2010 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
MODELING & SIMULATION, TESTING AND VALIDATION (MSTV) MINI-SYMPOSIUM
AUGUST 17-19 DEARBORN, MICHIGAN

Multi-physics Approach in Sub-System Modeling & Simulation (M&S) For a Gun Turret Drive Weapon System.

David D'Onofrio
Zhian Kuang
General Dynamics Land Systems
Sterling Heights, MI

ABSTRACT

For GDLS as an OEM in the defense industry working primarily as a system integrator, it is mission critical to develop a platform to weight/gauge/tradeoff requirements of various sub-systems in the final system product. Knowing sub-system performances in the final system on a physics bases, enables the system integrator more active roles in product R&D for requirement tradeoffs and price tag controls, instead of being passively driven solely by suppliers' perspectives. Designing a light weight system while maintaining their mission profile, can lead to the use of more flexible structures thereby imposing additional dynamics affecting the integration of weapon systems into the vehicle structure. Added to this, the dynamics of electromechanical actuators, mechanical tolerances and discrete controllers, creates an environment, each of which is defined by its characteristic physics. This paper discusses a multi-physics approach used different brand named solvers best for different physics to model and simulate a generic gun system mounted in a turret. The gun platform consists of the gun installed in a cradle, electro-mechanical actuators and a generic fire control system. The turret and gun platform was modeled with rigid bodies defining the majority of the structure using the CAE program ADAMS and flex bodies via FEA models where applicable (ex. gun tube). Two simultaneous electric drives that actuate gun motion were composed of a number of parts whose stack up tolerance could impact gun pointing performance. To handle this contingency, classical joints were replaced with contact forces creating the necessary boundary conditions allowing the additional degrees of freedom to be modeled, representing true machine like behavior. Finally, control systems were modeled in Matlab Simulink and co-simulated with ADAMS to create a complete virtual environment. This approach has lead to a more through understanding of this complex system through the integration of each domain physic's embodied in the individual systems.

INTRODUCTION

The goal of developing light weight combat vehicles is the motivation for developing modeling techniques that capture the various physics embodied in their designs. We have developed a test model representing a gun platform mounted in a turret structure coupled with electro mechanical actuators and a generic controller. The weapon system is driven by two electric gear drive actuators simultaneously driving the gun in elevation along with an electric gear drive motor that moves the turret in azimuth. The mechanical linkages were designed to include tolerances that would be representative of true mechanical system.

The goal of this effort was to develop a common modeling environment from which the unique physics embodied in the various systems of a design could be comprehensively integrated into a high fidelity model capable of providing engineering information from various disciplines. The type of physics represented in the model was chosen to represent that of the multi-displinary physics captured in mechanical dynamics, finite element analysis and non linear contacts and those embodied in electrical actuators and discrete controllers. Due to the complexity of this system, a new approach was developed that would enable the various electro/mechanical systems to be integrated into a multi-physics modeling and simulation environment. Using the paradigm of multi-physics, it was desired that this approach would provide the necessary tools and environment from which to analyze the complex behavior of a gun system. The objective of this effort was to allow engineers using this approach, to test the behavior of their designs using the virtual turret.

As companies seek to reduce weight, the transitioning mass reduction of components can lead toward the use of more flexible structures which in turn, increases the dynamic characteristics of the design. The resulting structural changes can have a ripple effect on system performance as the boundary conditions between components are now more sensitive to the individual dynamic behavior of the interconnecting parts. These undesirable behaviors can complicate the integration of weapon systems. As more components are added to the system, the complexity of the system increases lending itself to the type of analysis offered by multi-physics modeling and simulation.

Multi body dynamics, FEA and control systems do not share the same numerical foundation, thereby making them incapable of simultaneously solving coupled behaviors between their physical boundaries [1]. As a result, equations governing each type of physics are reductionalized into a set of equations that are solvable in the individual CAE application, usually in the form of a lumped mass model. Traditional CAE tools work well when used within the physical domain they were designed for. For example, Matlab/Simulink is good for lumped mass models when there is no coupling between boundary conditions. However, when analyzing systems where physical boundaries delineate one type of physics from another, lumped models are inadequate to describe the total physical effects occurring at these boundaries, hindering the ability to predict system behavior.

Modern M&S Computer Aided Engineering (CAE) programs are evolving into multi-physics platforms that are capable of handling the different physics occurring at the boundary conditions. Multi-physics treat simulations involving multiple physical models in two ways. First, by simultaneously solving the system exposed to variable loads, forces, pressures, electromagnetic, structural dynamics, fluid flow and other various coupled physics through evolving the individual integrators to communicate amongst them selves, secondly by using co-simulation.

This paper discusses the co-simulation method to analyze a generic weapon system. It uses ADAMS to solve the boundary condition at joints where parts come into and out of contact and also the way in which these contacts affect the bending modes captured in the FEA mnf models. Co-simulation is used to integrate the physics of the controller and motor models defined in Matlab/Simulink, to the mechanical models contained in ADAMS (see Figure 1)

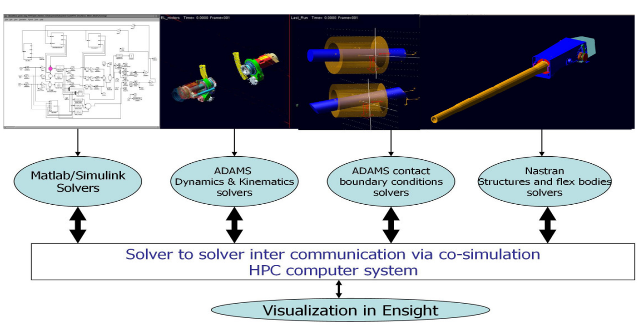

Figure 1: Multi-physics approach.

Modeling Effort

In order to determine both the fire control system behavior and performance, a virtual machine representing the gun had to be created. This virtual turret/gun was constructed from CAD models using Pro Engineer (Pro Eng) as the foundation of our effort ensuring that the mass properties and component tolerances would carry over into our dynamics/control modeling environment. Using this approach ensures that component to component tolerances and relative positions were maintained to design specifications. The turret system was modeled as rigid bodies using the multibody dynamics CAE program ADAMS. The Pro Eng models translated into the mechanical dynamics virtual modeling program ADAMS via Mechanism Pro tool.

The high number of inter-connecting parts that make up the sector gear, clutch, gear drives and spring loads (as with all real systems) contribute to stack up tolerances that could impact gun pointing performance. In order to account for the discontinuity (contacts on/off under dynamic conditions) within the tolerance of interconnecting parts, classical modeling joints were replaced (where applicable) with 3-D contacts allowing those boundary conditions to properly reflect the true physical interactions. Since the objective of the control system is to precisely point the gun muzzle on target, the gun subsystem was modeled with flex bodies in order to account for the bending modes of the gun tube using FEA modal neutral files (mnf's). These flex-body models, limited by FEA's 2-D contacts only, were inserted into the turret rigid-body model by defining the boundary conditions between the attachment points of the FE models and the appropriate joints and forces in the ADAMS model. The control systems for both the motor inner torque loops and gun rate outer loops were modeled in Matlab/Simulink.

Once in ADAMS, a quick sanity check was performed on mass properties and attention shifted to modeling the gear motor actuator, two of which are used to elevate the gun about a pinion.

Mechanical Model

Based on the system mobility/mechanisms study, the mechanical model has been broken down to a few major rigid body blocks and a few flex body blocks (the actual mechanical configuration is omitted due to ITAR regulations). The elevation motors have been modeled as rigid body entities as shown in Figure 2. Upon the motor output shafts, ADAMS motion controls are executing schemes of the electronic controller, directly downloaded from the real machine controller and implemented in

MATLAB/Simulink. It can be seen the frictional and on/off engagements (3-D contacts) of the motor/sector gear is the key both for true physical descriptions, and the model verifications when comparing simulation results to test data. It is noticed/emphasized that, with traditional FEA 2-D contacts, this mechanisms is impossible to be modeled correctly.

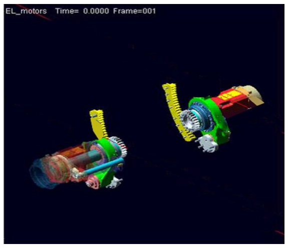

Figure 2: ADAMS model gear motor drives

Both the cradle bock and the gun block are analyzed in FEA software ANSYS as flex bodies (see Figure 3). The results are saved in a format "Modal Neutral File", and then imported into ADAMS rigid body model. In simulations, the dynamics would then reflect interactions (critically important for this model) of rigid bodies and flex bodies.

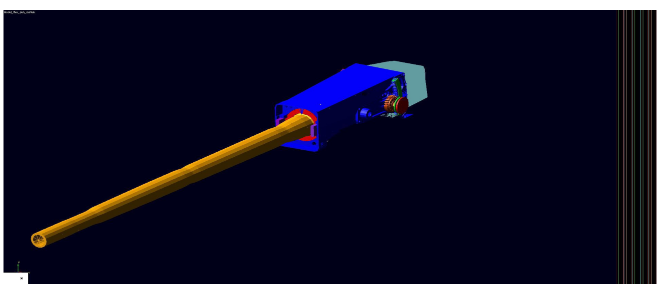

Figure 3: Generic flex gun assembly

Gear Motor

The gear motor consists of one side of the primary motor connected to a planetary gear box followed by the pinion gear. The other side of the motor is connected to a clutch which is connected to an intermediate gear followed by a backup secondary electric motor. The gear motor assembly is connected to the gun system through a pivot point attachment to the turret structure and a spring force engaging the gear motor pinion to the gun's sector gear.

Motor Model

The motors for the elevation drives consisted of a 3 phase Permanent Magnet Synchronous Machine (PMSM) with resolver feedback. The motor was modeled in Matlab simulink as shown in Figure 4. The motor windings were modeled in a Wye circuit configuration. The winding currents i_i, back emf voltage vbe_i, terminal voltage V_i, and torque profiles Kt_i are shown below [2]:

$$i_A = \frac{V_A - v_{be}}{z},\ i_B = \frac{V_B - v_{be}}{z},\ i_C = \frac{V_C - v_{be}}{z}$$

$$K_{T_A} = K_T \sin \omega t$$

$$K_{T_B} = K_T \sin(\omega t + \frac{2\pi}{3}) \quad \text{where } z = \text{coil impedance}$$

$$K_{T_C} = K_T \sin(\omega t + \frac{4\pi}{3})$$

$$v_{be_A} = \dot{\Theta} k_{emf} \sin \omega t$$

$$v_{be_B} = \dot{\Theta} k_{emf} \sin(\omega t + \frac{2\pi}{3})$$

$$v_{be_C} = \dot{\Theta} k_{emf} \sin(\omega t + \frac{4\pi}{3})$$

$$V_A = V \sin \omega t$$

$$V_B = V \sin(\omega t + \frac{2\pi}{3})$$

$$V_C = V \sin(\omega t + \frac{4\pi}{3})$$

Allowing the back emf and torque equations to co-exist as blocks in the simulink model allows the user to create either sinusoidal or trapezoidal profiles. In our model we used a sinusoidal back emf profile which upon summing the torques and applying the appropriate trigonometric identities produces the following torque relationship:

$$\Sigma T = \frac{3}{2} K_T \left(\frac{V - \mathring{\Theta} K_{emf}}{z} \right) \quad \text{where } \mathring{\Theta} = \text{rotor velocity}$$

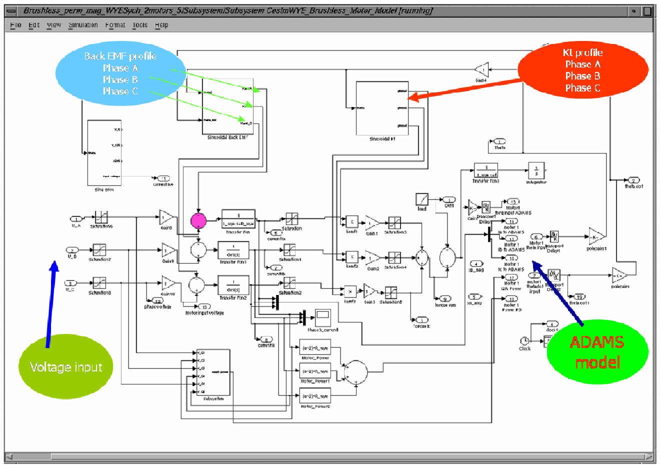

Figure 4: Motor model in Simulink

The torque output from the motor model is used to drive the motor rotor contained in the ADAMS model. The interface between the Simulink motor/controller model and the mechanical model in ADAMS occurs through an S block in Simulink.

Motor Controller

Field Orientated Control (FOC) was used to control the electromagnetic torque which defines the inner most actuator loop. FOC aligns the currents to the rotating magnetic field, producing torque that is proportional to the current in the windings. Current regulation is achieved by transforming its reference frame such that it is synchronous with the rotating rotor flux. The current space vector i_S is composed of the three phase currents i_A, i_B, and i_C shown in Figure 5, are ultimately transformed into a two dimensional time invariant reference system in a two step process.

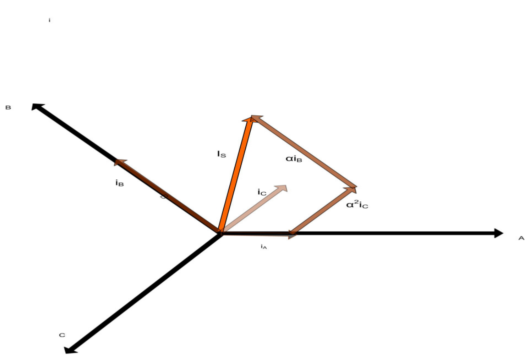

Figure 5: Stator space current vector and three phase currents (i_A, i_B, i_C)

The first step transforms phase currents i_A, i_B, and i_C into a time variant system composed of a two phase representation in the real α and imaginary β coordinate system using the Clark transformation [3,4]. This corresponding current space vector is then transformed into a time invariant d, q reference frame through the Park transformation [3, 4].

The second step invokes the Park transformation to transform the two phase orthogonal time variant system (α,β) into the (d,q) rotating reference frame. The d axis is aligned with the rotor flux and the flux/torque components of the current space vector are no longer dependent on the rotor flux position. With our (d, q) coordinate system moving in sync with the current space vector i_S , the torque and flux components now become time invariant and defined as i_d and i_q respectively. Since for synchronous permanent magnetic motors, the flux is fixed, the flux reference (or flux command) for the flux loop is set equal to zero. The torque command can be the output of the outer control loops and regulated with a PI controller. Once in this domain, a linear relationship between torque and current is achieved and the proper control effort can be implemented.

Gun Control System

The gun system has two primary modes of controlling the rate of the weapon in elevation. The first control mode enables gyros to measure absolute angular velocity of the gun and turret, such that the weapon remains pointing on the target independent of the vehicle's pitch and yaw. This mode allows the gun to be inertially stabilized in pitch (while the turret is inertial stabilized in yaw). The second mode, called non-stabilized mode, controls the gun directly from the gunner/commanders handles and uses feedback to control the gun. The gun is no longer inertially stabilized but does follow the commanded rate. The multi-physics analysis was performed with respect to the non-stabilized mode of operation before the program ended. All controllers were designed to include compensation for both the rigid body dynamics along with the first and second bending modes of the gun/cradle system.

The commanded gun rate acts as the reference command for the elevation loop. The velocity command from the external controller is acted upon by a compensation algorithm that sums one of the two motors tach signal (motor A) to create the compensated error signal that will drive both motors. This configuration corresponds to the Master/Slave configuration which is commonly used to for load sharing purposes as shown in Figure 6. Motor A is defined as the Master running in speed control mode while motor B is defined as the slave running in torque control mode. The external speed reference is used to derive the Master, while the output of the speed controller section is sent as a Torque/Control reference command to the Slave motor B. This configuration means that the current controller input for both Master and Slave are identical and the Slave is not contributing to speed control, only torque/Current control.

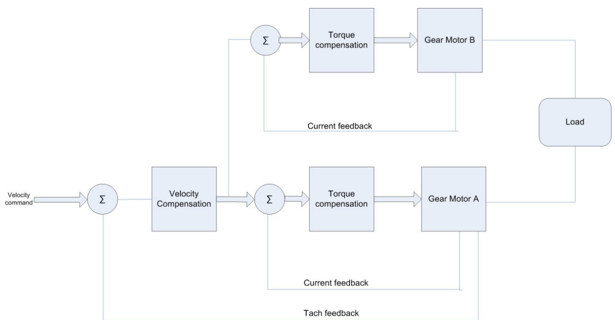

Figure 6: Master/Slave motor configuration

Results

With the virtual turret residing in ADAMS and both the fire control system and the motor controller modeled in Matlab/Simulink, the physics represented by these systems lends itself to the domain of multi-physics simulation and analysis. The dynamic and non-linear contact behavior of the mechanical system interacting with the discrete behavior of the digital motor/controller system, are cooperatively solved through the process of co-simulation. Co-simulation allows Matlab/Simulink to process its discrete models using its ode4 (Runge-Kutta) integrator based on the variables received from ADAMS. At the completion of its time step, Matlab/Simulink sends its output variables to ADAMS and waits for the ADAMS solver to calculate the solutions to its set of variables using its GSTIFF integrator. Upon completion of solving the state variables, ADAMS sends its data over the PIPE(Dynamic DATA Exchange) communication line to Matlab/Simulink and the process advances and repeats to the next time step. This process of co-simulation is initiated and controlled from the Matlab/Simulink environment. Notice that each CAE program is allowed to use its own solver to determine its solution. In this way, each tool uses the optimum solver for its own type of physics to solve its system of equations.

Modeling both the controllers and the motor models in Matlab/Simulink allows the integrators in Matlab to more efficiently solve the dynamical equations. This gives more latitude to the controls engineers to model more elaborate controlling schemes such as the FOC (discussed above) and allowed us to look at the current and back emf waveforms as well as power. In general, staying within the capabilities of Matlab allows a large versatile space from which a multitude of controllers of varying complexities can be analyzed using the virtual mechanical system. In addition, a thermal model could be used in this multi-physics concept (although we did not incorporate this) utilizing the motor/controller power generation and heat conductivity paths to show the thermal effects of this system.

The use of 3 dimensional contacts defining such mechanical interactions as gear to gear and spring loading revealed dynamic behavior that otherwise would not have been detected in the plant model.

Model Verification & Validation

A frequency response of a plant model was used on one particular program and analyzed with respect to measured data. Due to ITAR constraints, graphical comparison of technical data to model data is omitted. However, when looking at five particular modes of the measured plant response and comparing it to the multi-physics model, the modes were closely matched to within a maximum difference of 18 % as shown in Table 1.

Mode (Transfer function)	Percent difference between measured data and model data
f1	3%
f2	18%
f3	10%
f4	0.1%
f5	0.2%

Table 1: Transfer function of gun velocity .vs. torque comparing key modes of real system to multi-physics system in terms of percent difference

These numbers resulted from simply connecting the flex body and its mnf into the ADAMS model without any tweaking of the model. The modes generated in the model are sensitive to the boundary conditions as is expected. For instance, running the analysis in assembly mode (design position of all parts and their tolerances) produced modes f4 and f5 with 10% and 17% error respectively relative to measured data. However, allowing the system to settle due to gravitational loading closed up some tolerances and move f4 and f5 closer to the measured data as shown in Table 1. Adjusting the joints at the attachment points of the flex body also affected modes f1 and f2 allowing engineers to understand how joints and or contacts forces influence the frequency response of the mechanical system. Mode f3 is a function of the contact force acting in conjunction with the flex body. Applying friction to the rotor and tunnion joints affected the mode shape generated from the model yielding a closer match. One could investigate the use of bushings, 3 dimensional contacts, classical joints, and forces to aid in isolating what components are contributing to the responses measured in the actual hardware. Further investigation of the model performance is a continuing effort. The advantage of multi-physics modeling and simulation is in the degrees of freedom available to investigate the multitude of mechanical interfaces and its ability to track down fundamental root cause contributing to the dynamics and performance of a particular system.

Conclusion

Real systems are often composed of physical entities, each defined by its own category of physics. The gun weapon system as with most electromechanical systems is composed of rigid bodies, flex bodies, non linear contacts, electromagnetic actuators and discrete controllers. The physics represented by each of these systems lends itself to the solution space offered by the multi-physics simulation paradigm. The type of physics discussed in this paper was limited to electrical/controls and mechanical/structures, although this concept can be expanded to capture more types of physics than what was discussed.

The physics defined in the mechanical system were captured in the multi-disciplinary engineering fields of rigid body dynamics, finite element structural modal dynamics and non linear contact forces. They were co-simulated with that of the electrical and discrete control system to simulate and analyze the gun system response. Using Matlab/Simulink as the environment to simulate both the electrical components of the motors and the discrete controllers offers the advantage of Matlab's integrators to simulate fast dynamics often incorporated into discrete controller design. This also allows the user to use the vast number of tools offered by each CAE program to provide the necessary fidelity that is desired.

The advantage of multi-physics modeling and simulation is its ability to leverage experimental mechanical investigations into the interconnectivity of the boundary conditions and their impact on the system response. This is much more cost effective then purchasing bushings, joints, and other force type devices along with their installation costs to try to determine their effectiveness through trial and error processes.

The multi-physics approach discussed in this paper has yielded the necessary interconnectivity of the various complex mechanisms into a coherent system. We believe this approach will lead to a more through understanding and better prediction of system performance of complex machinery and the results captured so far support the approach described in this paper. Ultimately, we believe that using the multi-physics process is a necessary tool that will lead to the successful integration of complex machinery into the wide range of vehicles used in the ARMY'S domain.

REFERENCES

[1] http://www.adina.com/multiphysics.shtml

[2]http://www.motioncontrolonline.org/files/public/DCvsACBrushless.pdf, John Mazurkiewicz, Baldor Electric

[3] N.J. Nasek, "Field Oriented Control of Motors", MPC Products Corporation

[4] "Field Orientated Controls of 3-Phase AC-Motors" , Texas Instruments Europe, #BPRA073, 1998

.