Predicting the dynamic Stability of Small-Caliber Ammunition

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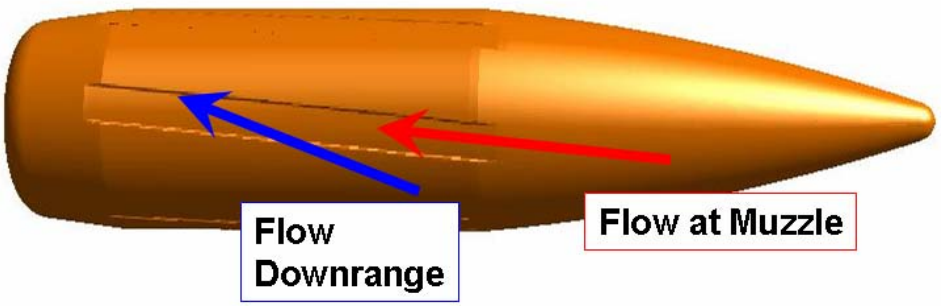
Possible Improvement of Prediction Methods for Dynamic Stability

Standard tests fire rounds at muzzle twist rates at downrange velocities.



Muzzle twist rates do not accurately resemble spin conditions downrange.

A comprehensive study and comparison of the stability characteristics of two 5.56 mm projectiles at different downrange spin conditions will determine the most accurate method in obtaining the stability characteristics in future tests.

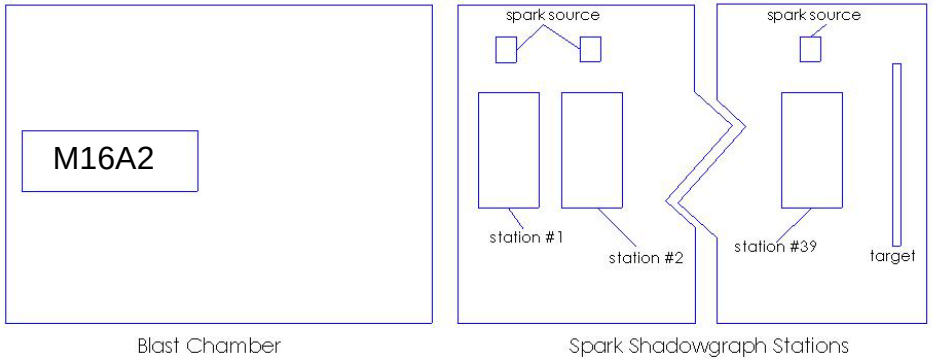
Experiments were carried out in the ARL Aerodynamic Experimental Facility

The 100-m long Aerodynamic Experimental Facility is operated by the Aerodynamics Branch at ARL

39 direct image orthogonal shadowgraph stations in 5 groups

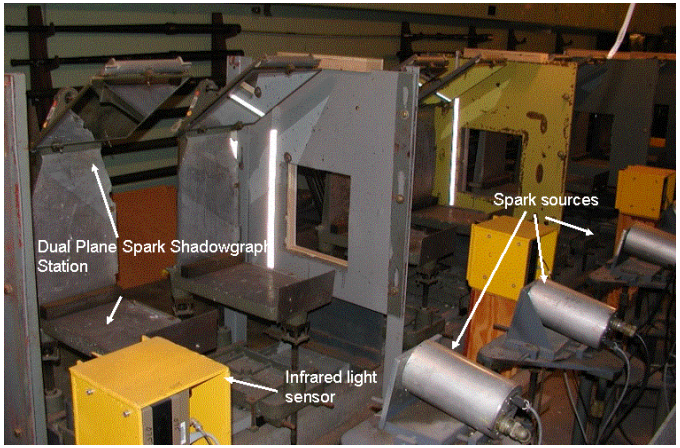
Image window is less than 14 inches across

Spark source triggered at a recorded time after infrared sensor detects passing projectile



Gun muzzle is located 1.8 meters from 1st station for this test

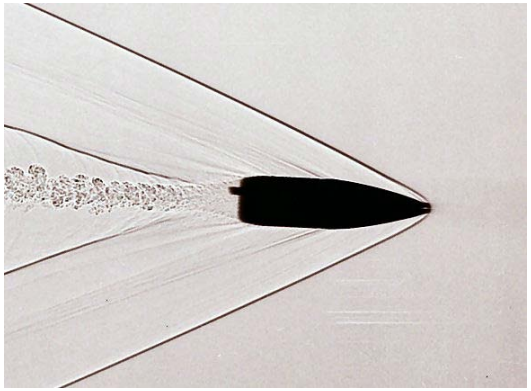
Spark Facility Layout



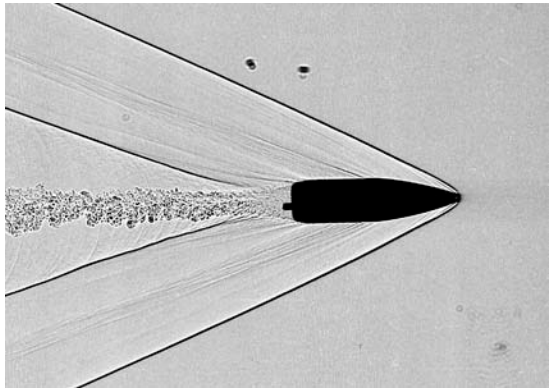
Dual Plane Spark Stations

The dual plane spark shadowgraphs are used to obtain projectile position as a function of time

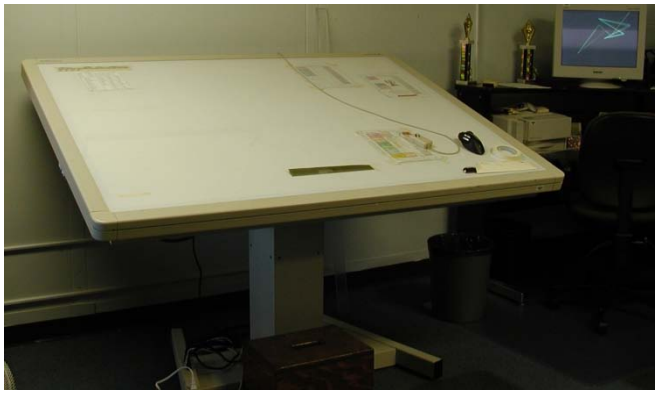
Shot 26598 – M16A2, muzzle velocity



45 vertical



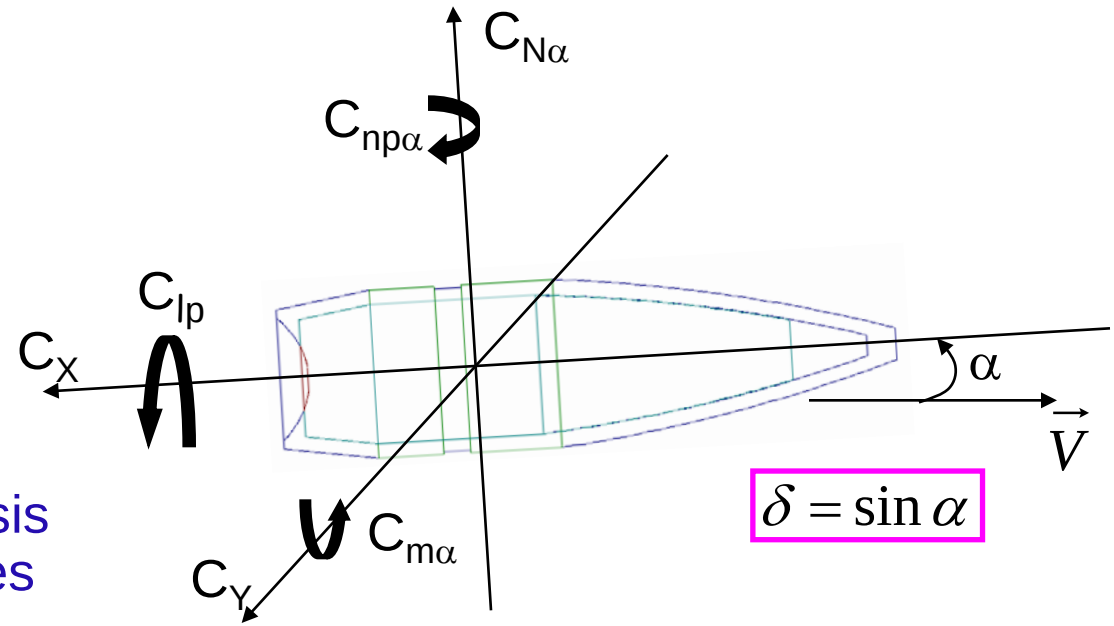
45 horizontal



Film read using a precision light table to determine spatial coordinates and angular orientation of the projectile including roll

Data relative to earth fixed range coordinate system

Data is reduced for a 6-DOF fit in order to obtain an aerodynamic model and motion fit



$$\delta = \sin\alpha$$

Aero Range Facility Data Analysis Software – ArrowTech Associates

$$C_X = C_{X_0} + C_{X_2}\delta^2$$

$$C_{m_\alpha} = C_{m_{\alpha 0}} + C_{m_{\alpha 3}}\delta^2$$

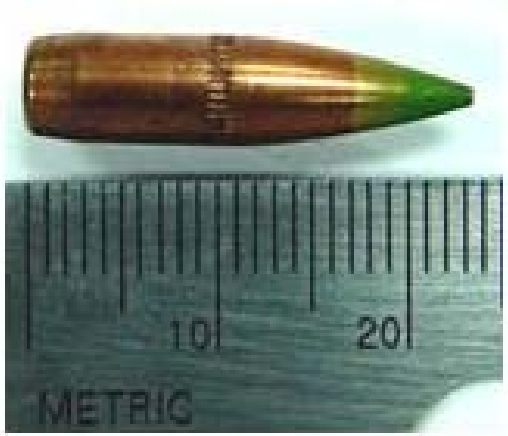
$$C_{N_\alpha} = C_{N_{\alpha 0}} + C_{N_{\alpha 3}}\delta^2$$

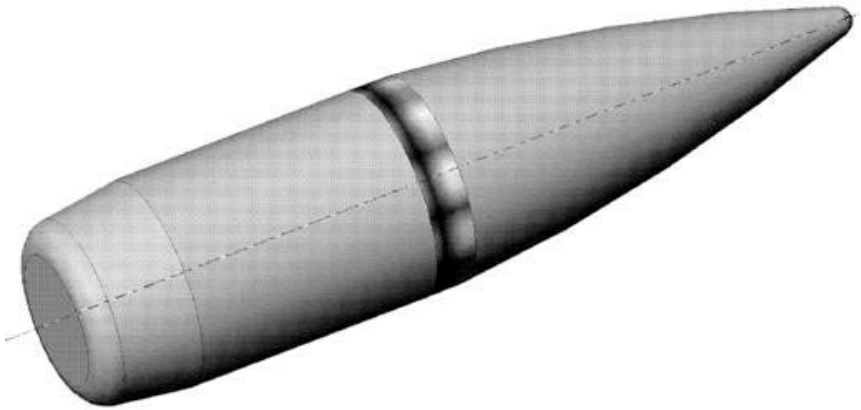
$$C_{n_{p_\alpha}} = C_{n_{p_{\alpha 0}}} + C_{n_{p_{\alpha 3}}}\delta^2$$

$$C_{m_q} = C_{m_q} + C_{m_{\dot{\alpha}}}$$ ← Not shown

Results of the M855 Aerodynamics Test were used to determine its stability characteristics

- M855 projectiles were fired at velocities simulating ranges of 0, 200, 400, 500 and 600-m.
- Fired at muzzle twist rate (1rev in 7 in) from M4 and M16A2 barrels.
- Yaw inducers used as needed.





- Stability characterization at muzzle spin and downrange spin rates.
- Yaw limit cycle analysis at muzzle spin and downrange (adjusted) spin rates.

Pitch Damping Exponents can be determined from linear theory

Pitch damping exponents: $$\lambda_{F,S} = -\frac{1}{2}\left[H \pm \frac{P(2T-H)}{\sqrt{P^2-4M}}\right]$$

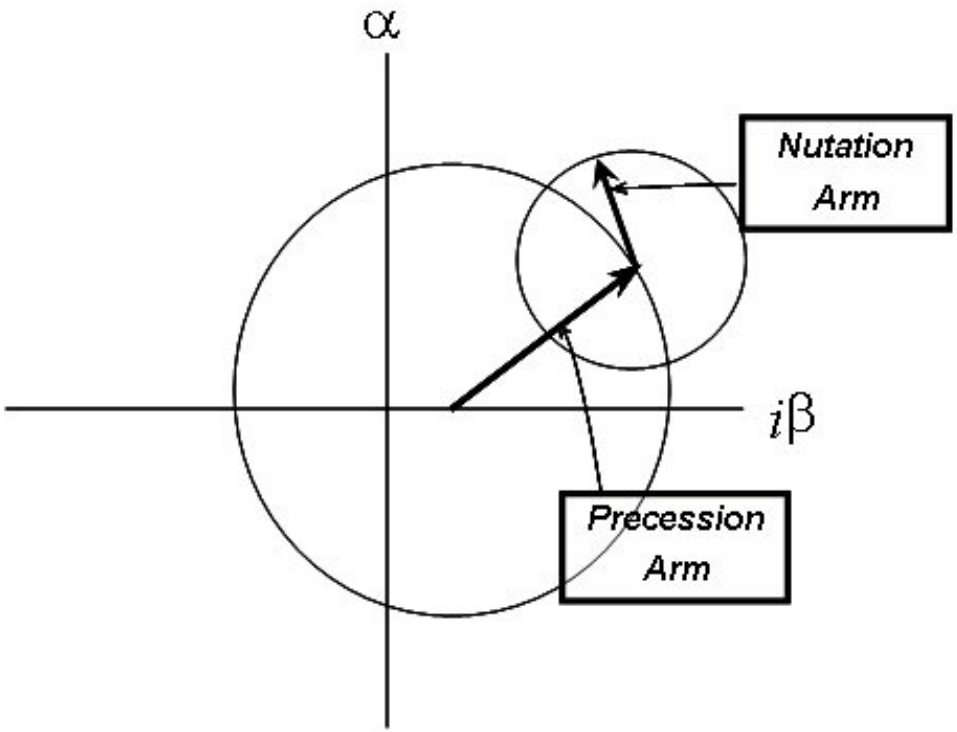
In which

$$P = \frac{I_x}{I_y}\left(\frac{pd}{V}\right) \qquad M = \frac{C^*_{m_\alpha}}{k_y^2}$$

$$H = C^*_{L_\alpha} - C^*_D - \frac{\left(C_{m_q} + C_{m_{\dot\alpha}}\right)^*}{2k_y^2}$$

$$T = C^*_{L_\alpha} - \frac{C^*_{n_{p\alpha}}}{2k_x^2}$$

$$k_x^{\ 2} = \frac{I_x}{md^2} \qquad k_y^{\ 2} = \frac{I_y}{md^2} \qquad * = \frac{\rho S d}{2m}$$



Note: $$C_{L_\alpha} = C_{N_\alpha}\cos\alpha - C_X$$

$$C_D = C_{N_\alpha}\sin^2\alpha + C_X\cos\alpha$$

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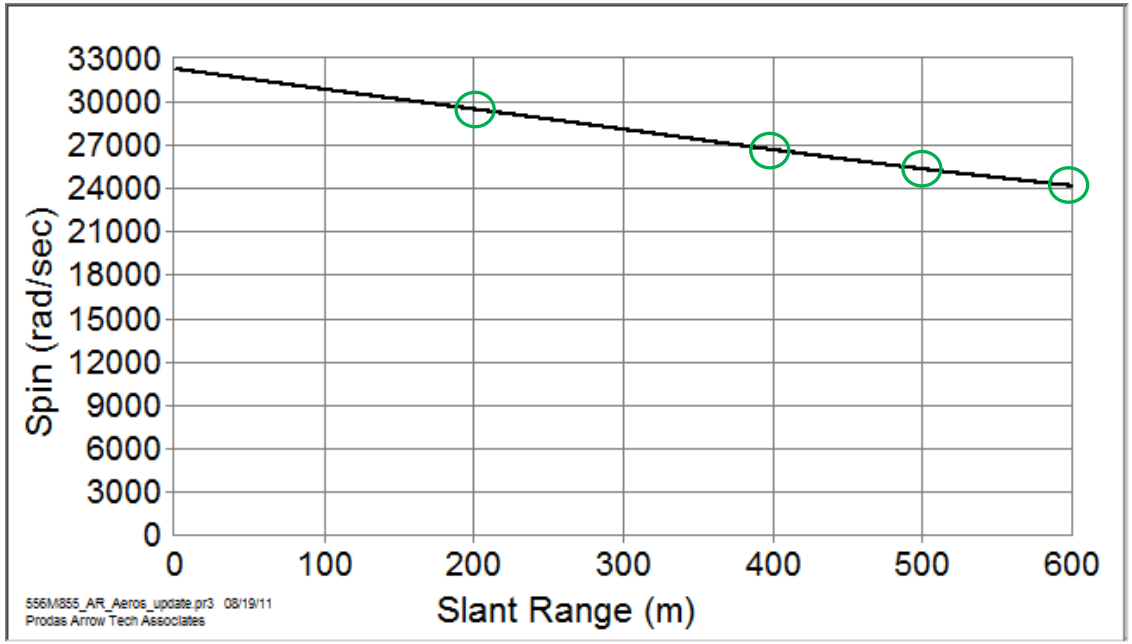
Pitch Damping Exponents are recalculated at downrange (adjusted) spin rates

Axial force and roll damping coefficients from 6-DOF fits input into PRODAS to determine downrange spin rates.



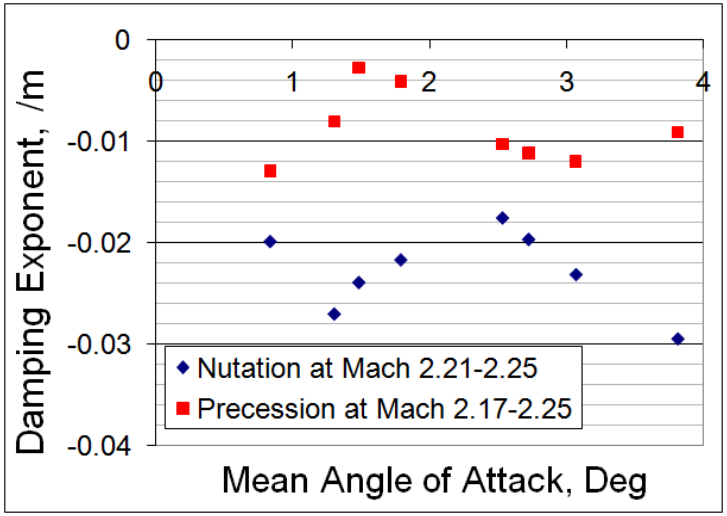
New spin rates are input and used to update the damping exponents

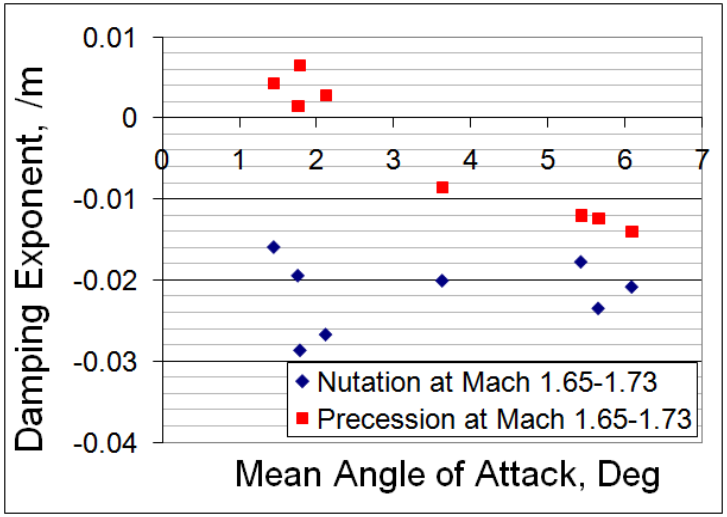
$$\lambda_{F,S} = -\frac{1}{2}\left[H \pm \frac{P(2T - H)}{\sqrt{P^2 - 4M}} \right]$$

Only “P” changes

Slow mode instability appears by Mach 1.7 for M855 using either experimental or adjusted spin

Experimental Spin

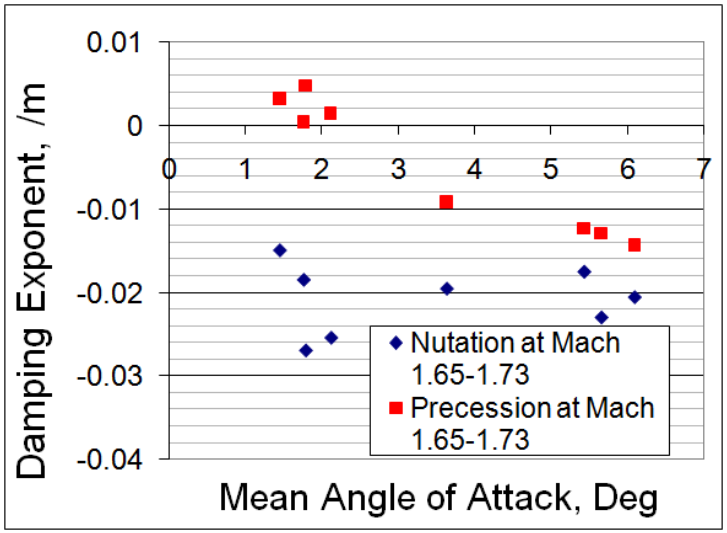




Round Stable at Mach 2.2

Slow mode instability appears at Mach 1.7

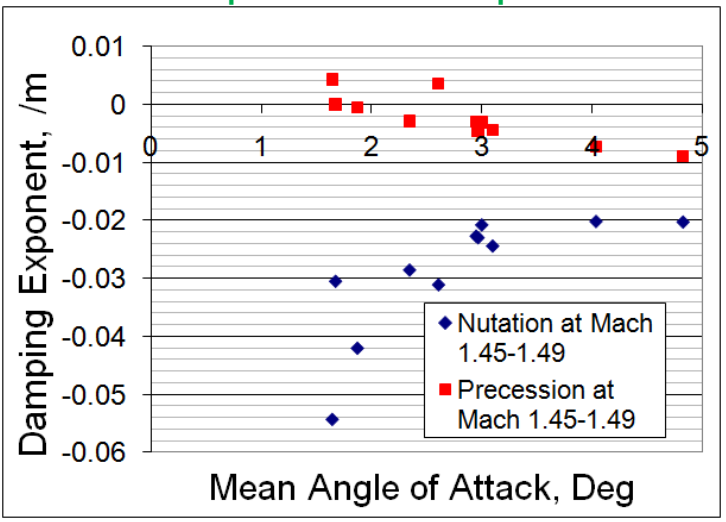
Simulated spin decreases magnitude of instability



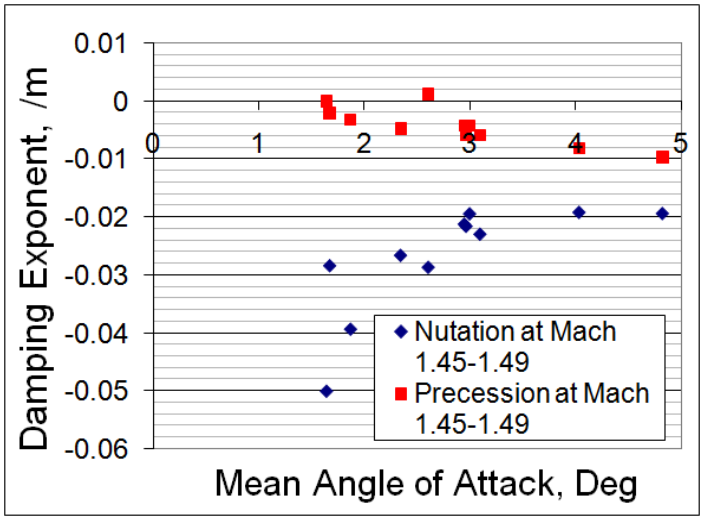
Simulated Spin

Using adjusted spin values decreases the damping exponents as compared to experimental values

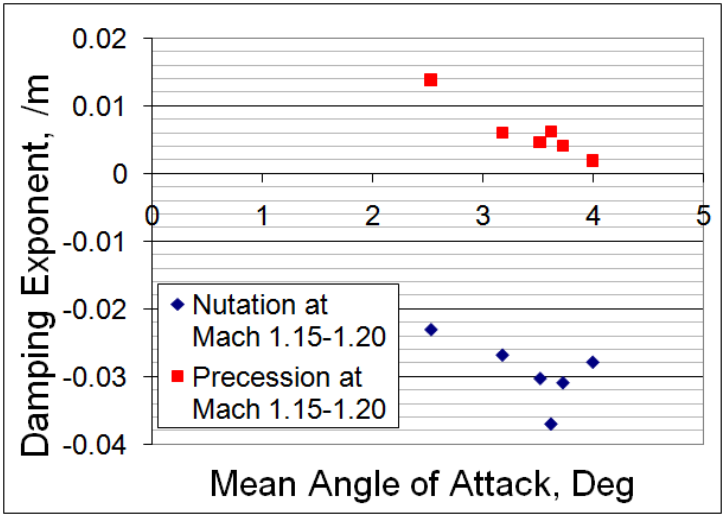
Experimental Spin



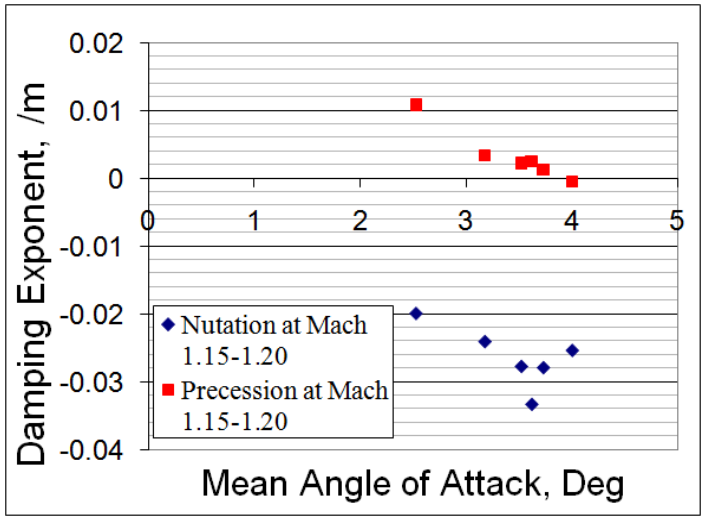
Simulated Spin



Precession and Nutation arm damping exponents are decreased.



Yaw limit cycle still exists, but is reduced by ~0.5°

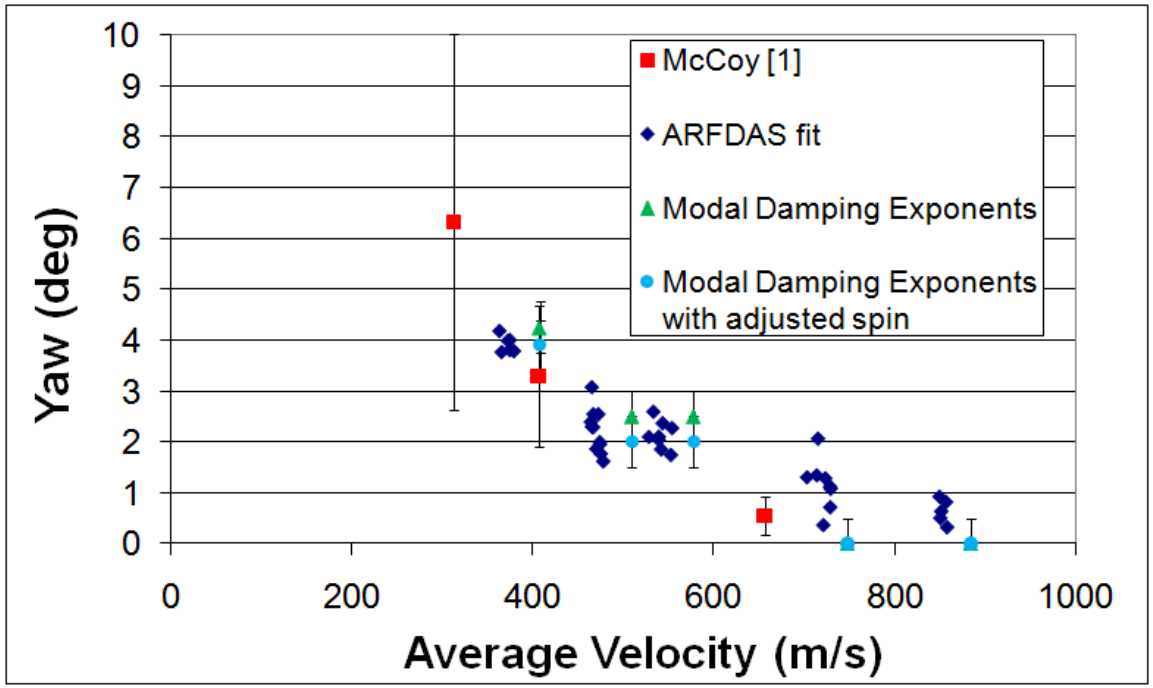


Total Yaw of M855 increases with decrease in velocity under simulated conditions as well as in flight

Average yaw observed 100-m from the muzzle in the spark range (ARFDAS fit)

McCoy data rounds measured at actual downrange locations

Modal damping exponents show expected max yaw for the given velocity



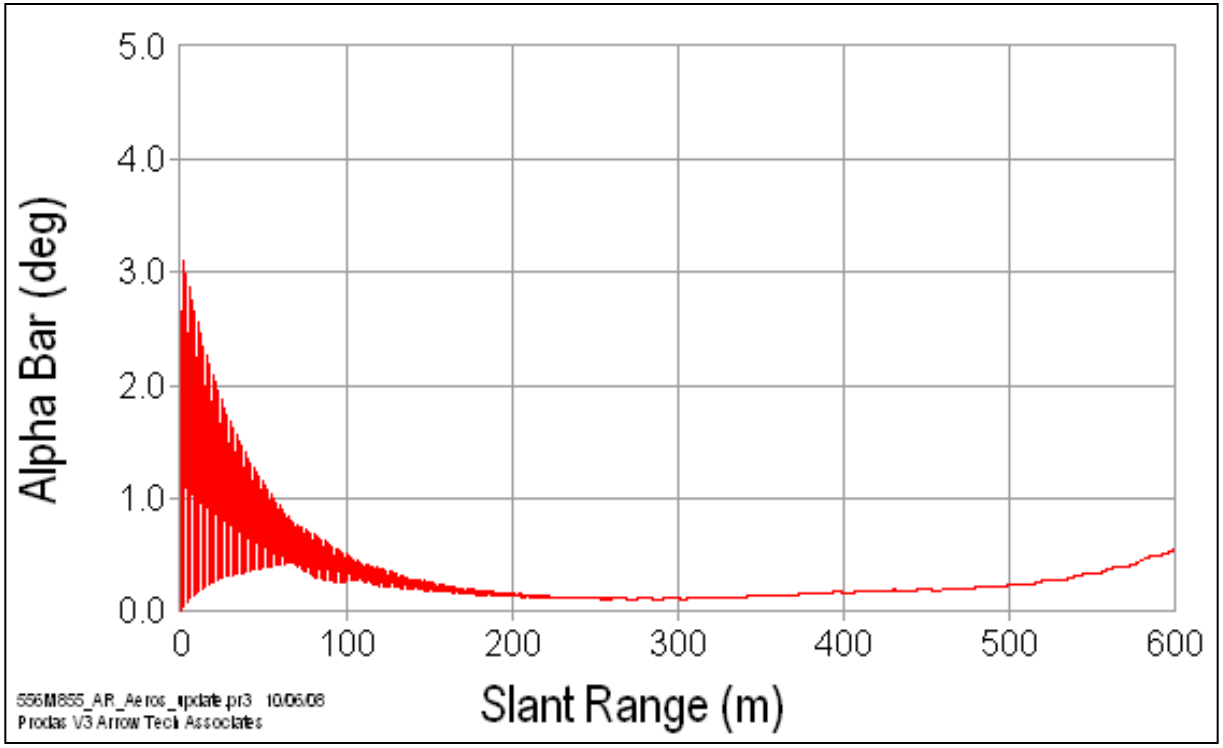
Yaw growth begins to occur at velocities around 600 m/s.

Yaw limit cycles may be as large as 6°(McCoy) but would require additional testing at lower velocities to verify.

Simulation of projectile flight failed to produce expected yaw growth

PRODAS simulation using aerodynamic coefficients generated from range tests.

Minimal yaw growth observed – less than one degree at 600-m

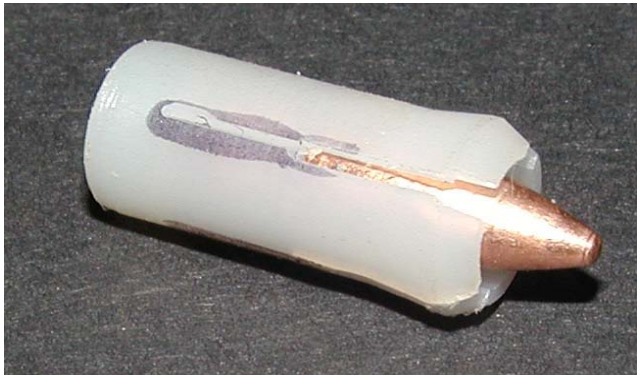


Two possible explanations:

- a small mass asymmetry exists
- spin rate must be matched in the experiment

Results of M193 Aerodynamics Test were reanalyzed to determine effect of matched spin on stability

- M193 projectiles were fired at velocities simulating ranges of 0, 200, 400 and 600-m.
- Fired using two methods
  - Standard firing with muzzle twist from M16A2 barrel
  - Fired from Mann barrels to match down range spin rates
- Yaw inducers used as needed.
- Rounds fired from Mann Barrels required the use of sabots.



- Previous analysis of aerodynamic coefficients showed differences in methodologies likely insignificant
- Stability characterization at muzzle spin rate, adjusted downrange spin rate, and matched spin rate.

Stability can be characterized by examining the Gyroscopic and Dynamic Stability Factors

Gyroscopic stability factor must be greater than one to be stable.

$$S_g = \frac{P^2}{4M}$$

Dynamic stability factor can be defined as: $$S_d = \frac{2T}{H}$$

Stable rounds must remain within the dynamic stability bound defined as : $$\frac{1}{S_g} < S_d\left(2 - S_d\right)$$

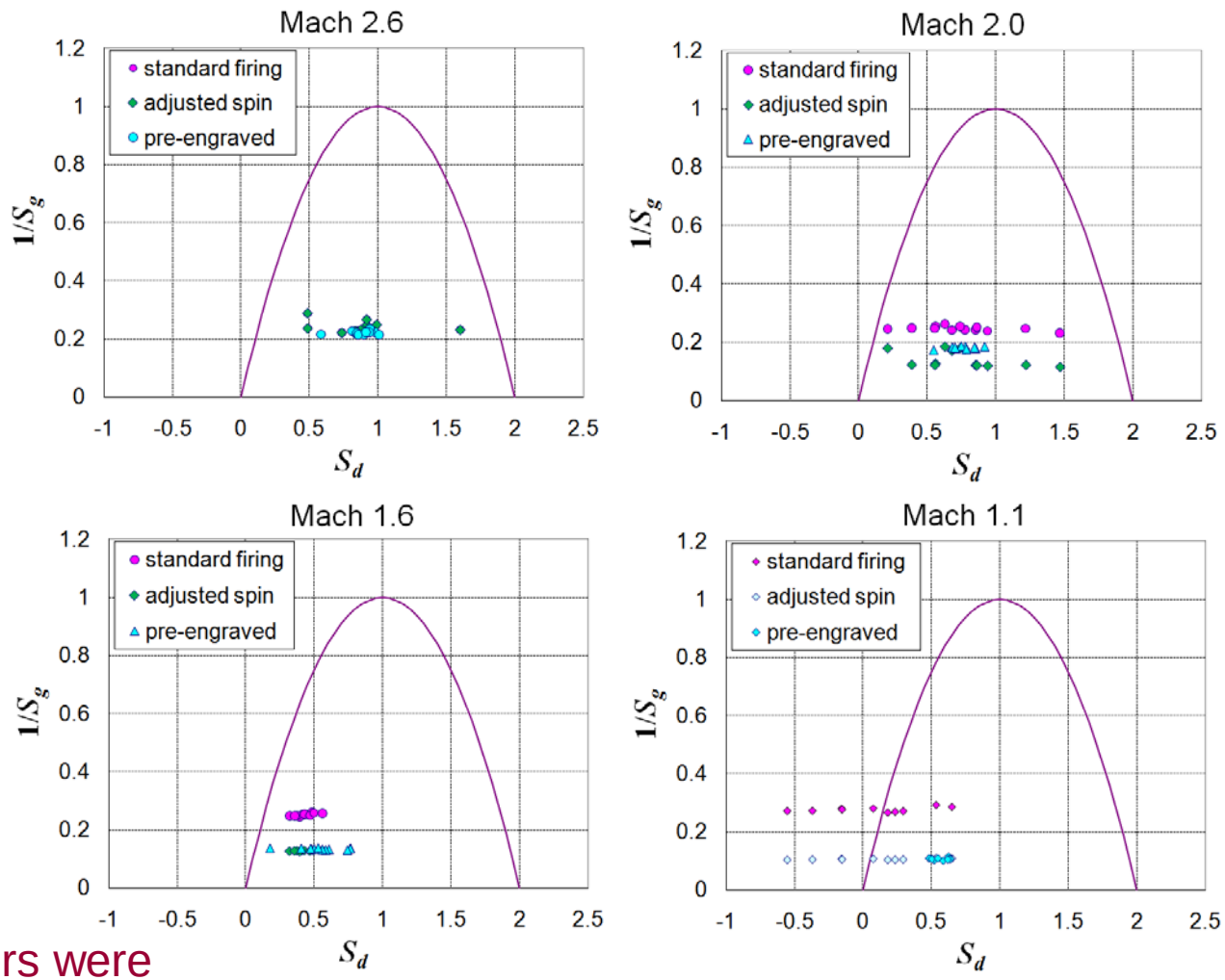
Reminder: $$P = \frac{I_x}{I_y}\left(\frac{pd}{V}\right) \qquad M = \frac{C^*_{m_\alpha}}{k_y^2} \qquad H = C^*_{L_\alpha} - C^*_D - \frac{\left(C_{m_q} + C_{m_{\dot{\alpha}}}\right)^*}{2k_y^2} \qquad T = C^*_{L_\alpha} - \frac{C^*_{n_{p\alpha}}}{2k_x^2}$$

Gyroscopic and Dynamic Stability of the M193 depends on firing methodology

Initial yaw levels vary from 1.5-8 degrees.

Rounds with adjusted spin display improved dynamic stability.

Yaw limit cycle evident at Mach 1.1 for standard firing and adjusted spin analysis.



Rounds at all Mach numbers were both dynamically and gyroscopically stable for the matched spin (pre-engraved) firings.

Additional shots with lower yaw levels would be needed to confirm lack of yaw limit cycle for M193 projectile.

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Summary

- Standard M855 tests shows yaw growth beginning at 400-m, ultimately growing to 4.5 degrees at 600-m.
- Stability analysis with simulated spin rates can reduce the yaw limit cycle of the M855 by approximately 0.5 degrees.
- Previous full range shots for M855 do not show evidence of a yaw limit cycle until 600-m.
- PRODAS simulations of the M855 do not show evidence of a trim angle at 600-m.
- Gyroscopic and dynamic stability analysis of the M193 show yaw limit cycle is present at 600-m for muzzle spin and adjusted spin cases.
- Matched spin experiment for the M193 is gyroscopically and dynamically stable at all Mach numbers tested

Conclusions

- Level of dynamic instability will be predicted at a higher level than in actuality when muzzle spin rates are used.
- Adjusting spin rates of rounds initially analyzed with muzzle spin does improve the results, yet still predicts yaw growth at earlier ranges than what can be expected at real range.
- Use of in-flight spin rate is necessary to determine the stability of the round at downrange velocities.
- Lower velocities must be investigated if an accurate yaw limit cycle is to be determined

Questions?