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M433 CENTER OF MASS LOCATION THROUGHOUT FUZE ARMING CYCLE

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14. ABSTRACT

The effects on the center of gravity of the M433 40-mm round due to the arming of its M550 fuze while in flight were studied. The results of this study would be used to assist in determining whether this center of gravity change contributes to instabilities during the round's flight. The study was performed using dynamic simulation software. A virtual model of the M433 round was built, and the location of the center of gravity was tracked throughout the arming cycle of the fuze.

The results show that the center of gravity in the round does change throughout the fuze's arming cycle and the flight of the round. It is undetermined at this stage in the process whether these center of gravity changes contribute to the instabilities of the round in a substantial way. More testing and correlation with additional simulations is recommended before any final answers can be reached.

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M433, Center of mass, Center of gravity, Fuze, 40 mm, Dynamic analysis

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INTRODUCTION

As part of the 40-mm Integrated Project Team (IPT) that was composed to baseline and improve the M433 and M430 rounds, the U.S. Army Armament Research, Development and Engineering Center Weapons Technology Branch (WTB), Picatinny Arsenal, New Jersey was asked to construct a computer simulation that would track the center of gravity change in the M433 due to the arming of the fuze while the round is in flight. This data would be used to determine what, if any, effects the center of gravity changes have on the pitch and yaw of the round throughout its flight.

The study was performed using *MSC/Adams (Adams)*[1] dynamic simulation software. This software allows the user to make a virtual model of a mechanical system using part files from *Pro/Engineer (ProE)*[2]. The parts are given the mass properties of their respective materials, and motions and forces are applied to the model so that it behaves as it was designed to. In this particular simulation, the round was given a velocity and spin that ramped up from zero to the muzzle velocity and muzzle spin rate in a time that corresponds to when the round would leave the barrel. The spin and velocity were then effectively turned off and the round was allowed to fly freely through space while the location of the center of gravity in the x, y, and z directions was tracked.

The simulations yielded results that will be helpful in determining the causes of M433 flight instabilities, and particularly, they will be useful in determining whether the fuze design is one of the contributors to instabilities.

MODEL GENERATION

Background

The 40-mm ammunition team assembled an IPT with the intent to baseline and improve the M433 and M430 rounds. One of the main concerns with the current M433 round is its flight instabilities. The IPT plans to quantify these instabilities with the spark range testing that is being performed for the round. The IPT expressed a desire to not only determine how much instability there was with the round, but to try to determine what the contributors of instability are. To do this, the WTB was asked to construct a simulation of the flight of the round, mainly focusing on the time during which the fuze is arming. To take this a step further, a desire arose to find out how the arming of the fuze affects the center of gravity of the round.

The M550 fuze used in this round is mechanical, and operates using the centrifugal force of the spinning round to rotate the detonator into position. The detonator is allowed to rotate because it is mounted on a gear with an axis that is misaligned with the axis of rotation of the M433 round. A proportionately larger mass is located on the same gear and opposite the detonator, allowing the mass to rotate the detonator. The gearing system is used to control the speed that the detonator rotates, so that a prescribed amount of time passes before the fuze is

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[1] *MSC Adams*, MSC Software Corporation, Santa Ana, CA, 2005.
[2] *Pro Engineer*, PTC Parametric Technology Corporation, Needham, MA, 2005.

armed. To arm, the detonator rotates until it is in line with the path of the firing pin, allowing the firing pin to strike it on impact. A picture of the fuze with the necessary parts labeled can be seen in figure 1. Due to the complex rotation of misaligned weights, there is good a possibility that the center of gravity changes enough to make the round unstable in flight. The simulation constructed by the WTB was designed to quantify these center of gravity changes.

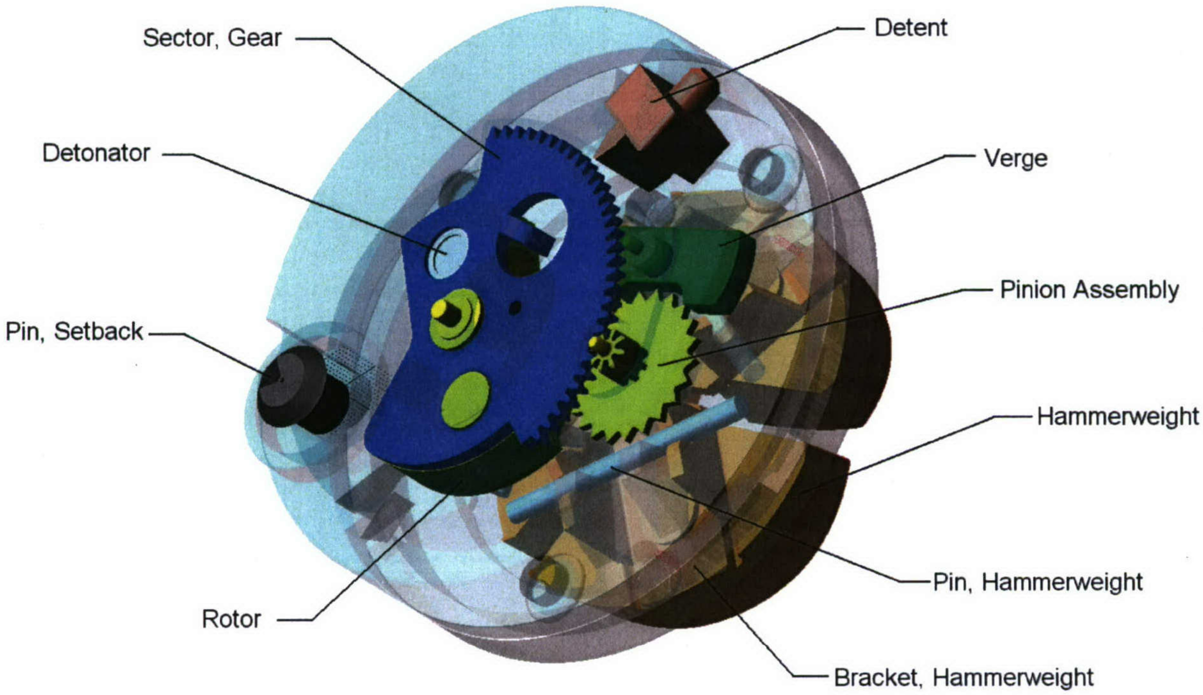

Figure 1
Labeled picture of M550 fuze parts

Approach

Initially, the *ProE* files needed to be checked to verify that they were assembled in accordance with the design. This was done because the WTB has had problems in the past with *ProE* files being improperly constrained, leading to potentially incorrect results. The most critical problem with the *ProE* assemblies for the M433 round was that the fuze was assembled at an incorrect rotational orientation to the body of the round. After correcting the problems with the *ProE* assemblies, the model could be brought into *Adams* to commence the simulation work.

Adams is a dynamic simulation software package. This software allows engineers to take solid models of parts and assemblies from *ProE* and assemble them into a virtual model. This virtual model is then constrained so that a simulation can be performed that will operate like a real-life version. The simulation outputs a host of engineering data that can be used in program decisions or as inputs to more simulations.

Originally it was desired that a fuze model that already existed be used in the *Adams* model of the M433 round. This fuze model would be combined with the rest of the round and the simulation would be done. After several iterations, it was determined that the existent fuze model would not work with the new model of the rest of the round, likely due to differences in the versions of the software used to create each. A new fuze model would have to be built.

Before any models were run, the parts from *ProE* needed to be brought into *Adams*. The WTB, along with MSC Software, developed a special interface program that allows parts to quickly and easily be brought into *Adams* as parasolids rather than as shells, which is the geometry type created when going directly from *ProE* to *Adams*. This was done to ease the creation of joints inside of *Adams*. Parasolids give the *Adams* user much more control over the placement and definitions of joints and constraints in the models than a translation of geometry coming directly from *ProE*'s default interface.

When the parts have all been transferred into *Adams* and are verified to be in the correct starting position, their material properties could be added. There are several options available in *Adams* to input material properties. Generally, *Adams* parts initially only need a mass and moment of inertia. *Adams* has a library of material properties available for most commonplace materials, and generally these are used, as they are found to be quite accurate and seem to work well with the program. Most of the parts in this model were found to be made of common materials and the *Adams* library was sufficient for material properties. Several parts were made of materials that were not available in the *Adams* library. These parts were defined from material properties found at www.matweb.com[3], a recognized material property database. A listing of the parts and their respective material properties can be found in table 1.

Table 1
Material properties used in simulation

Part number	Part name	Material	Density	Information from
19203 9219872	Sector, Gear	Brass	0.3087 lbm/in.^3	*Adams* Database
19203 8864598	Pin, Firing	Aluminum	0.0989 lbm/in.^3	*Adams* Database
19203 9266693	Centerplate	Aluminum	0.0989 lbm/in.^3	*Adams* Database
19203 8886358	Housing, Escapement	Polycarbonate	0.007 lbm/in.^3	www.matweb.com
19203 8886368	Pinion Assembly	Brass	0.3087 lbm/in.^3	*Adams* Database
19203 8883760	Actuator	Aluminum	0.0989 lbm/in.^3	*Adams* Database
19203 9295652	Cap	Aluminum	0.0989 lbm/in^3	*Adams* Database
19203 8886340	Ring, Retaining	Steel	0.2818 lbm/in^3	*Adams* Database
19203 8886344	Skirt	Aluminum	0.0989 lbm/in^3	*Adams* Database
19203 8886350	Ogive	Aluminum	0.0989 lbm/in^3	*Adams* Database
19203 8886352	Liner, Spitback	Aluminum	0.0989 lbm/in^3	*Adams* Database

[3]www.matweb.com, Automation Creations, Inc., Copyright 1996-2005.

Table 1
(continued)

Part number	Part name	Material	Density	Information from
19203 8886356	Body, Fuze	Aluminum	0.0989 lbm/in^3	*Adams* Database
19203 9276544	Liner (One Piece)	Copper	0.3217 lbm/in^3	*Adams* Database
19203 9276546	Cup, Boattail	Steel	0.2818 lbm/in^3	*Adams* Database
19203 9276672	O-Ring	Nitrile Rubber	1.2 g/cm^3	www.matweb.com
19203 8864602	Pin, Hammerweight	Steel	0.2818 lbm/in^3	*Adams* Database
19203 8886359	Plate, Top	Aluminum	0.0989 lbm/in^3	*Adams* Database
19203 8837991	Cup	Aluminum	0.0989 lbm/in^3	*Adams* Database
19203 8886365	Verge Assembly	Brass	0.3087 lbm/in^3	*Adams* Database
19203 8886361	Detent	Zinc Alloy	6.599 g/cm^3	www.matweb.com
19200 12999862	Pin, Setback	Steel	0.2818 lbm/in^3	*Adams* Database
19203 8886354	Housing, Spitback	Aluminum	0.0989 lbm/in^3	*Adams* Database
19203 9219873	Rotor	Sintered Brass	7.7 g/cm^3	From TDP Drawing
19203 8864599	Hammerweight Assembly	Steel	0.2818 lbm/in^3	*Adams* Database
	Explosive Fill		1.8 g/cm^3	Calculated

When all parts were given material properties, joints and constraints could be added. There are many types of joints and constraints available for use in *Adams*. To best constrain a model, it is first very important to understand the physics behind the model. This will allow the user to apply the right types of constraints for any given situation. Joints essentially allow a user to remove specific degrees of freedom that two parts have relative to each other. With this particular model, many parts needed to be locked together with a fixed joint, so that they did not move in relation to each other. This would correspond to parts that were put together with an epoxy or a press fit, for example, removing all degrees of freedom. The gears were all constrained with revolute joints, allowing only rotational motion about a single user-specified axis. This model also used several translational joints, which allow two parts to slide along a single axis relative to each other.

In addition to joints, there are also many parts that need to be in direct contact with each other. As with joints, there are many types of contacts that can be used in *Adams*. The models done by the WTB typically use what are referred to as "Solid to Solid" contacts in *Adams*. This means that the user chooses two solids, and these solids are in contact any time their outer shells reach a point in which they would cross through each other. Although these are the easiest to define, there are many cases where these do not run efficiently in *Adams*. In cases with high forces or accelerations, the parts that are in contact tend to penetrate through each other, greatly slowing down the run time of a simulation and resulting in inaccurate results.

Because of this, it is prudent to use simpler types of contacts if at all possible. There are, however, times where it is simply not possible, such as if two parts are irregularly shaped or if they slide against each other while in contact. Some simpler types of contacts involve the use of curves, points, planes, or spheres. These types of contacts allow the user to define a curve, point, plane, or sphere that will be in contact with another curve, point, plane, or sphere. This greatly reduces the number of calculations that need to be done by the computer, therefore, decreasing the runtime for a given simulation.

After the geometries to be in contact are defined, the contacts can be given properties. This model was constructed with the assumption that all of the parts are perfectly rigid. While *Adams* is capable of analyzing flexible bodies, this is only prudent if the bodies are expected to experience a large amount of strain. With rigid bodies, some other assumptions need to be made with regard to the behavior of contacts. These assumptions are accounted for in the definition of the contact properties. These properties include the stiffness, force exponent, damping rate, and penetration depth of the contact. In essence, these properties define how far two parts are allowed to penetrate each other, and how quickly the parts velocities change when they come into contact. Initial estimates are made for these properties, but the values need to be iterated in many high speed impact cases since the properties don't directly correlate to real world numbers, and are highly dependent on the geometries and material properties of the two bodies in contact. The iterations needed to get these contacts working properly and efficiently account for much of the time spent in the optimization phase of these simulations. Figure 2 shows a screenshot of the model when it is ready to be analyzed in *Adams*.

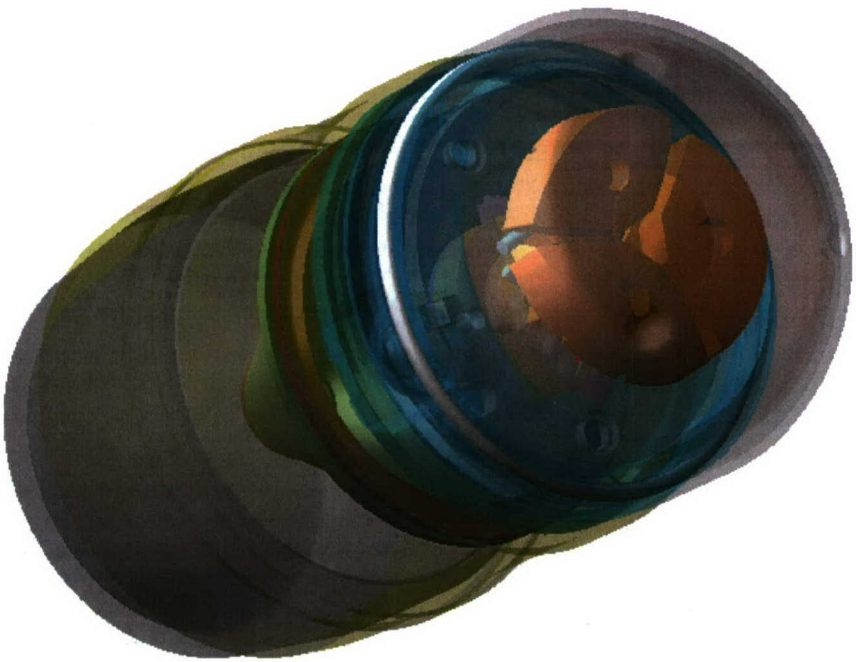

Figure 2
Screenshot of the M433 HEDP round in *Adams*

As in most models, several unforeseen obstacles slowed progress along the way. The first obstacle, as stated earlier, was the fact that the fuze model that was previously constructed was not compatible with the newest version of the software. In addition, it was found that because of the high accelerations and forces that the fuze experiences, many of the contacts were not functioning as expected. Most cases involved two parts impacting each other and penetrating an unacceptable distance into each other. The first major case of over-penetration was the detent. As the round begins to rotate, this detent slides outwards until it contacts the escapement housing. The problem that arose was that the angular acceleration was so high that the detent was pushing into the housing and slowing the runtime considerably. After several iterations of trying to optimize the contact, it was decided that the best solution would be to get rid of the contact and create a fixed joint that is activated when the detent moves into the correct position. Although this involved several otherwise unnecessary steps, the end result was a much quicker running model. However, due to the way the code is written, the fixed joint must be turned on when the simulation run is started. Therefore, the actual firing of the round does not take place until t = 5 ms in the model. This allowed the joint to be deactivated and the model to settle before the round was fired.

The final obstacle proved to be the most difficult to overcome. Again, the problem was that parts that were intended to be in contact were penetrating each other. The parts that were the problem in this case were the hammerweight brackets, hammerweight pins, and the centerplate. The hammerweights and brackets are designed to rotate outwards until the brackets come into contact with the centerplate. When they come into contact, however, the forces were high enough to continue to push the brackets through the centerplate. As they began to push through, the hammerweight pins also began to penetrate into the centerplate from the other side, as they were constrained to slide in their respective slots in the centerplate. Several iterations were run of this model to try to optimize the solid to solid contacts used here, but to no avail. A careful examination of this model showed that, although the hammerweight pins are allowed to slide in the centerplate, this is not needed, as the resting position of these pins is directly against the centerplate. This contact, therefore, was removed and the translational joint was replaced with a revolute joint, allowing the pin to only spin about its axis, with no translation in any direction. Although this did eliminate problems with the pins, the brackets were still penetrating into the centerplate. All valid types of contacts were defined (curve to curve, curve to plane, etc.) and runs were attempted, but the same problems arose each time the simulation was run. The final solution involved some specific contact parameter modification and some assistance from the software vendor. These modifications alleviated the problems immediately.

Adams was used to iteratively run a simulation, view its results, make changes to the model, and re-run the simulation. The verification for this particular simulation was making sure that the fuze armed between 220 and 350 ms per the notes on the escapement assembly drawing, part number 19203 8886357. The target was an arming time of 285 ms, as this falls half way between the minimum and maximum values. The fuze, therefore, was verified separately from the rest of the assembly to decrease run time, since the rest of the round has no effect on the arming time of the fuze. The muzzle velocity and muzzle spin rate of the M433 round are 76 m/s (3 in./ms) and 62 rev/s, respectively. The simulation was run by ramping the velocity and spin rate up to these values in a time that corresponds to when the round would leave the barrel. Assuming constant acceleration throughout the length of the barrel, that time was calculated as follows

$$v_f = v_0 + at$$

$$s = v_0 + \frac{1}{2}at^2$$

Where:

v_f = final velocity (3 in./ms)
v_0 = initial velocity (0 in./ms)
a = acceleration (unknown)
t = time (unknown)
s = displacement (10 in.)

The displacement was known to be 10 in. for a 12 in. barrel. Eliminating time, using an initial velocity of zero, and combining the two equations yields

$$v_f^2 = 2as \text{ or } a = \frac{v_f^2}{2s}$$

Using all of the known values, the acceleration was calculated to be 0.45 in./ms^2. To calculate for time

$$s = \frac{1}{2}v_f t \text{ or } t = \frac{2s}{v_f}$$

Solving for t yielded a value of 6.67 ms. This corresponds to the time that the M433 round would leave a 12 in. barrel. This was used as the time that the round would take to accelerate from zero to its muzzle velocity and spin rate of 76 m/s (3 in./ms) and 62 rev/s, respectively. In addition, this is the time that the motions were turned off and the round was allowed to fly freely through space.

To alter the arming time, friction was added to the system. An assumption was made that since all of the gears interact with each other, it would be valid to add friction to only one of these gears. The friction on this gear, then, would be far more than it would be on a real fuze, but since there is no way to quantify this friction value, it would be determined by trial and error and would not affect the results of this simulation. This friction value was changed iteratively until the arming time matched the target value of 285 ms. Altering only a single friction value made this phase quicker and far more predictable than if there were multiple parts with friction in the model.

The simulation was run for 350 ms. The x, y, and z centers of gravity were tracked for the entire time of simulation with a custom command written to do so, and the program output the change in center of gravity from the initial at-rest position in each direction. The command was written to complete the following calculations at each time step

$$\left(\sum \left(displacement_{partCG} * m_{part}\right)\right) / m_{total}$$

Each part's mass was multiplied by the displacement of its center of gravity. These were then summed for all parts, and divided by the mass of the entire M433 round. This calculation was performed for the x, y, and z directions. The results were then plotted.

RESULTS

The results showed that, as expected, the arming of the fuze does change the center of gravity of the round. In addition, it is apparent that the initial center of gravity of the round, although close, is not at the round's axis. The resting position of the fuze assembly when the round has completely armed also does not produce an axial center of gravity. These may come to be important issues to be addressed as the round is improved.

The change of center of gravity in the X direction was minimal and almost immediate. This is due to the fact that the only change in that direction is due to the setback pin (which was assumed to be in its rearward position immediately), and the weights that rotate when the round spins. The plot shows that the center of gravity in this direction quickly stabilizes and doesn't change through the rest of the flight of the round. This can be seen in figure 3.

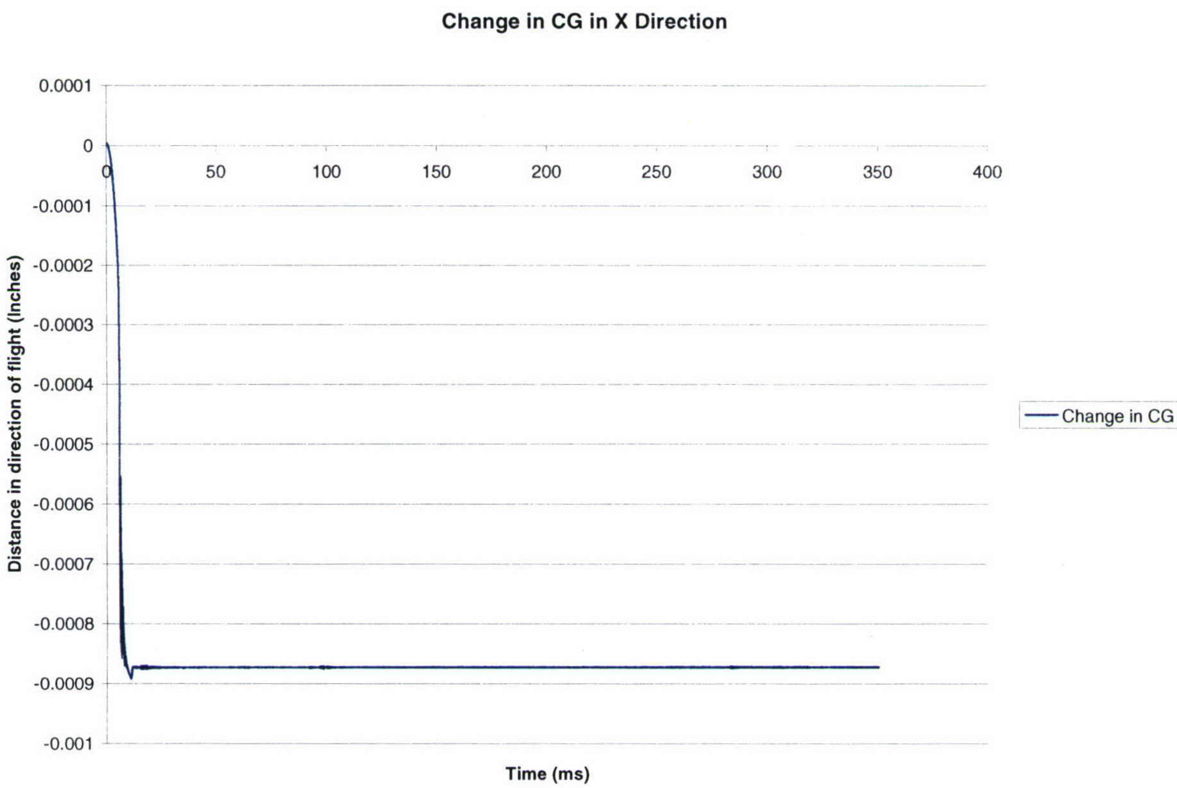

Figure 3
Change in center gravity in direction of flight

Adams output a plot of the Y center of gravity change over time and a plot of the Z center of gravity change over time. These can be seen in figures 4 and 5. All of the plots show noise at the beginning of the simulation. This is because the round was not fired until 5 ms into the simulation. The first 5 ms were used to let the model settle before firing. This can be seen in each plot. To better see how the center of gravity changes, a plot was produced using the previous data to show the path that the center of gravity takes as the fuze arms. Although time is not taken into account in this plot, it shows a cross sectional view of the Y and Z positions of the round and its center of gravity throughout the fuze's motion. The plot shows that the largest offset from the axis (0,0 on the plot) is when the fuze is completely armed. The center of gravity path can be seen in figure 6.

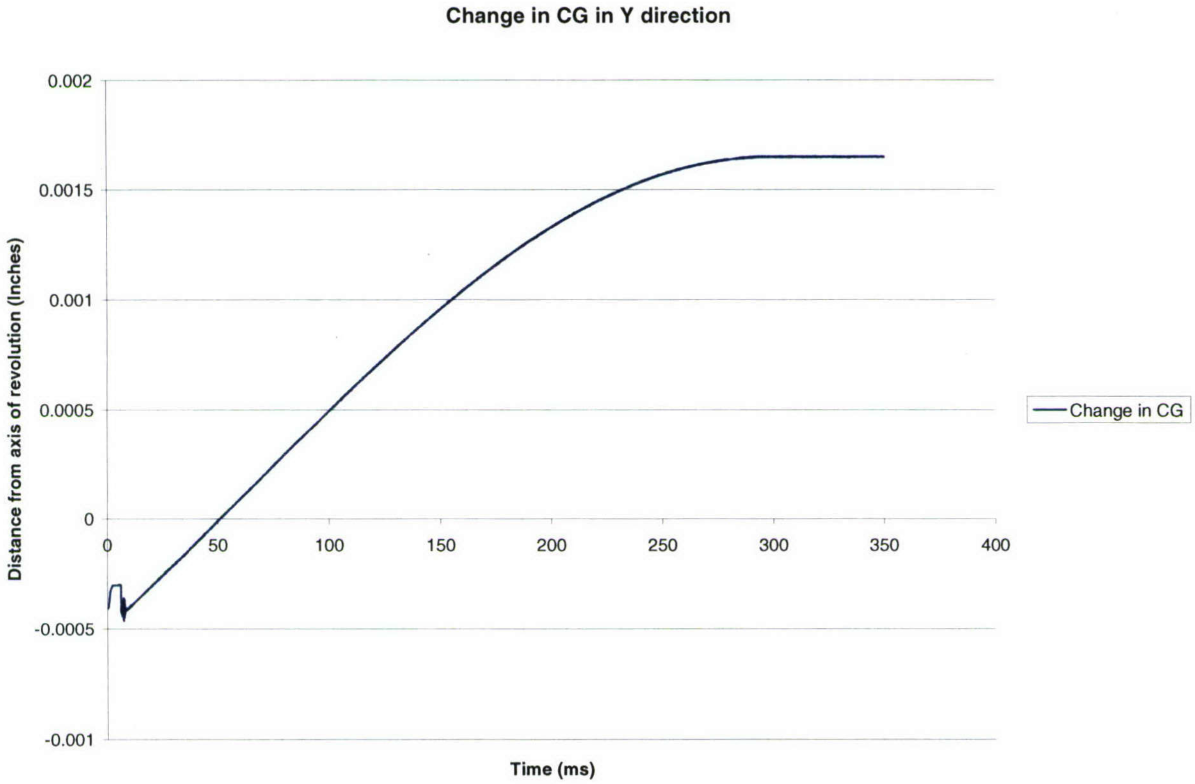

Figure 4
Center of gravity change in Y-direction over time

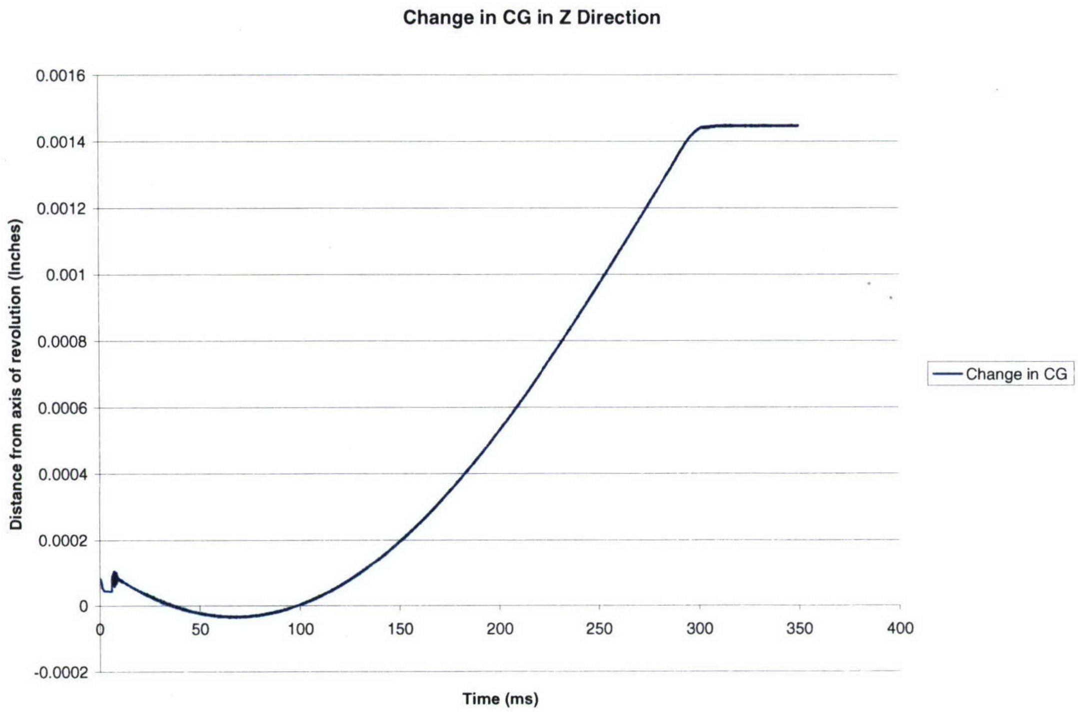

Figure 5
Center of gravity change in Z-direction over time

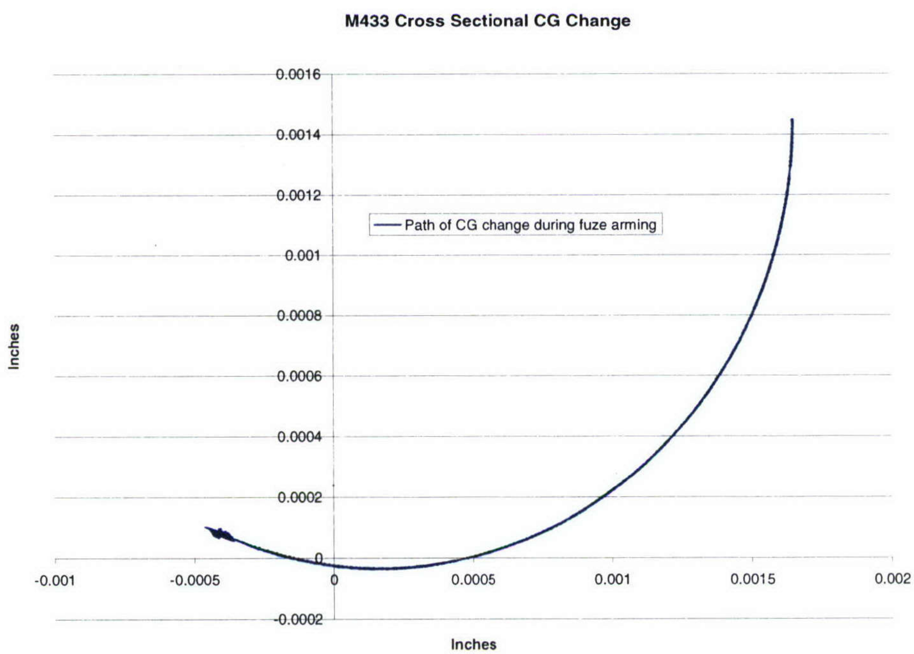

Figure 6
Center of gravity path throughout the cross-section of a M433 round

CONCLUSIONS

The results from the *Adams* simulation show that a center of gravity change occurs during the arming of the round's fuze. This center of gravity change takes the center of gravity offset from a value of approximately 0.000415 in. from the axis of revolution of the round when in the safe position, to 0.002196 in. from the axis of revolution of the round when in the armed position. At first glance these seem to be very small and perhaps negligible. Although this may be the case, an object spinning at approximately 3720 revolutions per minute can produce enormous angular accelerations even with only a small offset mass. Dynamic simulation alone cannot determine whether the center of gravity changes are a substantial contributor to the instabilities of the round. Correlation with spark range and other testing will have to be performed to determine whether there is any effect on the aeroballistics of the round. Further simulation work as well as experimental testing is recommended to reach any final answers.

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