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Design and Evaluation of an Electromechanical Actuator for Projectile Guidance

by Ilmars Celmins

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14. ABSTRACT
An ongoing Army requirement is for actuators for guided munitions. This report describes an electromechanical actuator concept using a tubular solenoid. Preliminary test results reveal the capabilities and limitations of the actuator concept.

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1. Introduction

As the Army moves towards the development and fielding of a variety of guided munitions, there is a recurring requirement for various actuation mechanisms that can provide the guidance authority. This report documents the design and testing of an electromechanical actuator concept. The basic concept and function are described without reference to any particular weapon program.

2. Actuator Design Requirements

2.1 Initial Design Specifications

Initial actuator requirements can be summarized as follows:

- 55,000 g launch acceleration
- Actuation over ¼ turn of a 30 Hz roll rate (8 ms actuation time)
- A maximum of 12 actuations during the flight
- The actuator had to fit within a nominal 25 mm diameter by 50 mm long fin hub

2.2 Additional Performance Requirements

After the feasibility of the design concept was established, it was decided to check into the possibility of using a similar concept on a projectile that would have a longer flight time and require additional actuations (up to 400 actuations).

3. Design Concept

3.1 Actuator Design Concept

The basic design concept was to keep things small and simple, with a minimum number of moving parts. Small parts would have less inertia, which served two purposes: 1) less inertia means short actuation times can be achieved with minimal force; and 2) lower mass means lower forces as a result of launch acceleration.

The basic design concept is shown in figure 1. A tubular solenoid is used to retract an angled sliding block. The angled face of the block pushes on a spring steel tab. A portion of the tab extends into the air flow, generating shock waves that impinge on the fins and cause a deflective force due to the pressure difference across the fins.

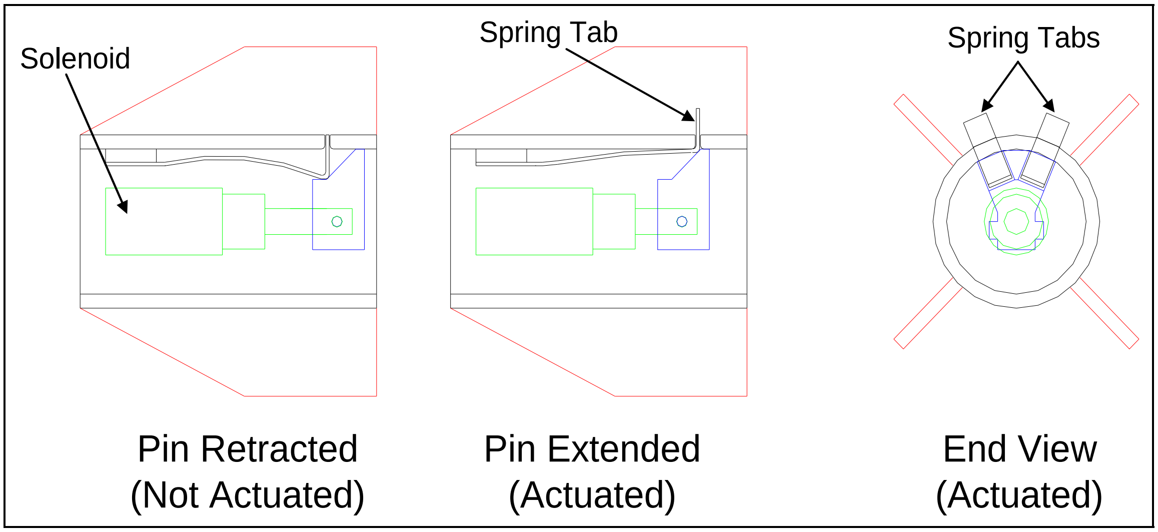


Figure 1. Actuator design concept.

3.2 Solenoid

Figure 2 shows the tubular solenoid selected for this application was the series S-69-38, which was manufactured by Magnetic Sensor Systems of Van Nuys, CA (www.solenoidcity.com). The solenoid with a coil wire size of 33 AWG was selected, resulting in a nominal coil resistance of 5.9 Ω. Magnetic Sensor Systems was chosen because they had small solenoids that were readily available and easy to purchase through their Web site.

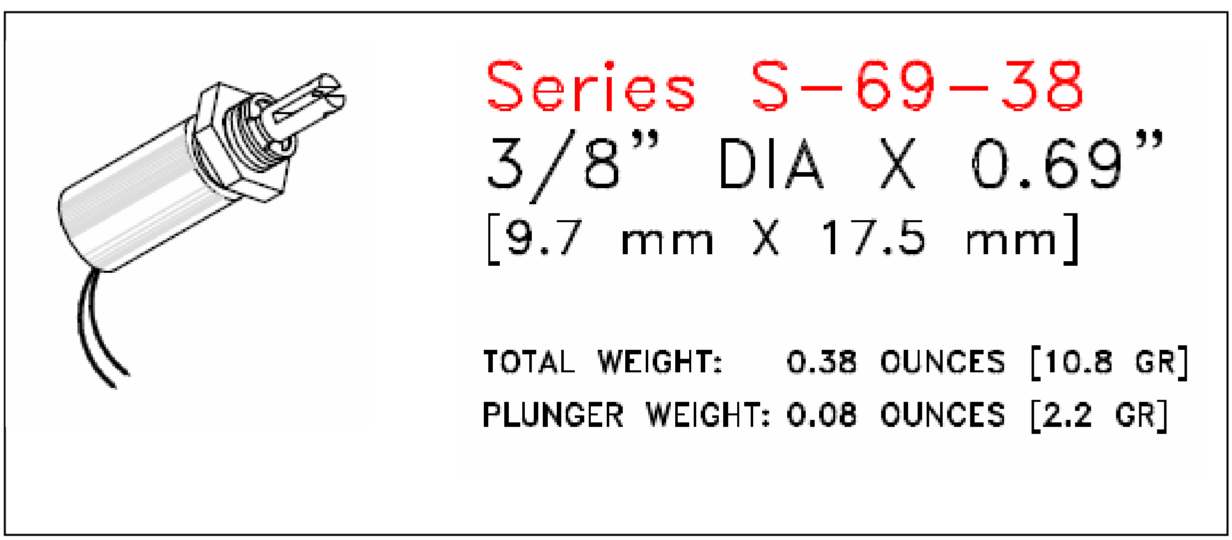


Figure 2. Tubular solenoid.

4. Testing and Evaluation

4.1 Shock Testing

The first parameter evaluated was whether the selected solenoid would be able to withstand the required shock loading that it would experience during launch. A test fixture was designed and fabricated to hold the solenoid in the launch orientation. An aluminum block was attached to the plunger to simulate the slider block mass. The assembly was tested on the U.S. Army Research Laboratory (ARL), Advanced Munitions Concepts Branch (AMCB) shock table at increasing peak accelerations, up to the upper limit of the shock table (36,000 *g*'s). There was no visible or measurable effect on the solenoid. The electrical resistance of the coil had not changed, and it still functioned normally after shock testing.

4.2 Performance Parameters

Figure 3 is a chart showing solenoid retraction force vs. displacement. The different curves represent varying levels of ampere turns (AT), and the duty cycle that each of the levels can maintain is listed as a percentage. It is readily apparent that as the duty cycle is decreased (and the power is increased), the pull force increases dramatically.

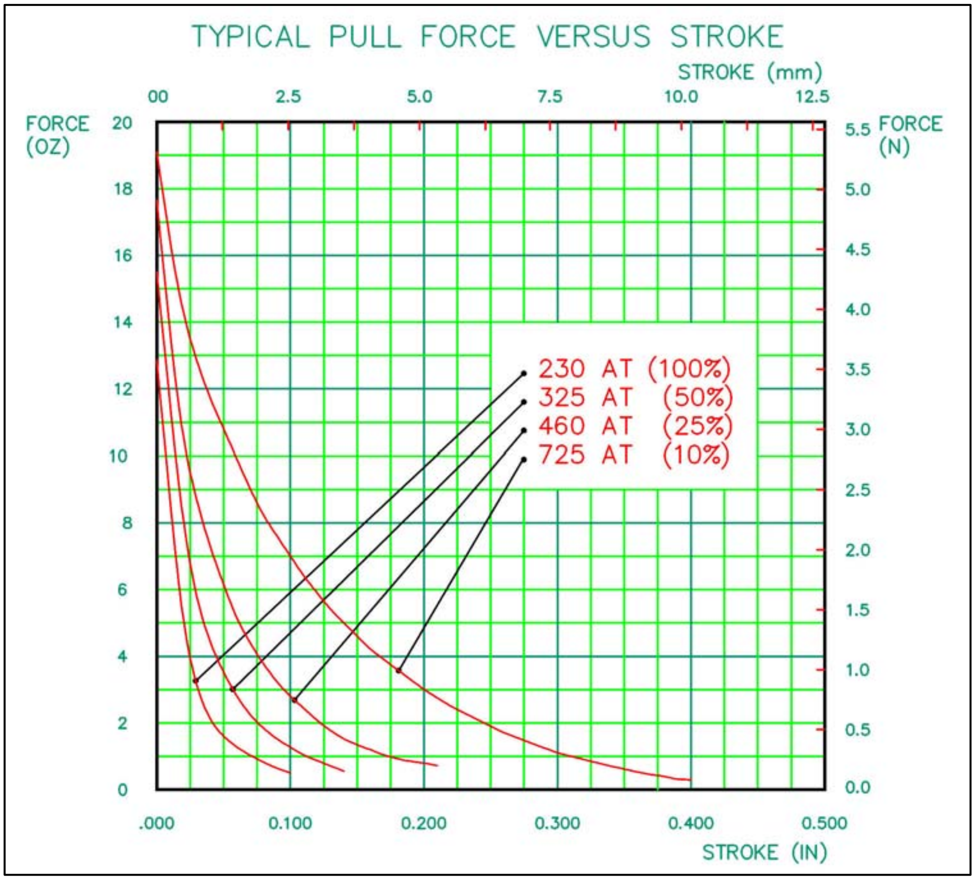
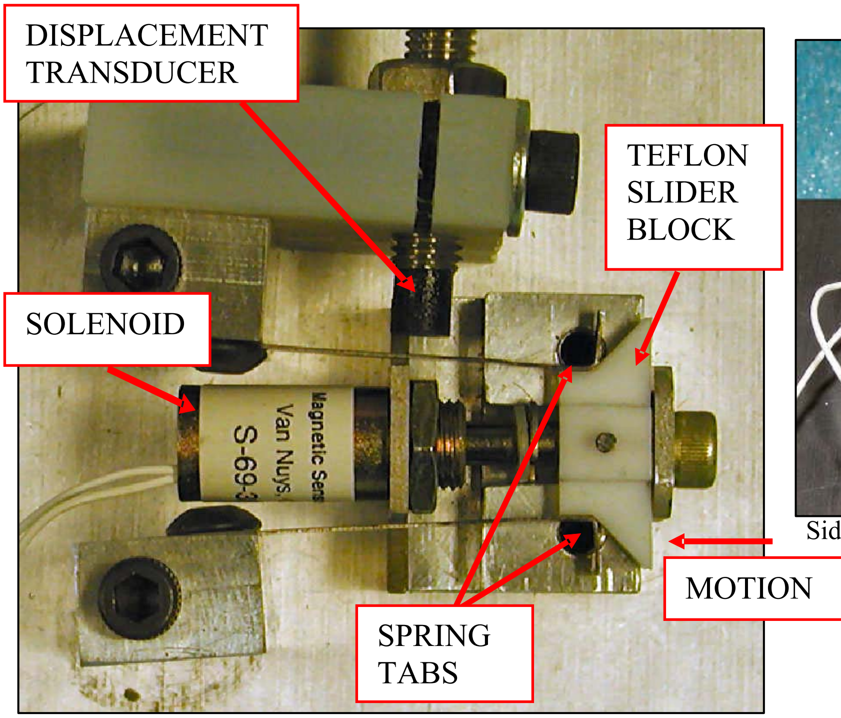


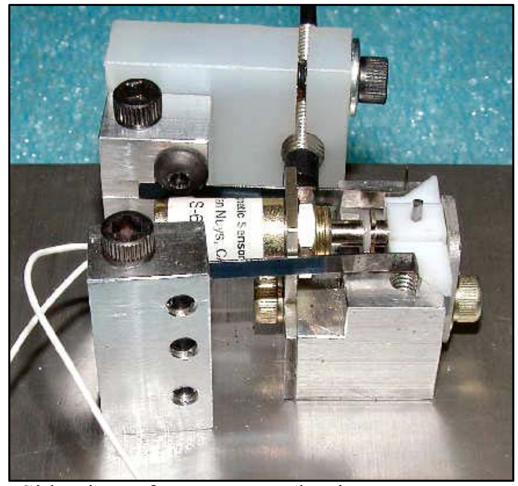
Figure 3. Solenoid pull force vs. stroke.

In the initial application, the solenoid only needed to retract a limited number times during its lifespan; making it difficult to translate this operating condition to an equivalent duty cycle. Because it was unknown how much current the solenoid could handle before it became damaged, it became necessary to explore the operating regime outside of the range of data provided by the manufacturer. We needed to know how much the solenoid could be electrically overloaded and what the response would be.

4.3 Actuator Performance Measurements

A test fixture was designed and fabricated to quantify the actuator performance parameters. The fixture was designed to closely replicate the expected operating configuration, while allowing adjustments to the parameters of interest. The test fixture is shown in figure 4.





Side view of actuator mechanism

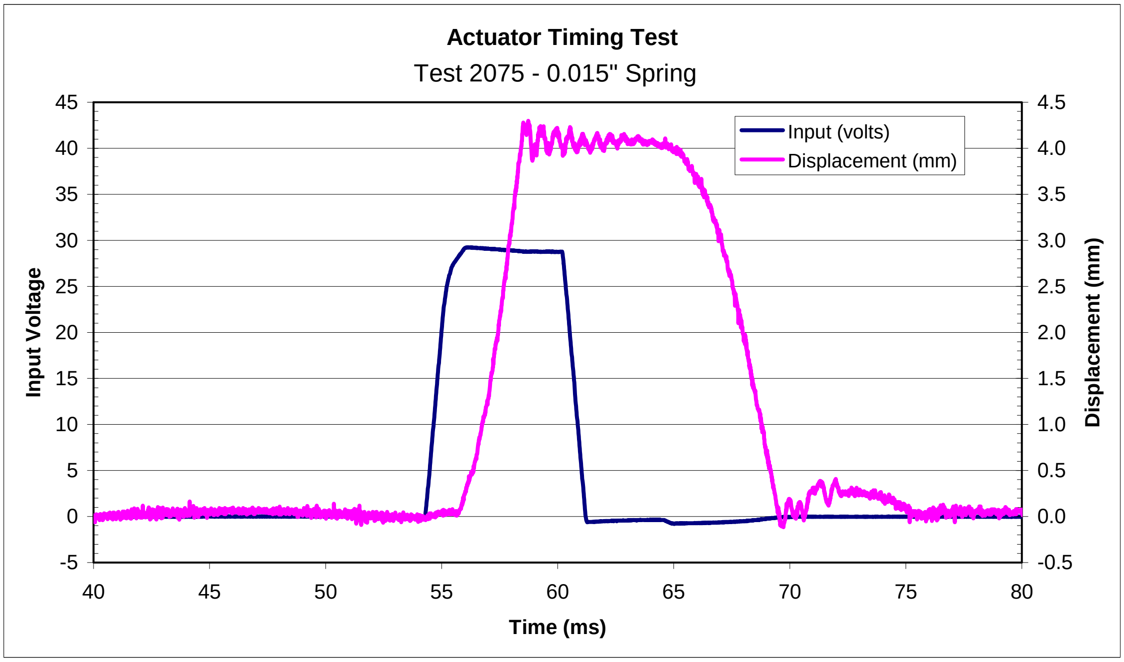
Figure 4. Actuator mechanism test fixture.

The solenoid was mounted to actuate two spring tabs, as it would in the actual application; although in the actual configuration, the tabs would be next to each other. A displacement transducer measured the spring deflection. Three different spring thicknesses were tested: 0.015 in. (0.38 mm), 0.020 in. (0.51 mm), and 0.028 in. (0.71 mm), which allowed for measuring the effects of varying spring stiffness.

An adjustable power supply was used to energize the solenoid with short duration pulses. The pulse width and magnitude were varied during the tests.

4.3.1 Single Pulse Test Results

The first series of tests involved sending a single pulse to the solenoid. These tests were used to quantify the effects of voltage and spring stiffness on the response time and magnitude. Figure 5 shows sample data from one of the tests.



Input Voltage		Displacement		Current	
Rise Delay (ms) :	0	Rise Delay (ms) :	2.946	Rise Delay (ms) :	0.448
Rise Time (ms) :	0.616	Rise Time (ms) :	1.467	Rise Time (ms) :	0.75
Dwell Time (ms) :	5.287	Dwell Time (ms) :	8.613	Dwell Time (ms) :	5.029
Fall Time (ms) :	0.593	Fall Time (ms) :	2.229	Fall Time (ms) :	0.706
Peak Voltage (volts):	29.209	Peak Displacement (mm) :	4.044	Peak Current (amps) :	5.237

Figure 5. Sample result from a single pulse actuation test.

For this test, rise time was defined as the time required to get from 20% to 80% of the peak value; dwell time was the time the signal remained above 80%; and fall time was the time to fall from 80% to 20% of the peak value.

Key findings from the single pulse actuation tests were as follows:

1. The solenoid could not be burned out by a single short duration pulse within the limits of the power supply. (The rated power for a 10% duty cycle was 20 W. During testing, 250 W pulses were applied with no detrimental effects.)
2. The solenoid/spring-tab assembly provided adequate response time to meet the 8 ms actuation time requirement.

3. There was a delay of several ms between the time power was applied and the solenoid responded. This is not expected to be a problem, because this lag time can be accounted for in the guidance algorithm.

The data was further analyzed to determine the operating parameters and optimum configuration.

4.3.2 Single Pulse Test Data Analysis

Figure 6 shows peak displacement vs. voltage for the three different spring thicknesses. The basic trend is that as spring thickness and stiffness increase, more voltage is needed in the solenoid to overcome the spring force. For the thickest spring, it was not possible to reach peak displacement within the voltage limits of the test setup. In this setup, the difference in peak displacement between the thinner two springs is believed to be from calibration variability.

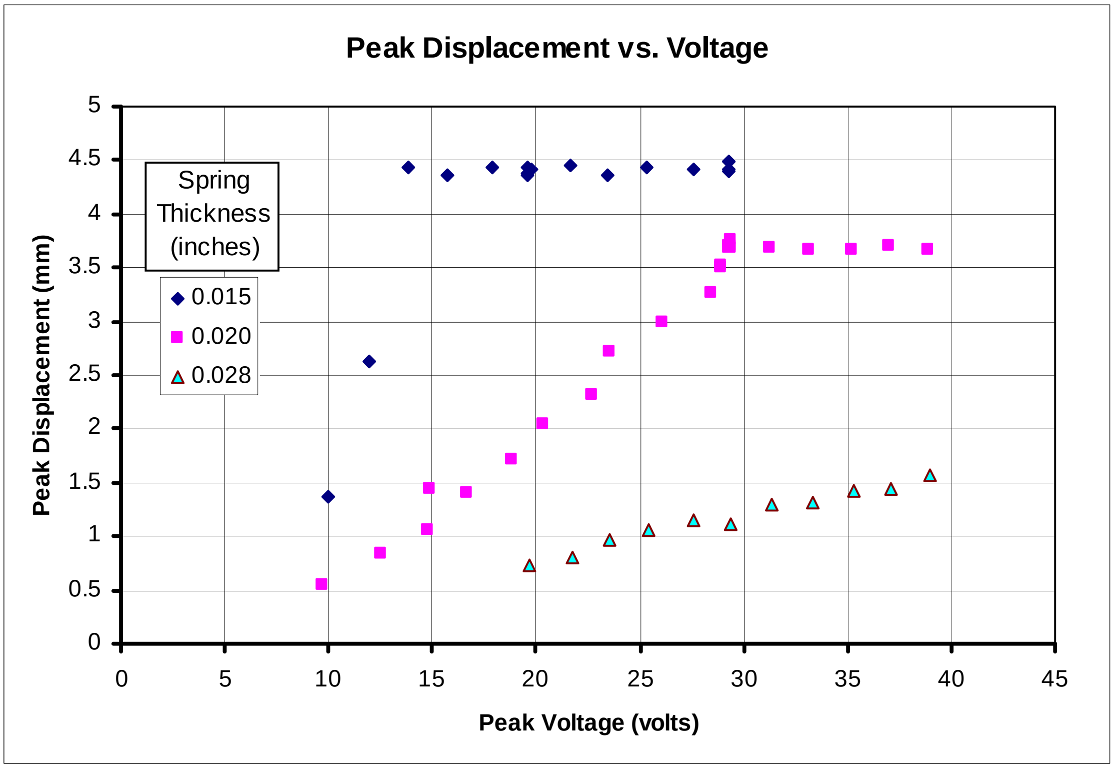


Figure 6. Peak displacement vs. voltage.

Figure 7 is a graph of rise time vs. voltage. This graph only includes data from the tests that reached peak displacement as shown in figure 6. The trend indicates that as voltage and solenoid force is increased, the time to reach peak displacement decreases.

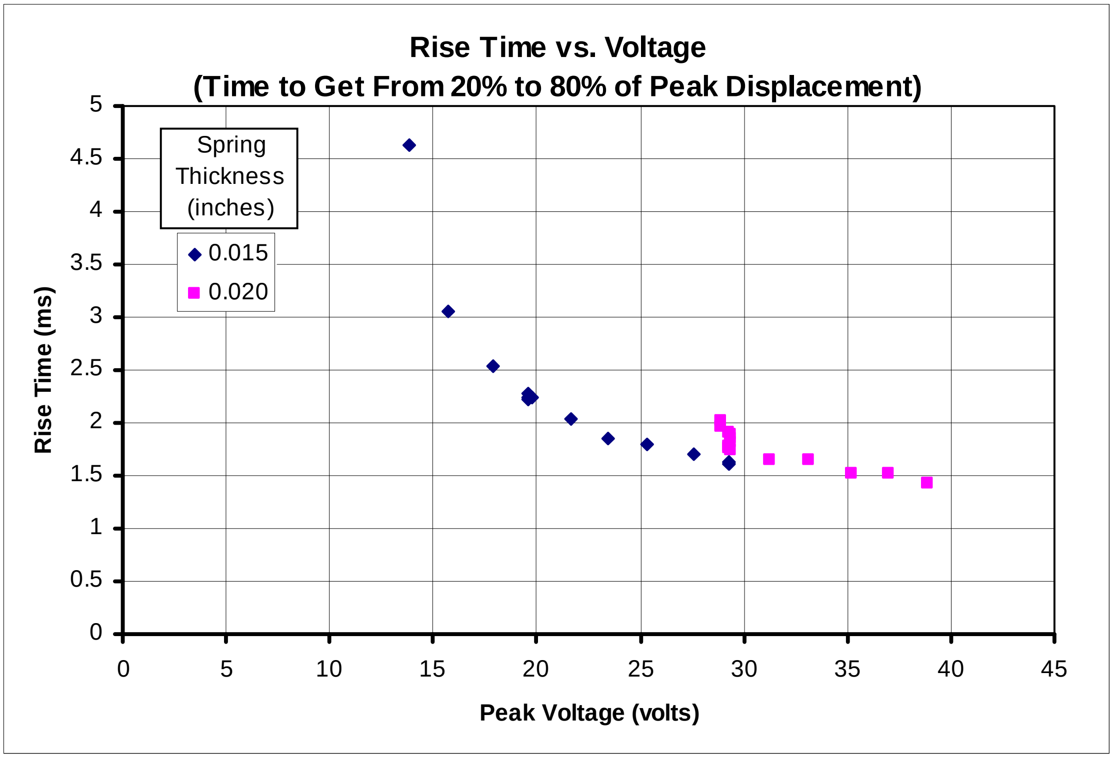


Figure 7. Rise time vs. voltage.

Figure 8 shows fall time vs. voltage. As can be expected, the fall time is independent of voltage, but is determined solely by the spring force.

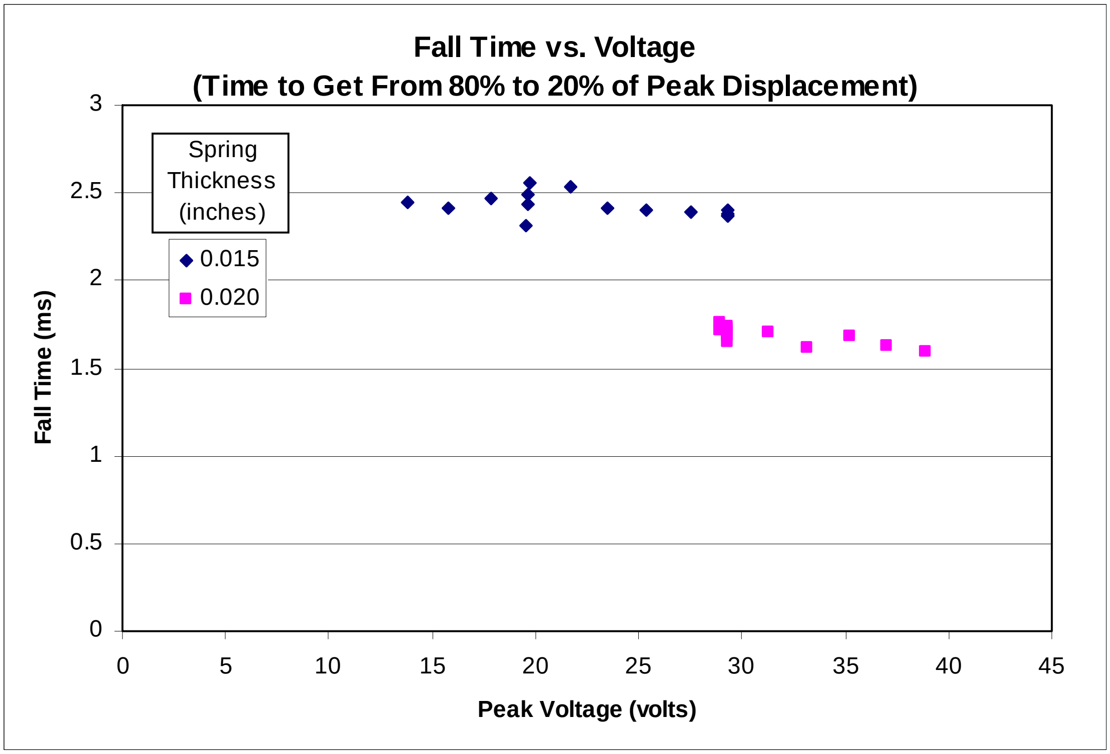


Figure 8. Fall time vs. voltage.

Figure 9 is a combination of figures 7 and 8, showing both rise and fall times. The circles on the chart highlight regions where rise and fall times are approximately equal. These regions were arbitrarily chosen for further in-depth investigation. For the 0.015 in. thick spring, a 20 V pulse provided a rise and fall time of approximately 2.4 ms, and for the 0.020 in. spring, a 30 V provided a 1.7 ms rise and fall.

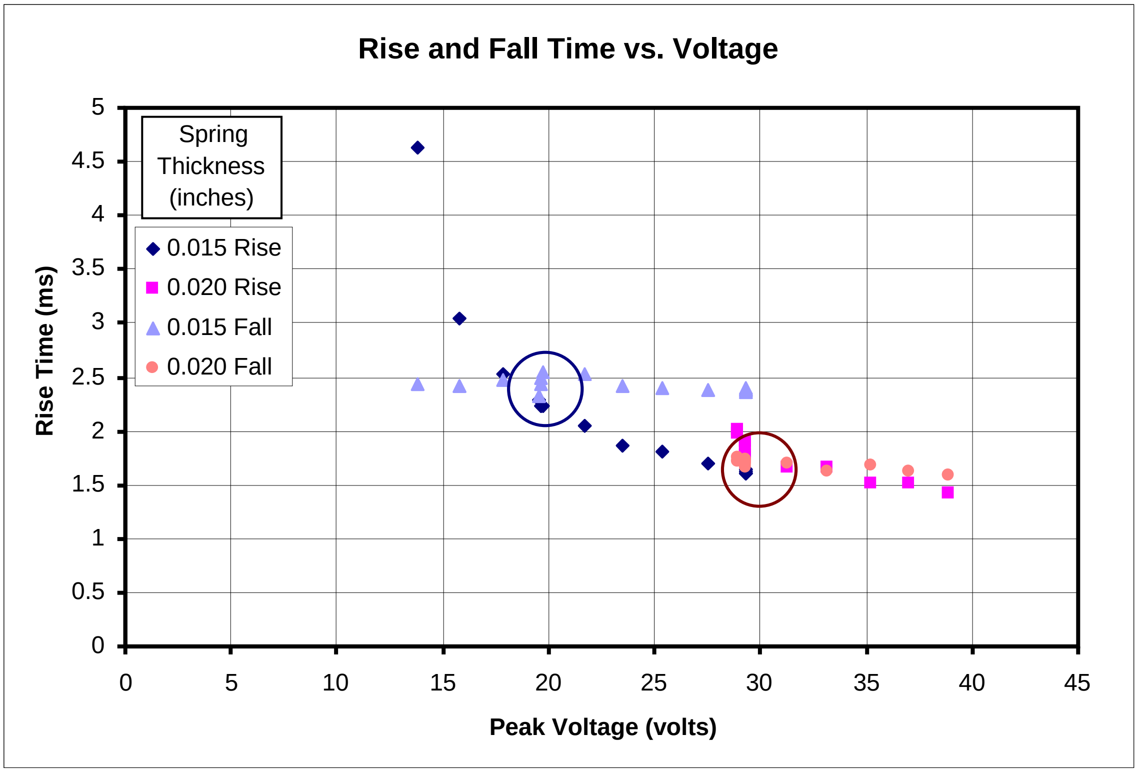


Figure 9. Combined rise and fall time measurements.

The effect of a single pulse of 20 V peak amplitude applied to the 0.015 in. thick spring is shown in figure 10. For this configuration, the graph illustrates the approximate 6 ms elapse from the time voltage is first applied until peak displacement is reached. In addition, the amount of time the spring tab is extended to at least half of its maximum displacement is also approximately 6 ms. Using this value as the minimum actuation time and assuming actuation must occur over ¼ of a turn, the minimum time required for the projectile to make one rotation is 24 ms. This translates to a maximum roll rate of 42 Hz, which is greater than the initial 30 Hz requirement.

A corresponding estimate for the 0.020 in. spring with a 30 V pulse, based on the differences in rise and fall times from the 0.015 in. spring, is a maximum 54 Hz roll rate.

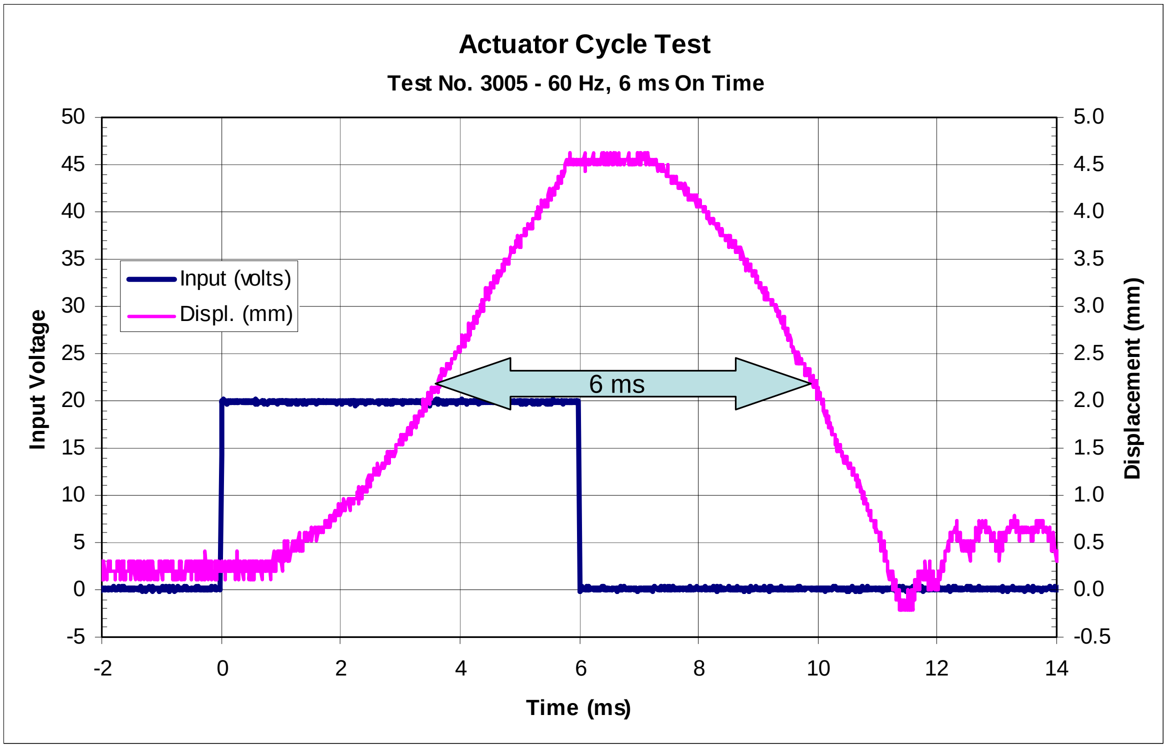


Figure 10. Single 20 V, 6 ms pulse, 0.015 in. spring.

4.3.3 Multiple Pulse Test Results

A string of 10 consecutive pulses is shown in figure 11. The pulses were generated at a frequency of 60 Hz. (This test was performed before the maximum roll rate had been calculated.) The test results demonstrate that the actuator is capable of multiple rapid actuations.

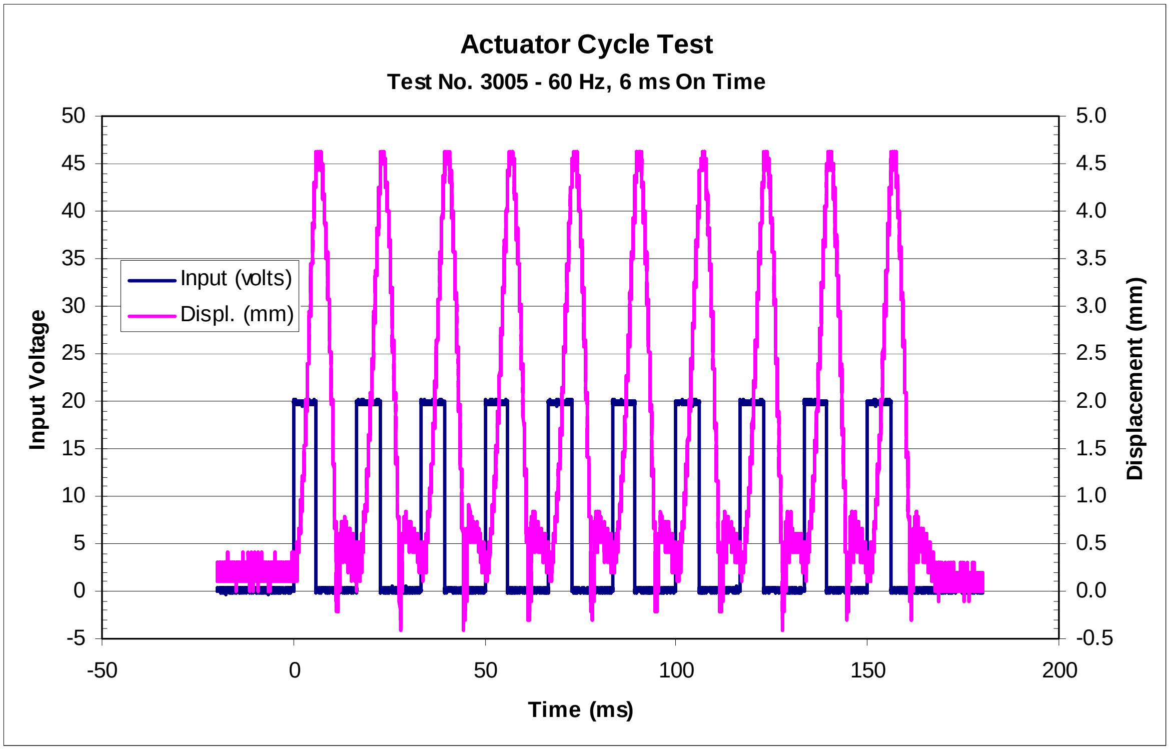


Figure 11. Series of ten 20 V, 6 ms pulses, 0.015 in. spring.

The next step was to evaluate how well the mechanism worked when a large number of actuations were required. Figure 12 shows performance when 20 V, 6 ms pulses were applied at a frequency of 60 Hz for 15 s (900 actuations). The figure shows peak displacement starts to decrease as more cycles are run. A closer examination of the data shows performance starts to degrade after about 20 cycles.

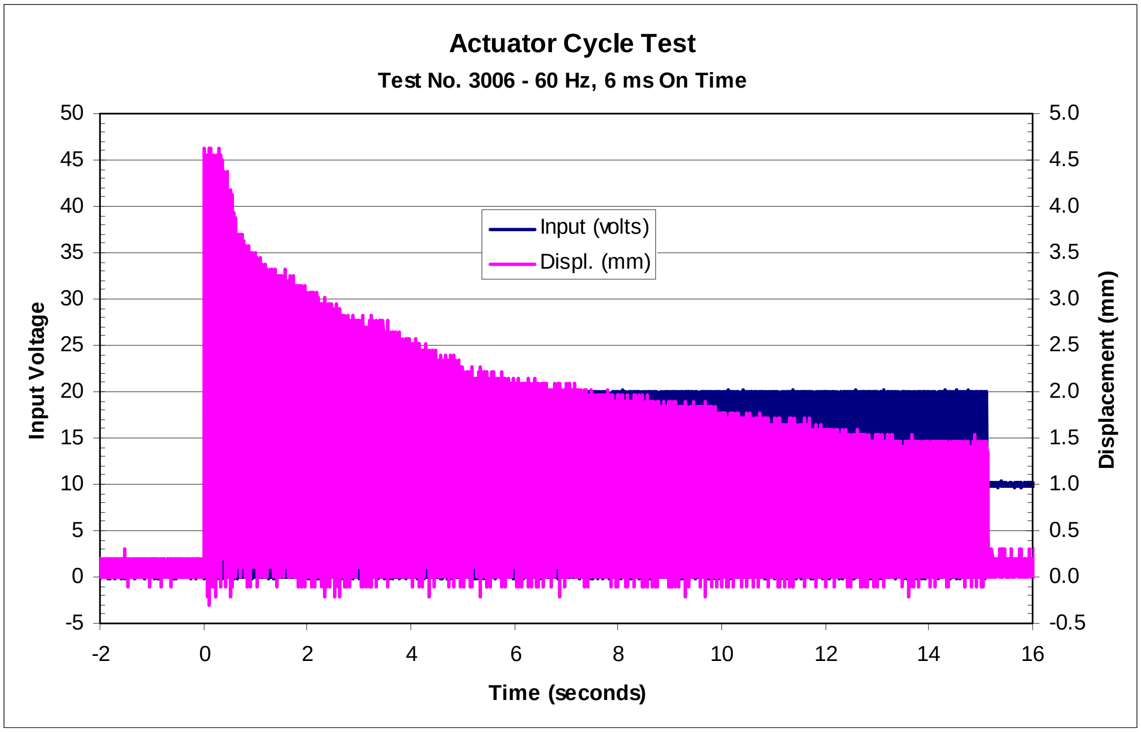


Figure 12. Stress test of multiple 20 V, 6 ms pulses, 0.015 in. spring.

4.3.4 Multiple Pulse Test Data Analysis

Performance degradation is suspected to be due to overheating of the solenoid. The manufacturer's specification for this solenoid is 2 W at 100% duty cycle or 8 W at a 25% duty cycle. In the current application, the actuator would be activated for ¼ turn, which would correspond to a 25% duty cycle.

The solenoid coil has an internal resistance of 6 Ω. At 20 V, the current is 3.33 A ($I = V/R = 20\ V/6\ \Omega$). The power being dissipated by the solenoid is 67 W ($P = V \times I = 20\ V \times 3.33\ A$). Because the solenoid is being operated at over eight times its rated power, overheating could be expected.

The expected performance was also calculated for the 30 V pulse with the 0.020 in. thick spring. Since the performance at 20 V degraded after approximately 20 pulses of 6 ms duration, the total energy input can be calculated as 8 J ($E = P \times t = 67\ W \times (20 \times 0.006\ s)$). For 30 V, the power input would be 150 W. Since the pulse duration is estimated to be 4.6 ms, it can be expected that performance would degrade after 12 cycles, which would provide a total energy input of 8 J.

It should be noted that these preliminary tests were of the proof-of-principle variety, and that it may very well be possible to improve on the performance of the actuator concept by changing some of the parameters (e.g., solenoid coil size).

Conclusion

A concept for an electromechanical actuator for projectile guidance has been developed. The actuator concept utilizes a tubular solenoid to activate spring tabs, which in turn generates a diversion force due to interaction of shock waves with the projectile fins.

Preliminary testing of the design concept was performed, and the expected performance parameters were determined. The preliminary results indicate that this actuator design would be suitable for projectiles with short flight times and/or limited numbers of required actuations.

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