Using ADAMS 6-DOF Models to Predict Flight Behavior of Navy Mine Countermeasure Systems

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Introduction

The United States Navy is currently developing tactical systems to address the threat of extensive mines in the beach zone and surf zone during amphibious assaults. These mine countermeasure systems will effectively neutralize the mines present, and allow the formation of ingress and egress lanes from the sea to the beach, permitting the movement of personnel and materiel.

The surf zone is defined as the area from the beach high water mark out to a ten foot water depth. This is an area of extremely dense mine and obstacle concentration. The mine threats present in the surf zone include a vast array of anti-tank and anti-personnel type mines. Both pressure plate actuated and tilt rod actuated mines are present, which can be buried in the sand or placed directly on the ocean floor.

The Naval Surface Warfare Center, Indian Head Division is developing several mine countermeasure systems which employ bulk high explosives, including both net systems and line systems. The Distributed Explosive Technology (DET) system is essentially a large (180 foot wide by 180 foot long) net of high explosive detonating cord designed to eliminate mines in the shallow surf zone (between the high water mark of the beach and out to a three foot depth). The net is deployed and spread out by two solid propellant rockets. The Shallow Water Assault Breaching (SABRE) system is a 390 foot long line of bulk explosive charges deployed by a single solid propellant rocket. SABRE is designed to eliminate mines in the surf zone between three and ten foot water depth, when fired in a salvo of parallel SABREs spaced across the width of the assault lane. M58 is a 350 foot long line system similar to SABRE that is currently fielded for clearance of land mines in the beach zone.

Trajectory models created in ADAMS (Automated Dynamic Analysis of Mechanical Systems), of DET, SABRE and M58 have proved to be invaluable tools during the design, development, testing and improvement of these mine countermeasure systems. Without ADAMS to perform virtual modeling of candidate mine countermeasure designs, it would have been necessary to build and flight test numerous prototypes, at a cost of approximately $100,000 per test. This paper will discuss the use of our ADAMS models to predict the flight behavior and deployment load histories of DET, SABRE and Python-M58.

DET Clearance Predictions

Description/Objective

The DET mine countermeasure system is a 180 foot long by 180 foot wide array of explosive detonating cord, which is packed into a 9 by 5 by 5 foot container. The system also includes two MK 22 Mod 4 rocket motors, which propel and spread the explosive array over and onto a minefield. A photograph of the packaged, ready-to-fire system, with two MK 22 rocket motors installed on the launcher, is shown in Figure 1.

Figure 1. DET System

Upon ignition, the rocket motors travel along their launch rails, and extract the explosive detonating cord array from the container. Upon extraction, parachutes on the rear of the array assist in the spreading of the net. Figure 2 shows a schematic of the ideally spread explosive array.

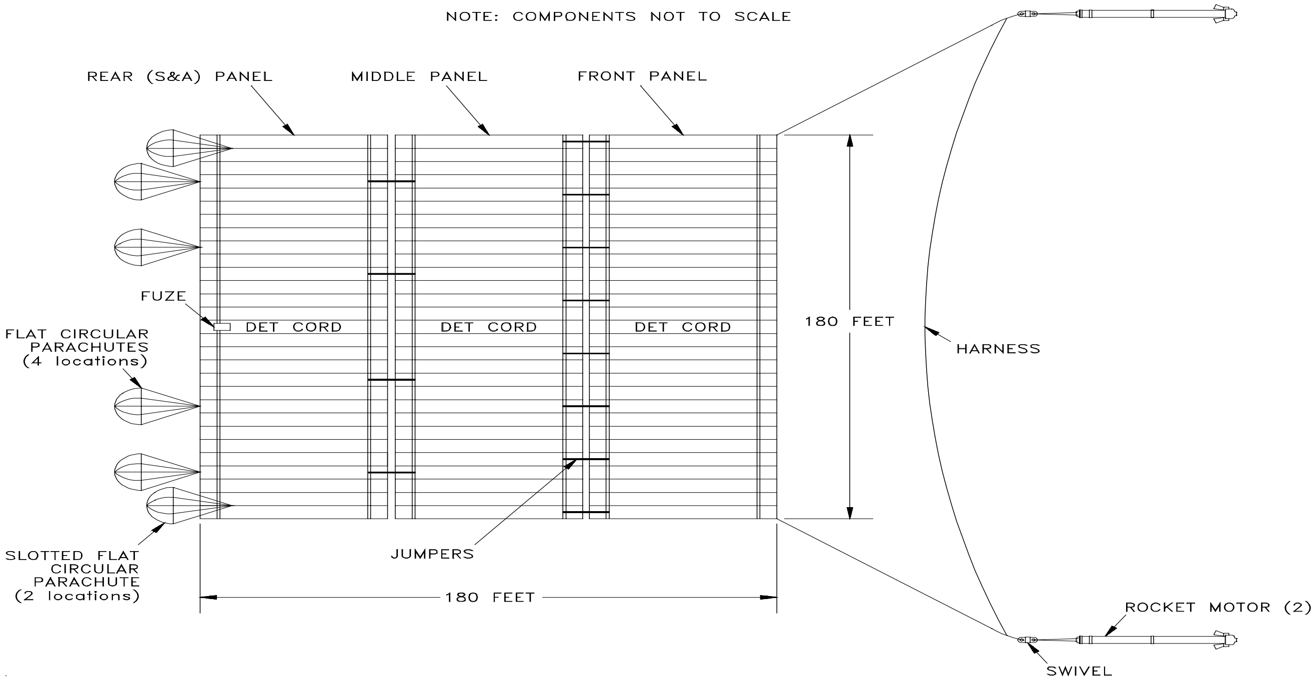

Figure 2. Schematic of Fully Spread DET Array

Both the DET and SABRE mine clearance systems have been designed to be fired from the deck of the Navy's primary amphibious assault vehicle, the LCAC (Landing Craft Air Cushioned) hovercraft (see Figure 3).

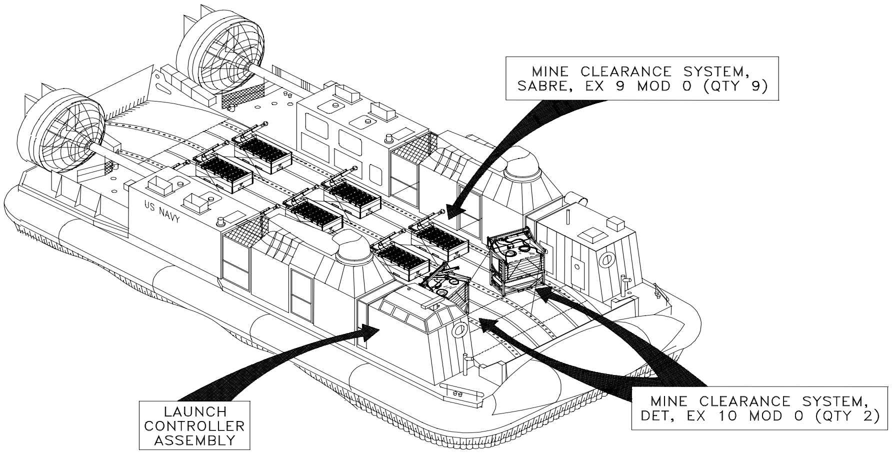

Figure 3. Hovercraft Deck Layout Showing Locations of DET & SABRE

Due to the hazardous nature of the DET system, the relatively tight quarters of the LCAC, and the extreme conditions under which DET must operate (high winds, high sea states, extreme temperatures), there has been great concern that the deploying explosive array may strike the launch craft structure. Therefore, a predictive model of the flight trajectory of the DET system with respect to the LCAC launch platform was needed. Thus, an ADAMS model capable of simulating the entire flight dynamics of the deploying DET system was created (see Figure 4). Then, the model was successfully used to predict the minimum DET to LCAC clearances during deployments under extreme environmental conditions.

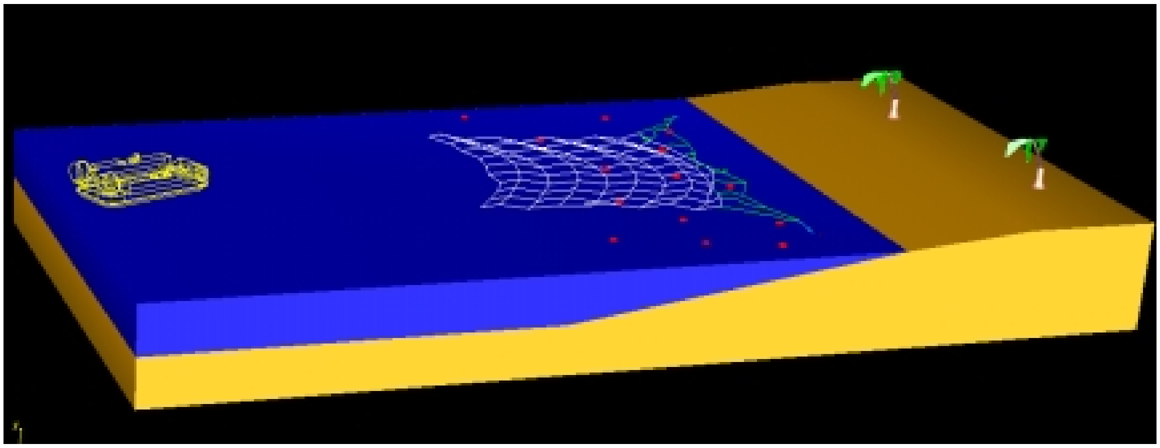

Figure 4. ADAMS Model of DET Showing Final Array Resting Position

Modeling Approach

Portions of this model were developed in conjunction with the Mechanical Dynamics Inc. Consulting Services group, in particular Mr. John Janevic.

The ADAMS DET trajectory model consists of an array of POINT_MASS parts connected by user-written single component forces that represent the DET network of nylon, kevlar, and detonating cord. Since every intersection of detonating cord and nylon structural members (16,200) can not feasibly be modeled, because of excessive file sizes and run times, the array lines are lumped together and modeled as a 10 by 10 grid of point masses. Point masses are used, since all the forces on each array part are acting through the center of gravity, which helps to decrease run times. Additional point masses are used to represent the harness. All the point masses are connected by user-written SFORCES, which apply a tension-only spring-damper force whenever the distance between the respective point masses is greater than the amount of nylon rope or detonating cord between the parts. The damping coefficients and spring stiffnesses of these SFORCES are adjusted to represent the different structural materials present in the DET system.

Two additional PARTs, representing the rockets, have action only single component forces applied to them to denote the rocket thrust. This thrust force is included in the dataset as a series of SPLINE statements, representing the different thrust versus time histories as functions of temperature. The actual mass moments of inertia of each rocket, determined in Pro-Engineer, are included in each rocket PART statement. Also, since the masses of the rockets decrease during their flight, a separate time-varying inertial GFORCE is applied to each rocket.

Aerodynamic forces are present throughout the explosive array, as well as on parachutes along the rear of the array, and are included via user-written VFORCES. Aerodynamic properties of the net were determined during wind tunnel tests at the University of Michigan. Drag and lift coefficients versus angle of attack are included as polynomial functions in the VFOSUB. All aerodynamic forces are determined with respect to a relative part velocity; therefore, the model allows the user to prescribe different environmental wind speeds and directions.

Joint constraints and motion statements control the six possible movements of the LCAC launch craft during high sea states (roll, pitch, yaw, surge, heave, and sway). In fact, each individual degree-of-freedom of the launch platform can be prescribed in a separate MOTION statement. These usually take the form of a simple harmonic motion, with amplitudes and frequencies adjusted depending on the sea state being modeled. An IMPACT function is used to apply a normal SFORCE, perpendicular to the moving LCAC deck, to ensure that the array POINT MASSes and rocket PARTS move in concert with the oscillating LCAC. Finally, additional IMPACT SFORCES, at a lower relative height, are present to model the water or ground impact of the deployed array.

Model Postprocessing

The model described above is capable of predicting the flight behavior of the entire DET system. However, in order to measure the clearance between the deploying DET and the LCAC launch platform, several additional postprocessing steps were developed. First, an accurately dimensioned representation of the LCAC hovercraft was created in Pro-Engineer. Using the ADAMS to Pro IGES translator, this geometry was imported into an ADAMS command file. This command file is read during AVIEW sessions to import the LCAC geometry into ADAMS graphics animations. Then, with the LCAC geometry displayed in the graphics file, animations are run with the base marker and camera position selected to observe the DET system deploying over the bow ramp of the LCAC. A similar animation can be played with the LCAC side wall used as a reference. This method permits a direct reading of the system to launch platform clearance versus time. By holding the cursor at the arrays closest point relative to the bow ramp or side wall, the minimum clearance can be “dragged out” and measured after each animation (Figure 5).

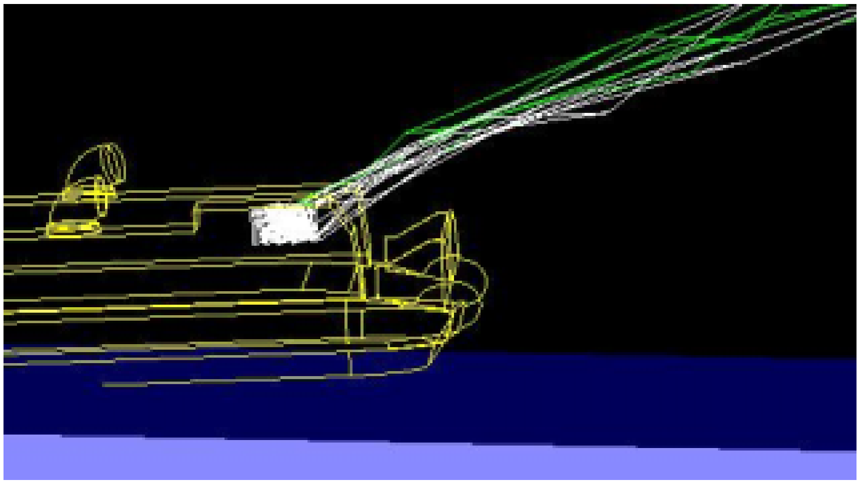

Figure 5. ADAMS Animation of DET Clearance Over LCAC

Model Validation

Validation of the DET model was accomplished by comparing the ADAMS predictions to measured trajectory and clearance data obtained during actual flight tests conducted at Eglin Air Force Base and Fort A.P. Hill, Virginia. During several tests, high speed cameras were positioned in locations corresponding to the LCAC bow ramp height and side wall edge. Graduated witness boards and poles opposite each camera were included so that positions of the array could be measured off the video. Also, to validate this clearance prediction approach, tests of a sister system to DET (called the Surf Zone Array) were conducted off an instrumented, hydraulically actuated 6-DOF motion platform. A similar trajectory model was used to predict clearance over critical structural components (see Figures 6 & 7).

Figure 6. Motion Platform Test Setup

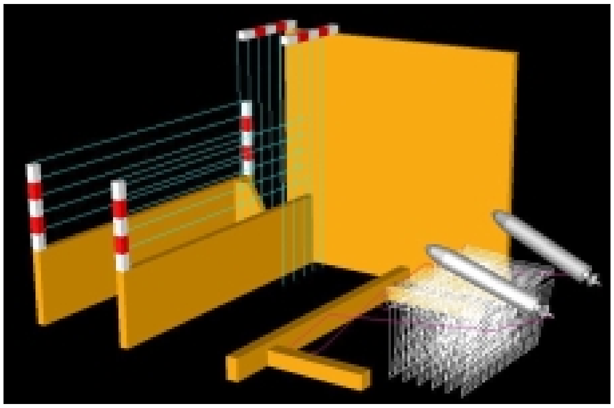

Figure 7. ADAMS Motion Test Model

ADAMS predictions of DET system clearances over critical LCAC structures show good agreement with test measurements to date. Efforts are ongoing to increase the fidelity of these predictions under the full range of motion and environmental conditions.

SABRE Line System Loads

Description/Objective

The SABRE system (for shallow water mine clearance) has an explosive length of 390 feet with 10-pound bulk charges every 3 feet. The charges are connected on both sides by strength members consisting of Type XXVI nylon webbing (see figure 8). The system is packed in a shipping container as shown in figure 9. Deployment is accomplished using a Mk 22 Rocket Motor that is launched from a rail that is mounted on top of the shipping container (see figure 9).

Figure 8. SABRE Line Segment (2 charges)

Figure 9. SABRE Pre-launch Configuration

The M58 system (for beach zone mine clearance) has an explosive length of 350 feet with ½-pound charges distributed continuously along its entire length. Currently a nylon rope passes through the center of the charges and carries the load during deployment. Under a manufacturing improvement effort, the Python program has proposed carrying the load on the exterior of the charges by braiding over the charges using a polyester weave. A Python-M58 system during manufacture is shown in figure 10. The M58 system is packaged in a shipping container similar to the SABRE container except the system and container are somewhat shorter (see figure 11). As with the SABRE system, the M58 system is deployed using a Mk 22 Rocket Motor.

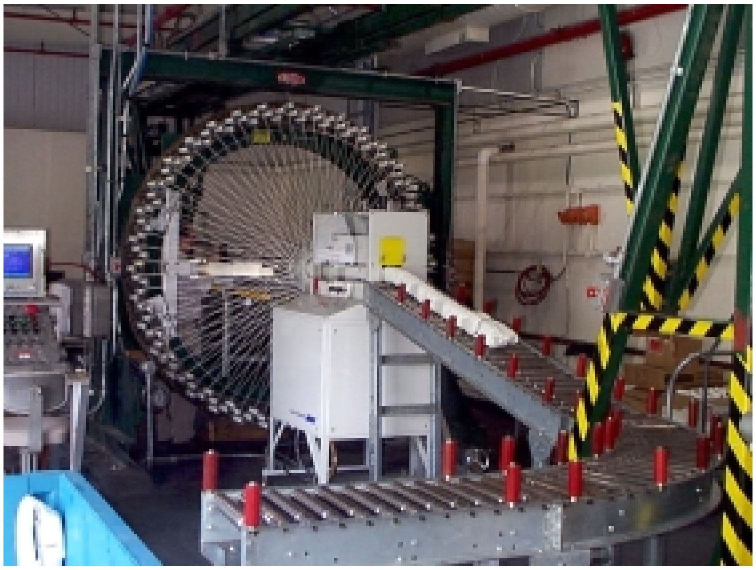

Figure 10. Manufacturing of Python-M58 system

Figure 11. M58 system in Shipping Container

A critical issue in the development of line systems is the strength of the line. If a single strength member fails the entire line system may fail, potentially resulting in a mission abort. For this reason, ADAMS models have been created for both the SABRE system and the M58 system.

Modeling Approach/Results- SABRE

The SABRE system was modeled using ADAMS rigid body parts for each component of the SABRE system including: the rocket motor, connector, inert interface unit, 130 live charges, and the fuze. The thrust of the Mk 22 Rocket Motor at nominal, cold and, hot operating conditions was included as spline statements within the model. The thrust force is applied to the rocket part using a VFORCE statement containing a AKISPL function. Switching between thrust splines is efficiently handled by using an integer variable within the AKISPL function to specify the spline desired.

In the SABRE model, the webbing strength members are represented by SFORCE statements that connect each charge to the next charge. The model, as in the actual system, uses two strength members (i.e. two SFORCE statements) between each charge. Within the SFORCE statement, the strength of the webbing material is represented by a BISTOP function. Although the BISTOP function permits both tensile and compressive loading, only the tensile portion of the function is actually utilized when modeling SABRE deployments.

As in the DET model, IMPACT functions are used to support the charges prior to their pick-up by the rest of the SABRE line. The SABRE aerodynamic forces are represented by VFORCE statements including a VFORCE statement to represented the parachutes that trail the system. Also as in the DET model, the pitch, heave and, roll of the LCAC can be simulated, if desired.

The load versus stretch characteristics of SABRE strength members with their unique attachment to the charges were determined in slow-rate tensile tests (see figure 12). The nylon is clearly a nonlinear stiffening material. A curve fit of the data was completed to determine the parameters in the following equation, $F = Ax^B$. The BISTOP function permits nonlinear (e.g. stiffening) springs, as well as, linear damping. The equation provided in the previous paragraph was used to represent the spring portion of the BISTOP function and the damping constant was adjusted to provide dynamic load values consistent with values measured in actual test firings. The ultimate dynamic strength (11,757 pounds) of the webbing material was determined by pulling samples to failure in a series of air gun tests.

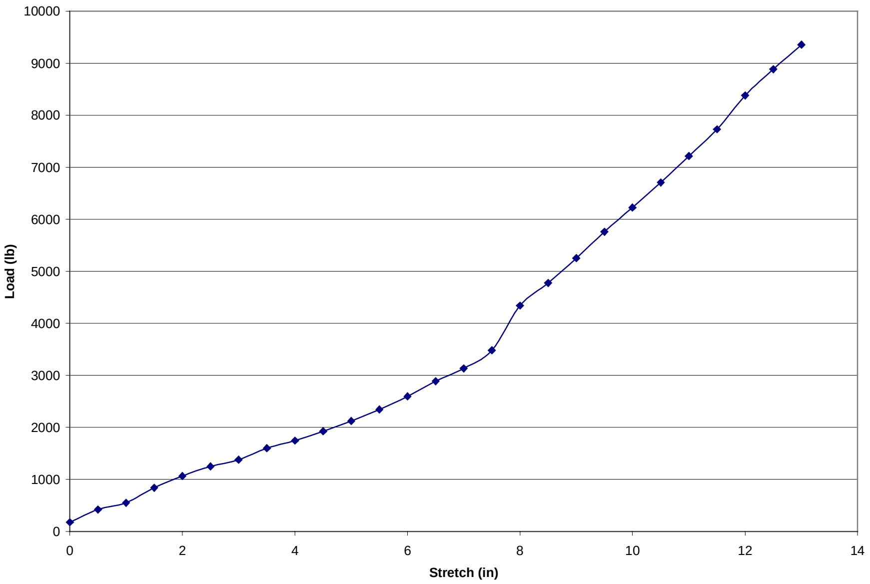

Figure 12. SABRE Tensile Test, Type XXVI Webbing on SABRE Charge

Within the SABRE model, a REQUEST statement was created for each SFORCE that represents the webbing segment between each charge. To obtain the maximum force for each segment a command file was created that automates the process of obtaining the maximum value for each REQUEST. The results were exported to a text file that was imported into Microsoft Excel for plotting (see figure 13). Based on these results, a factor of safety of 1.8 was calculated for the system.

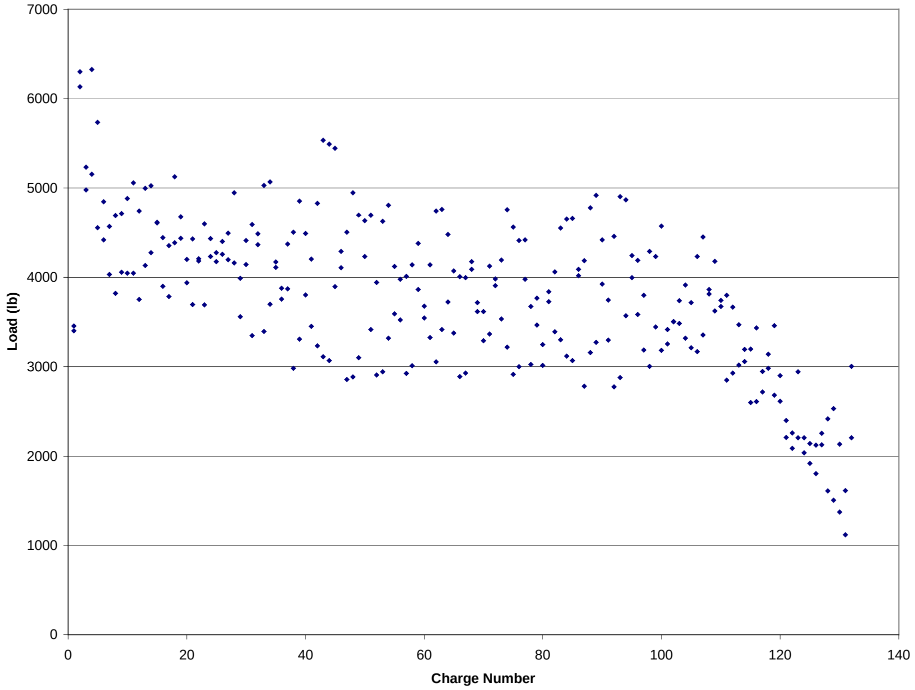

Figure 13. SABRE Maximum Loads in Webbing Segments

Modeling Approach/Results- Python/M58

An ADAMS model of the Python-M58 system was created that is similar to the SABRE model. The number of charges in the Python-M58 model was increased, however, to 700 to match the actual number of charges in the system. A single SFORCE statement was used between each charge to represent the polyester weave that surrounds each charge.

To characterize the strength properties of proposed Python-M58 system, tensile tests were performed on 2-charge inert line segments at pull rates ranging from 50 in/s to 200 in/s (see figure 14). There was considerable interest in the properties of the braid at higher rates since photographic coverage of M58 deployments indicated the relative velocity between two adjacent charges may be as high as 20 ft/s (240 in/s). The high rate experienced in M58 deployments could not be duplicated by the tensile tester, however, it was hoped the pull tests completed at the highest rate (i.e. 200 in/s) would be representative of the rates expected during deployment (i.e. 240 in/s). It was also expected that by testing at a variety of test rates, the dependence of strength characteristics on rate could be characterized.

Figure 14. Python-M58 2-charge Tensile Sample

The results of the tensile tests are summarized in figure 15. Although the tensile tester grip moved at a high rate 50-200 in/s, the rate of expansion between the charges was much lower (15-59 in/s). This is due to the large stretch of the polyester weave at the two ends of the test sample (i.e. beyond the ends of the two charges).

Figure 15 indicates that the strength properties of the polyester-braided segments were not measurably different for the rate range investigated. A single curve fit was, therefore, obtained for the data and is also shown in figure 15. Unfortunately, the dynamic properties (e.g. damping coefficient) of the braided polyester could not be determined from the tensile tests performed to date. Additional testing may be required to characterize the dynamic properties of the polyester braid.

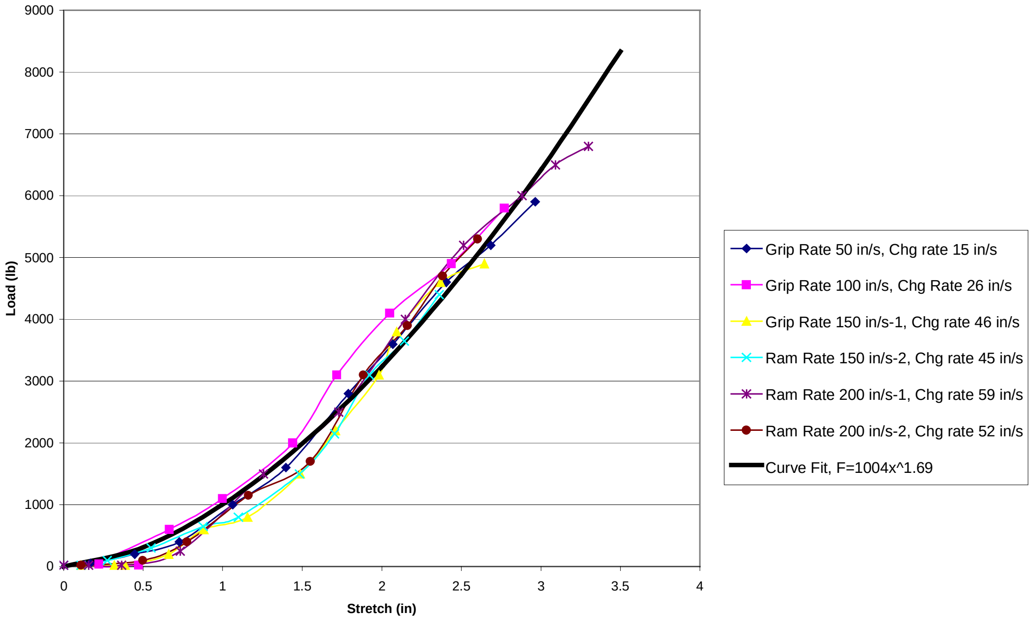

Figure 15. Tensile Test Results for the Python-M58 System

Summary

ADAMS models have been and continue to be instrumental in the development of mine clearance systems. Huge models have been created to represent the systems and these models have been used to simulate a variety of conditions of interest. This paper has outlined two uses of the models, to estimate clearance of the DET system over a bow ramp and for estimating line loads and safety factors for the SABRE and Python-M58 systems. The models have proven versatile for addressing these issues and many other issues such as deployment range and coverage area, performance in various sea states, and performance at extreme operating conditions. The models are cost effective since many of these conditions are difficult, if not impossible, to recreate in a test environment.

The U.S. Navy will undoubtedly continue to use ADAMS modeling to address many of its difficult problems in mine countermeasures. Future work will likely include additional tensile tests to better characterize strength members used in mine clearance systems and deployment of new unconventional mine clearance systems.