correlation departs shortly after the initial firing response. The test pitch trace indicates the trajectory departure from the simulated pitch trace. The trajectories then follow a nearly parallel course. The trajectory departure can be explained by the weapon elevation change revealed in the right plot. The weapon elevation change indicates that as the chassis is pitching back, the weapon is being depressed by nearly the same amount. The opposite weapon motion occurs as the chassis is pitching forward. This decoupling of the weapon elevation occurs for nearly one complete chassis pitch cycle. The weapon motion is then re-coupled with the chassis pitch motion for the remaining cycles. The weapon remains slightly depressed from the initial firing angle when it is re-coupled with the chassis. The correlation of the chassis pitch frequency and effective damping remain strong even with the relative motion of the weapon elevating mass.

## CONCLUSIONS

The improved correlation of the CTD simulation model with experimental data indicates that the model updates and enhancements are significant to the overall system response. Moreover, the suitability of the modeling changes was proven with the robust correlation across multiple shot elevations with only the appropriate initial weapon elevation setting as a change to the model. The contributions of the principal changes follow.

It was shown that integration of the recoil system with the physical system model was influential to both systems. The physical system responded with increased pitch response as the recoiling mass retracted and effectively reduced the composite pitch inertia. The recoil system side of the coupled system was shown to respond with a decreased stroke and lengthened cycle time due to the additional compliances of the vehicle model.

The hydro-pneumatic suspension unit performance curves are critical to the system response. Suspension unit performance is often generalized uniformly across a system model, yet it was shown that strong correlation is achieved when specific and individual performance data is used. These modeling details require performance defined as both a function of displacement and velocity.

Power train compliance becomes significant in the unstabilized firing of lightweight self-propelled howitzers.

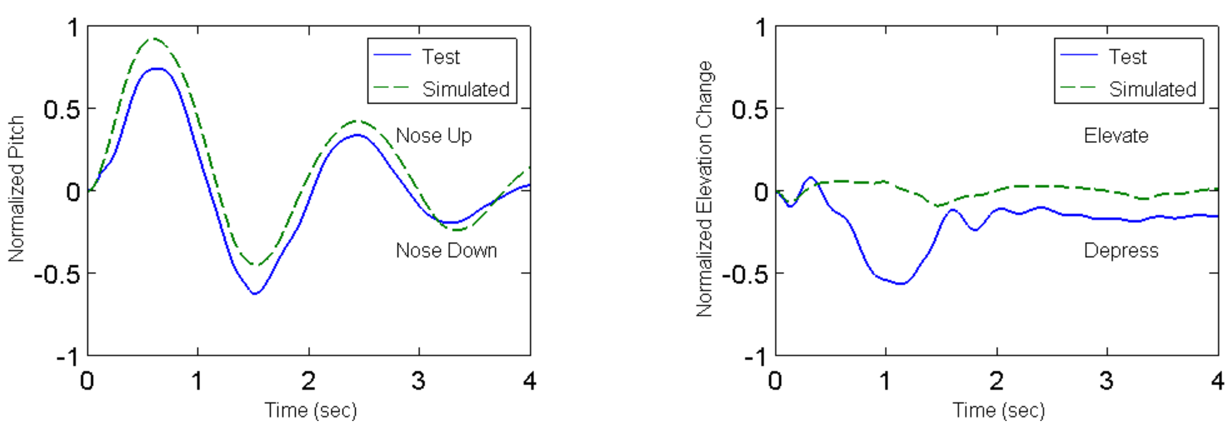


**Figure 11:** High QE Pitch and Elevation Correlation

Sprocket windup provides a means to store and release energy which influences the pitch and heave cycle combinations.

The motion that the gun pointing control system imparts to the vehicle firing response is significant. This was observed with the decoupling and re-coupling of the elevating mass motion to the chassis motion in the low and high quadrant elevation shots. These modeling changes of recoil system integration, suspension dynamics, and power train compliance each contributed to the correlation improvement. New modeling standards for future self-propelled howitzer programs at BAE Systems were established by the correlation results. The model enhancements and the standard integration of the active stabilization of the gun pointing control systems became the norm for firing stability simulation.

## ACKNOWLEDGEMENTS

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