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A Methodology for Characterizing Barrel Flexure Due to Tank Motion

by Mark Bundy, James Newill, Vince Marcopoli,
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Abstract

Barrel centerline curvature is known to influence the location of projectile shot impacts. Superimposed on the unique manufactured barrel centerline is the flexed barrel shape that can occur prior to firing while the tank is on the move. In order to understand and quantify the effects of barrel flexure on gun accuracy, it is necessary to determine what combination of fundamental mode shapes is most likely to occur. A method to accomplish this task is described in this report. The method is demonstrated by enumerating the 10 most likely mode shape combinations (flexed barrel shapes) that were found to occur in an M256 barrel mounted in an M1A2 tank while it traversed the RRC-9 bump course at Aberdeen Proving Ground, MD, at 15 mph.

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Barrel centerline curvature is known to influence the location of projectile shot impacts. Superimposed on the unique manufactured barrel centerline is the flexed barrel shape that can occur prior to firing while the tank is on the move. In order to understand and quantify the effects of barrel flexure on gun accuracy, it is necessary to determine what combination of fundamental mode shapes is most likely to occur. A method to accomplish this task is described in this report. The method is demonstrated by enumerating the 10 most likely mode shape combinations (flexed barrel shapes) that were found to occur in an M256 barrel mounted in an M1A2 tank while it traversed the RRC-9 bump course at Aberdeen Proving Ground, MD, at 15 mph.

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1. Introduction

Excluding aiming and pointing errors, tank gun inaccuracy can be compartmentalized into three areas. One source of variation is associated with the ammunition (e.g., variations in the projectile geometry and mass asymmetries and/or chambering differences between rounds). Another source of error arises from factors that can change from occasion to occasion within the same gun system, e.g., the effect of weather conditions such as temperature, sun, wind, and moisture, on component parts like the ammunition (Held, Webb, and Schmidt 1991). A third error category is attributable to variations in the barrel, e.g., wear conditions and/or centerline shape (Wilkerson 1995). This report deals with the latter source of error. In particular, the topic of discussion here is how the barrel centerline shape can be perturbed prior to firing on the move as a result of lateral flexing created by the vehicle motion.

Before proceeding, a brief discussion is in order on how firing on the move differs from static firing. Figure 1 portrays how the three previously mentioned contributors to gun inaccuracy can affect the fall of shot. For instance, the illustration conveys that for a given gun tube firing from a stationary vehicle on a given day, there will be a spread in target impacts (referred to as round-to-round or target impact dispersion [TID]) about a center of impact (COI). Note, even though projectile gravity drop is factored into the muzzle aim point, the COI will not necessarily lie on the target (cross in Figure 1).

The angle subtended at the muzzle between the COI and the expected (gravity corrected) target impact point (cross) is referred to as jump. Jump is primarily due to the effects of lateral and rotational motion imparted to the projectile by the barrel, sabot, and aerodynamic forces before it reaches free flight. Figure 1 (inset) breaks down the jump into a series of directional changes (as enumerated by Bornstein et al. 1988) caused by (1) a difference in the muzzle pointing angle at shot exit relative to the original line of fire, (2) a muzzle transverse (crossing) velocity at shot exit, (3) a transverse velocity of the projectile's center-of-gravity at shot exit relative to the muzzle (cg jump), (4) asymmetric lateral sabot discard forces, and (5) aerodynamic lift forces up to the point of the first maximum in yaw (Bundy 1999).

If the same gun and lot of ammunition were to be fired the next day, all other factors being the same, the impacts would likely be scattered about a different COI; such a shift in COI falls under the category of occasion-to-occasion jump error. On the other hand, if a different barrel was fired from the same tank on the same day with the same lot of ammunition, the scattering of impacts would likely occur about yet another COI; this phenomenon would be recognized as tube-to-tube jump variation.

Using data accumulated from a large number of tank, tube, occasion, and ammunition lots, an all-inclusive (occasion-to-occasion, plus tube-to-tube) mean jump for the entire fleet of tanks has been established and used to make an average/gross correction to the firing aim point for each ammunition type, known as the computer correction factor (CCF).

Firing on the move creates yet another source of error. The effects of varying barrel motion (flexure) due to tank travel are superimposed on the more repeatable barrel motion effects caused by the firing event itself (e.g., Figure 2, Guidos 1999), resulting in an increase in shot scatter. Thus, the moving TID (mTID) will be greater than the stationary TID (sTID), as illustrated in Figure 3.

Issues related to on-the-move firing performance can be subdivided into two parts: (1) prefiring effects, which address the dynamic behavior of the gun tube during on-the-move vehicle operation, and (2) firing effects, which address the in-bore dynamics of the projectile. The focus of this study is limited to the former, but ultimately, it is hoped that the insights gained here will suggest modifications to the fire control system that will improve the overall on-the-move system accuracy.

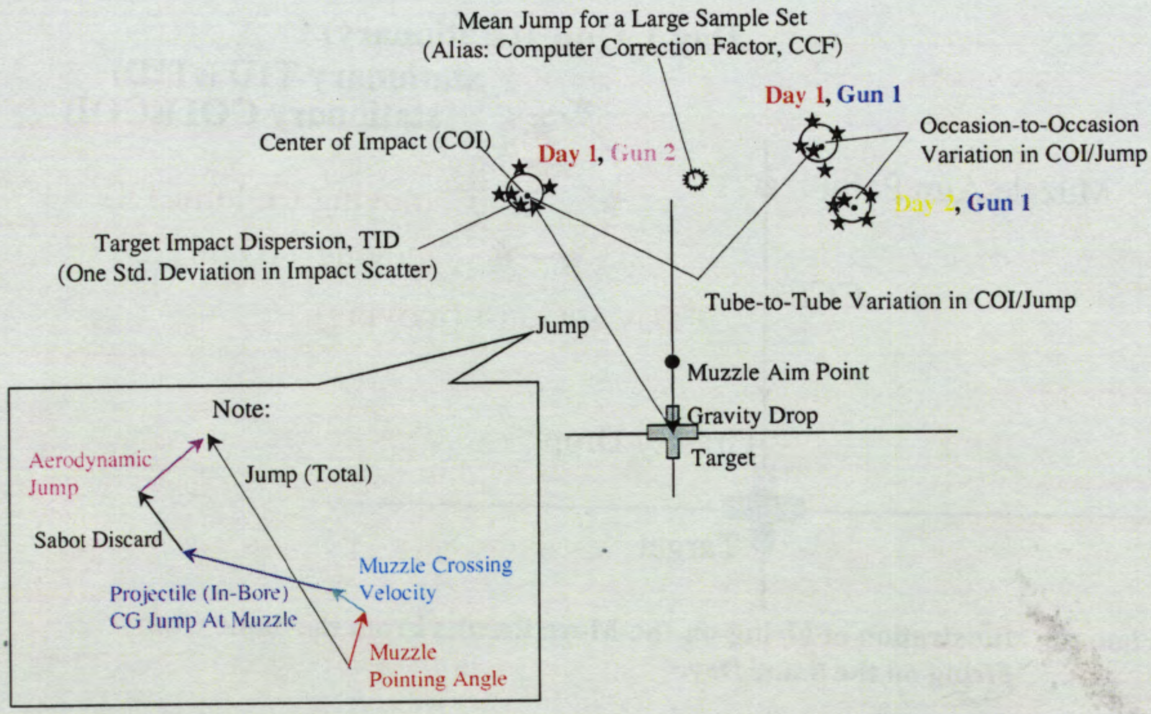


Figure 1. Typical Stationary Firing Results.

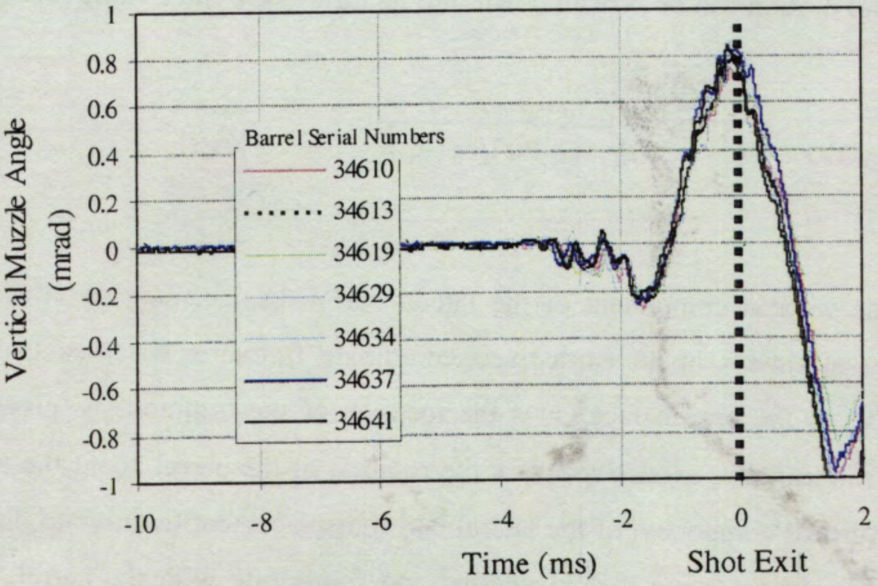


Figure 2. Example of Barrel Motion Repeatability for an M256 Barrel Firing M865E3 Training Rounds (Courtesy of Guidos 1999).

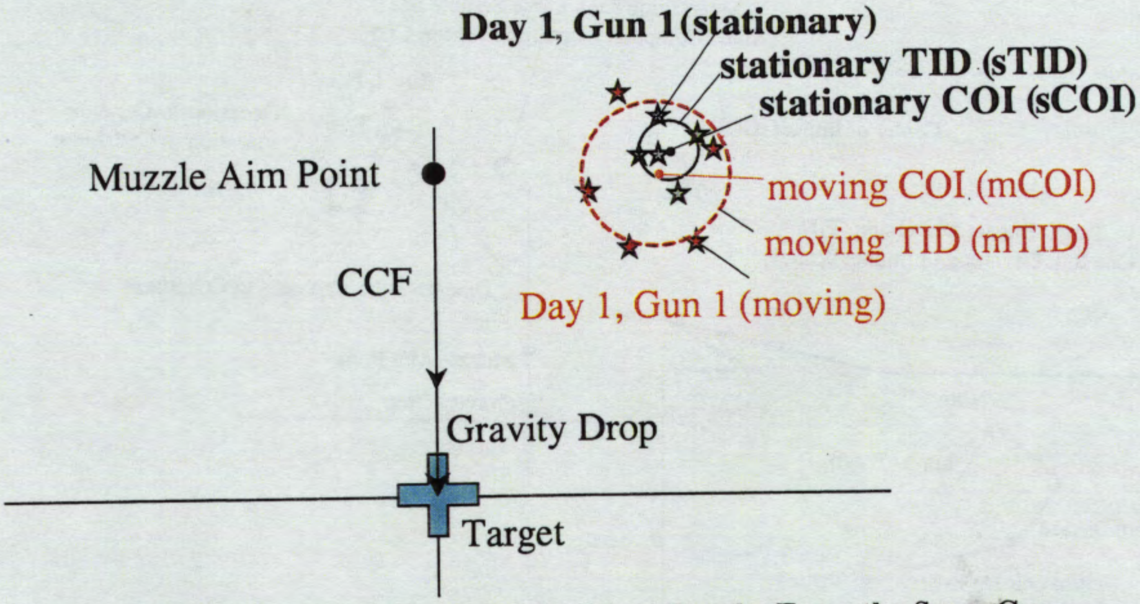


Figure 3. Illustration of Firing-on-the-Move Results From the Same Gun Firing on the Same Day.

2. Describing Barrel Motion

Prefiring barrel motion can be broken down into its rigid-body and flexing mode components as follows:

$$y(x,t) \quad = \quad \overbrace{y_t(t) \ + \ \theta(t)[\,x - x_t\,]}^{\textit{rigid body}} \quad + \quad \underbrace{Y(x,t)}_{\textit{flexing mode}} \quad , \tag{1}$$

where y gives the vertical component of the lateral barrel displacement (relative to the static barrel centerline) at time t in an earth-fixed coordinate frame; x specifies the axial barrel coordinate relative to the breech face (x_t is the location of the trunnion); y_t gives the vertical displacement of the trunnion axis; θ specifies the rotation of the barrel about the trunnion axis; and Y gives the vertical component of the lateral barrel displacement (relative to the static barrel centerline) in a coordinate frame that is rotating and translating with the barrel. The flexing mode component, Y, can be further broken down into

$$Y(x,t) \quad = \quad q_1(t)\,Y_1(x) \ + \ q_2(t)\,Y_2(x) \ + \ q_3(t)\,Y_3(x) \quad , \tag{2}$$

where Y_i (i = 1, 2, 3) are the first three barrel flexing mode shapes (normalized to unity), and q_i gives the amplitude of each mode shape. It is assumed in Equation 2, and later shown to be the case, that no more than the first three mode shapes are needed to account for barrel flexing from tank motion. The next section discusses the rigid-body terms, θ and y_t.

2.1 Rigid-Body Barrel Motion Due to Vehicle Travel While Target Tracking

Current tank gunnery protocol calls for the periodic checking/adjustment of the gunner's sight line to ensure that it is coincident with the muzzle (bore scope) sight line, when both are aimed at a distant target and the tank is stationary. When targeting an object while the tank is on the move, an angle resolver is used to measure the sight rotation angle, θ, to within ±10 arc seconds (±0.05 mrad). (Briefly, an angle resolver functions by measuring induced voltage in a secondary winding as a function of its axial orientation in the field of a primary winding.) Based on the sight resolver output, a force is delivered to the barrel (through a hydraulically controlled piston actuator) that causes the barrel to rotate by the same amount as the sight, as measured by a (second) barrel-angle resolver. The resolver-actuator control is the essence of the current gun stabilization system, intended to keep the line of fire directed at the target, illustrated in Figure 4. As described, maintaining target pointing is critically dependent on the target-following abilities of the gunner (manifest in the sight resolver output); however, new technologies such as auto-tracking have the potential to significantly reduce the demands on the gunner during this process.

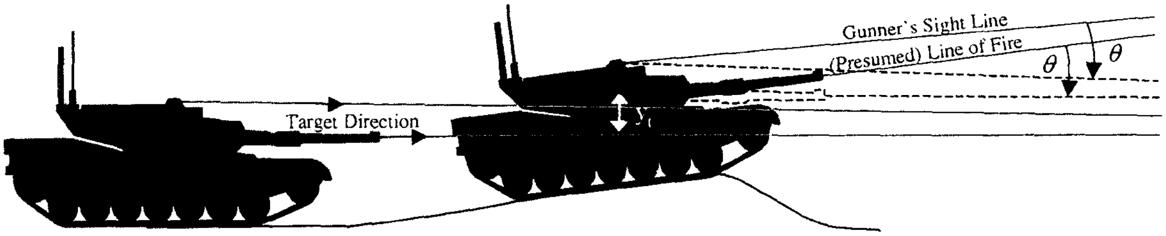


Figure 4. Caricature of Rigid-Body Motion of the Sight and Barrel While Target Tracking as the Tank Traverses a Bump.

The preceding discussion focuses on rigid-body gun pointing as a means of improving accuracy by keeping the line of fire directed at the target while the tank is traversing terrain disturbances that would otherwise cause the barrel to pitch (rotate) up or down. A secondary accuracy issue concerns the lateral velocity (jump) that would be imparted to the projectile at shot exit due to (1) rigid-body translation of the barrel caused by tank travel and (2) actuator-induced rigid-body rotation of the barrel enforced during target tracking. The jump derived from rigid-body translation and rotation for the moving, target-tracking barrel would be superimposed on the aforementioned crossing velocity jump. Knowing and compensating for projectile jump due to vehicle motion and target tracking would improve firing-on-the-move accuracy. The inclusion and use of a vertical plane accelerometer to determine $\dot{y}_t$, along with a knowledge of $\dot{\theta}$ (from the sight resolver output), could be used to determine such a firing-on-the-move correction angle, $\varphi_{rigid\text{-}body}$:

$$\varphi_{rigid\ \mathrm{body}} = \frac{v_{y,muzzle}}{v_{x,muzzle}} = \frac{\dot{y}_t + (x_m - x_t)\,\dot{\theta}}{v_{x,muzzle}} \quad , \tag{3}$$

where $v_{x,muzzle}$ is the standard launch velocity of the projectile and x_m is the breech-face-to-muzzle distance (note, positive $\hat{\theta}$ will be in the direction from positive $\hat{x}$ to positive $\hat{y}$, see Figure 5).

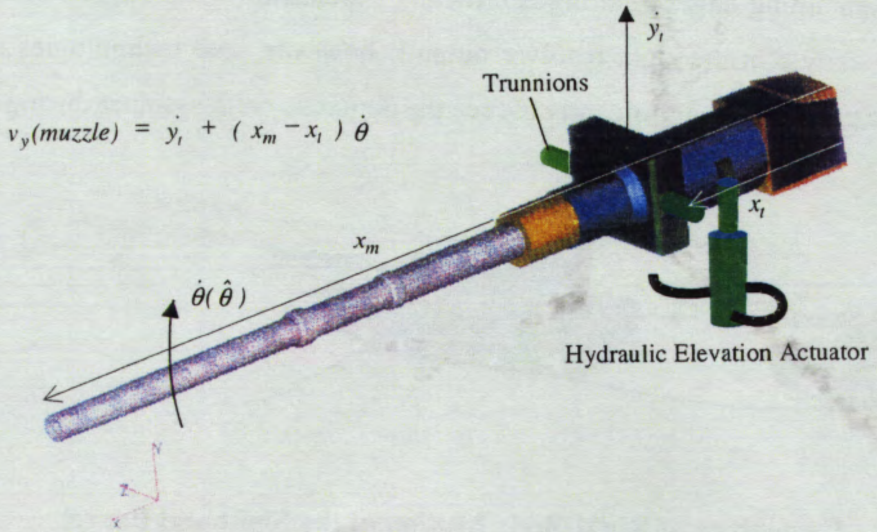


Figure 5. Rigid-Body Motion of the Barrel ($\dot{y}_t$ and $\dot{\theta}$) Due to Terrain and Actuator Forces.

Although it was possible to explicitly describe, via Equation 3, the effects of rigid-body barrel motion on the projectile (caused by target tracking and tank motion), quantifying the effects of barrel flexing on the projectile's flight path is not as easily done. In fact, such detail is not within the scope of the present study; the primary interest here is on how to determine and describe the dominant barrel flexing modes, and possibly conjecture as to their effect on the projectile.

2.2 Barrel Flexing Modes and Tube Shapes

Modeled as a system of point masses connected by spring-like forces, the fundamental barrel flexing modes can be determined by solving the appropriate mass-stiffness matrix. The first three mode shapes for the M256 120-mm barrel are shown in Figure 6; all shapes are normalized to unity. Note, all three mode shapes pass through zero at the location of the trunnions (~53 in, 1.35 m) and actuator (~35 in, 0.89 m), where the point masses are considered to be pinned. Recall, in principle, rigid-body motion accounts for the displacement as well as rotation of the line passing through the actuator and trunnion points (Equation 1), relative to which the mode shapes of Figure 6 are referenced. (In actuality, for modeling barrel mode shapes, it would be more appropriate to consider the barrel pinned at the front and rear load-bearing surfaces within the recoil mount; for simplicity, however, this is not done here.)

3. Barrel Flexing Due to Tank Motion

The shape of the flexed barrel at any given time is determined by the mode shape amplitudes, q_i, according to Equation 2. Figure 7 shows a typical time sample of the mode shape amplitudes for the M256 barrel mounted on the M1A2 tank, traversing the bump course referred to as RRC-9 at Aberdeen Proving Ground, MD. As indicated, the first mode is the dominant one. While traversing RRC-9, the ratio of amplitudes $q_1{:}q_2{:}q_3$ was found to be on the order of 25:5:1. This being the case, it is possible to adequately characterize/model flexing of the M256 barrel over this course by summing over just the first two mode shapes in Equation 2.

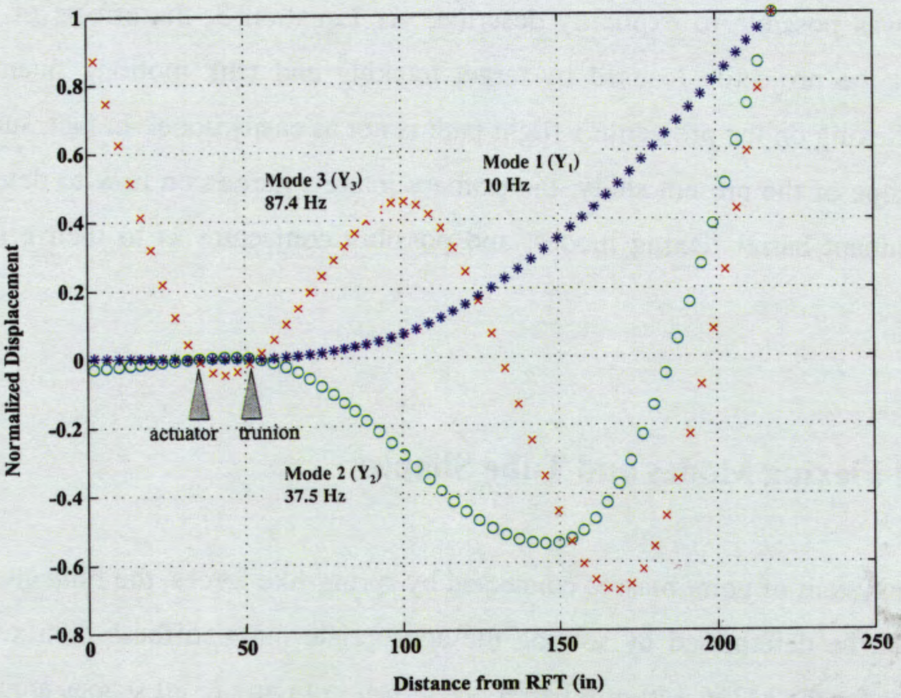


Figure 6. First Three Fundamental Barrel Flexing Mode Shapes (Normalized to Unity) for the M256 120-mm Barrel.

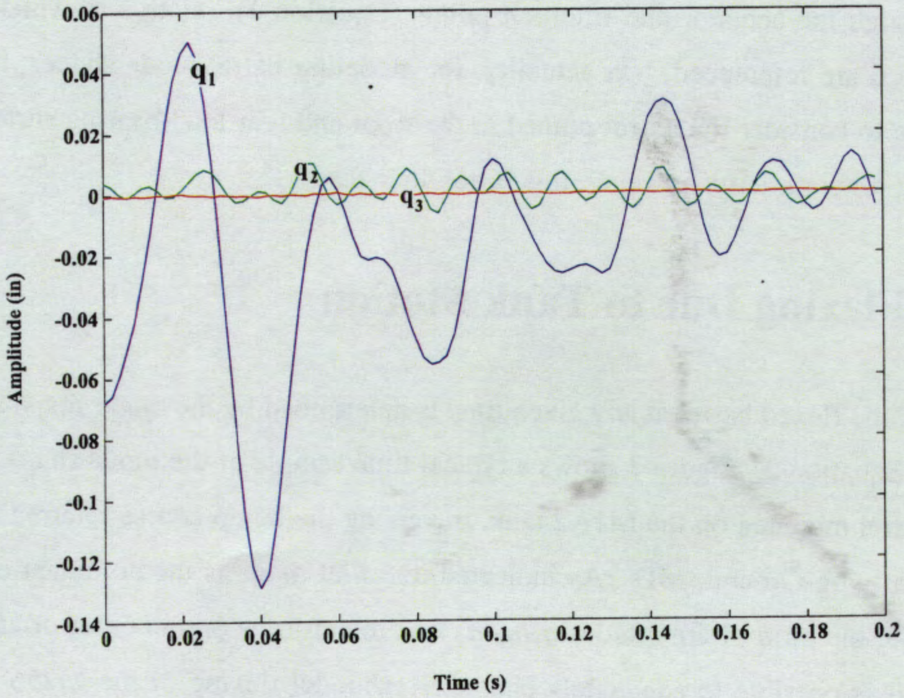


Figure 7. Typical Mode Shape Amplitudes While Vehicle Is in Motion.

Figure 8 illustrates how the ratio of q_1/q_2 can be discretized by counting the number of occasions that a given ratio (within some tolerance band) occurs over a given time span. Figure 9a shows how the distribution of ratios q_1/q_2 varies, over the range from –50 to +50 in increments of 1, while an M1A2 tank traversed RRC-9 at 15 mph (taking an elapsed time of 20 s and generating 9,000 data samples). (This type of accounting/plotting will fluctuate somewhat with the points selected and the width of the increments, but in general, trends will be independent of these factors.) For instance, it can be seen from Figure 9a that the value of q_1/q_2 between –1.5 and –0.5 occurred most often, 523 times out of the 9,000 time increments sampled (this same peak location occurred when the sampling was refined tenfold). Figure 9b shows the equivalent results, only plotted in the nondimensional format of frequency-of-occurrence.

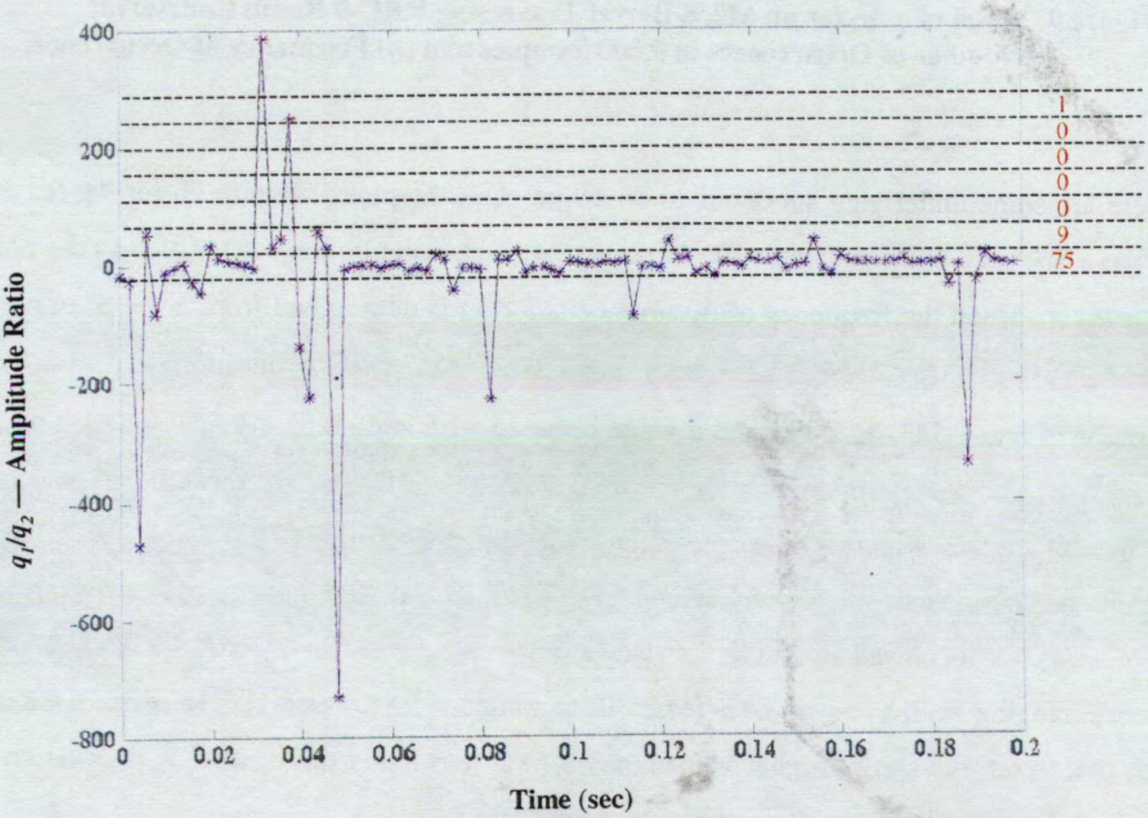


Figure 8. Typical Ratio of q_1/q_2 While Vehicle Is in Motion—An Example of Data Discretization by Banding.

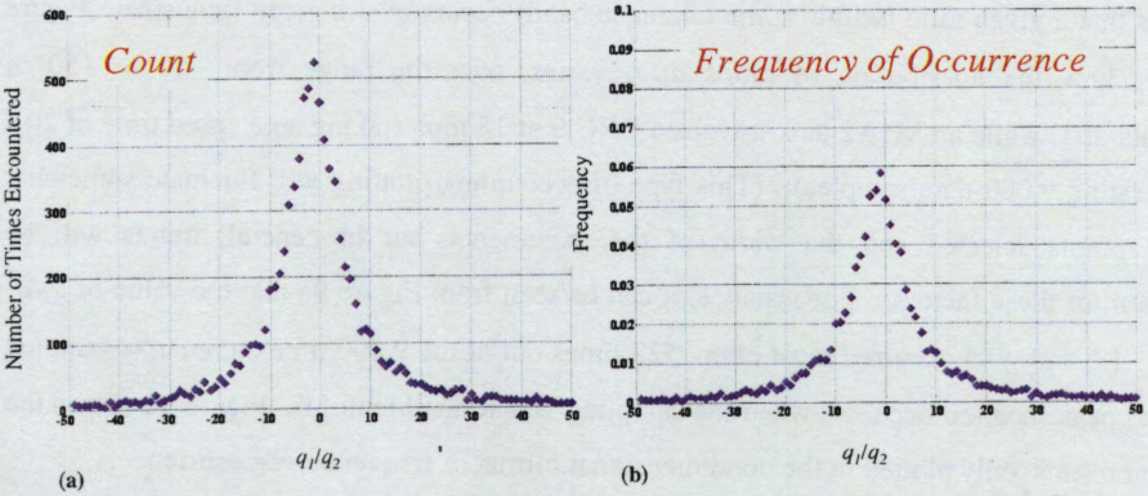


Figure 9. Ratio of q_1/q_2 for an M256 Barrel Traversing RRC-9 Bump Course: (a) Number of Occurrences in 9,000 Samples and (b) Frequency of Occurrence.

There are some underlying subtleties to be aware of in the plot of Figure 9b (or 9a, for that matter) as elaborated upon in Figure 10. In particular, each point on the curve (such as the point where $q_1/q_2 = -1$ and the frequency of occurrence is 5.8%) is determined from a set, S, of ratios q_1/q_2 that are all within $\pm\varepsilon$, the band tolerance (e.g., ± 0.5), of the point in question (e.g., out of the 9,000 ratios of q_1/q_2, 523, or 5.8%, had a value between -1.5 and -0.5). Hence, for each point, median values can be determined for q_1 and q_2 within the corresponding set S. These median values are plotted in Figure 10, as essentially the third dimension of Figure 9b. Before discussing the significance of these median values, it is informative to catalog the 10 most likely ratios of q_1/q_2, as displayed in Table 1. The top 10 cases are nearly equal in likelihood of occurrence, ranging from a low of 3.4% (case 10) to a high of 5.8% (case 1). However, there is a very gradual trend that shows higher values of q_1/q_2 are less likely to occur; this observation is shown more dramatically in the plots of Figures 9 and 10.

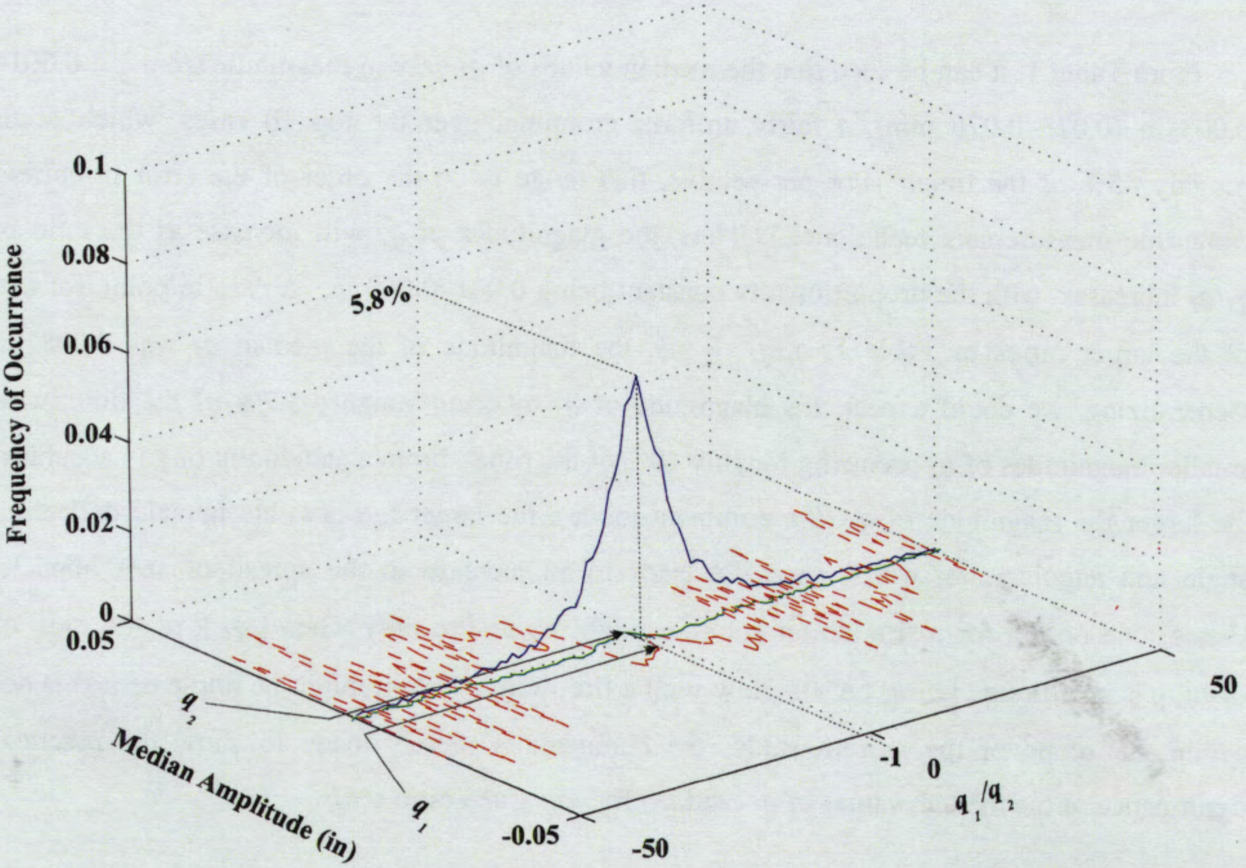


Figure 10. Frequency of Occurrence and Median Amplitudes for a Given Amplitude Ratio.

Table 1. Ten Most Likely Ratios of q_1/q_2

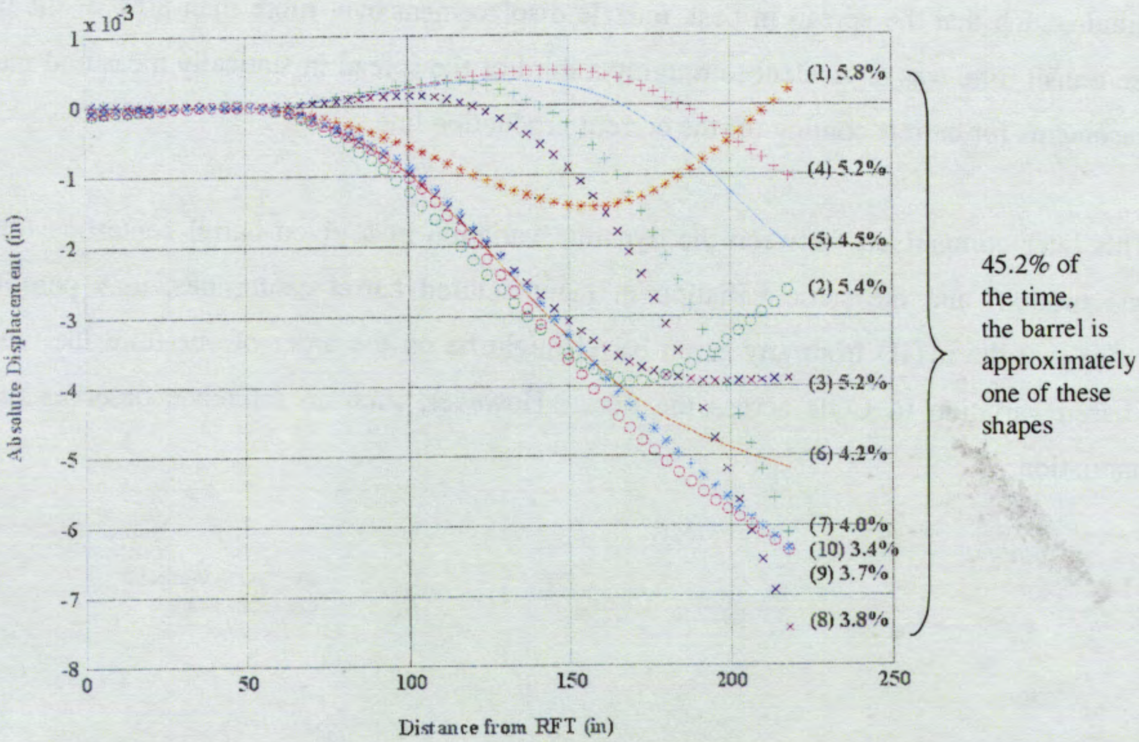
Probability Order	Ratio of q_1/q_2 (±0.5)	Frequency of q_1/q_2 Occurring (%)	Median Value of q_1 (inches $\times 10^{-3}$)	Median Value of q_2 (inches $\times 10^{-3}$)
1	−1.0	5.8	−1.5	+1.7
2	−2.0	5.4	−5.6	+3.0
3	−3.0	5.2	−5.8	+2.0
4	+0.0	5.2	−0.0	−1.0
5	+1.0	4.5	−0.9	−1.1
6	−4.0	4.2	−6.9	+1.7
7	+2.0	4.0	−4.0	−2.1
8	+3.0	3.8	−5.6	−1.9
9	−5.0	3.7	−8.0	+1.6
10	−6.0	3.4	−7.6	+1.2

Total — 45.2%

From Table 1, it can be seen that the median values of q_2 vary in magnitude from 0.001–0.003 in (0.025–0.076 mm), a fairly uniform grouping, over the top 10 cases, which occur roughly 45% of the time. (For perspective, this range is on the order of the error in current centerline measurement techniques.) Thus, the magnitudes of q_1 will increase as the ratio of q_1/q_2 increases, with the proportionality constant being 0.001–0.003 in. A case in point, for one of the larger ratios in Table 1, $q_1/q_2 = -5$, the magnitude of the median q_1 was 0.008 in. Generalizing, we could expect this magnitude of q_1 to occur roughly 3.7% of the time, with smaller magnitudes of q_1 occurring roughly 40% of the time. From a standpoint of gun accuracy, the larger the magnitude of q_1 (the dominant mode), the larger the possible muzzle deflection angle and angular rate, which generally leads to an increase in the spread of shot impacts. Hence, one option for a fire-inhibit solution might be to fire only when $| q_1 |$, or the ratio of $| q_1/q_2 |$, is small (e.g., $| q_1/q_2 | \leq 4$). How such a fire-inhibit system might be implemented is not within the scope of the current study; the comment is merely made to show the practical significance of the median values of q_1 (and q_2) for any given ratio q_1/q_2.

Figure 11 shows the barrel flexure profiles corresponding to each of the top 10 ratios listed in Table 1. The most undulating shapes are those with the highest proportion of second mode motion (e.g., cases 1–5). For the most part, the higher amplitude shapes are those dominated by first mode motion (e.g., cases 6–10).

The top 10 tube shapes in Table 1 and Figure 11 were obtained by searching the database of Figure 9b for any case where the frequency of occurrence exceeded 3%. When this search window was broadened to include any case where the probability was greater than 0.5%, 37 ratios were found that met this criterion. These 37 cases, plotted in Figure 12, represent the flexed barrel profile for a combined 82.5% of the bump-course transit time. The spread in peak amplitudes across this group is roughly 0.030 in (0.76 mm). Also shown in Figure 12, for comparison, is the average manufactured centerline shape for the M256 barrel (Wilkerson 1998). For the most part, the spread in manufactured barrel centerlines, as registered by their (peak) muzzle displacements, spans about 0.100 in (2.5 mm) (i.e., ±0.050 in [1.25 mm] on either side of the average shown).*



45.2% of the time, the barrel is approximately one of these shapes

Figure 11. Ten Most Likely Barrel Shapes Over Bump Course.

4. Summary and Conclusions

This report has documented a methodology to assess the superimposable effects of tank motion on the static barrel centerline shape of a rigidly rotating and translating barrel. It has been shown, for example, that for an M256 barrel in an M1A2 tank traversing the RRC-9 bump course at 15 mph, the resulting barrel flexure could be adequately captured by a linear combination of just the first two mode shapes (higher order mode shapes were not a significant factor). For roughly a third (34%) of the bump course transit time, the ratio of the first to second mode amplitudes was ≤ 3. Moreover, for this mixed-mode group, the median mode shape

---

[*] Although the acceptable tolerance in peak muzzle displacement (relative to a straight line) spans 0.160 in (4 mm), most manufactured barrel centerlines fall well within this tolerance limit.

amplitudes were relatively small (for reference, they were typically smaller than three times the magnitude of the current static centerline measurement error). The remaining two-thirds of the time, the barrel was essentially exhibiting first-mode motion, albeit with relatively large amplitude, such that the spread in peak muzzle displacement over more than 80% of the bump course transit time was equivalent to roughly a third of the spread in statically measured muzzle displacements for barrels coming off the current production line.

This later comparison, between the dynamic variation in a given barrel centerline (due to vehicle motion) and the static variation in manufactured barrel centerlines, may permit the inference that the mTID from any given barrel might be on the order of one-third the tube-to-tube-based variation in COIs across the fleet. However, such an inference deserves further substantiation.

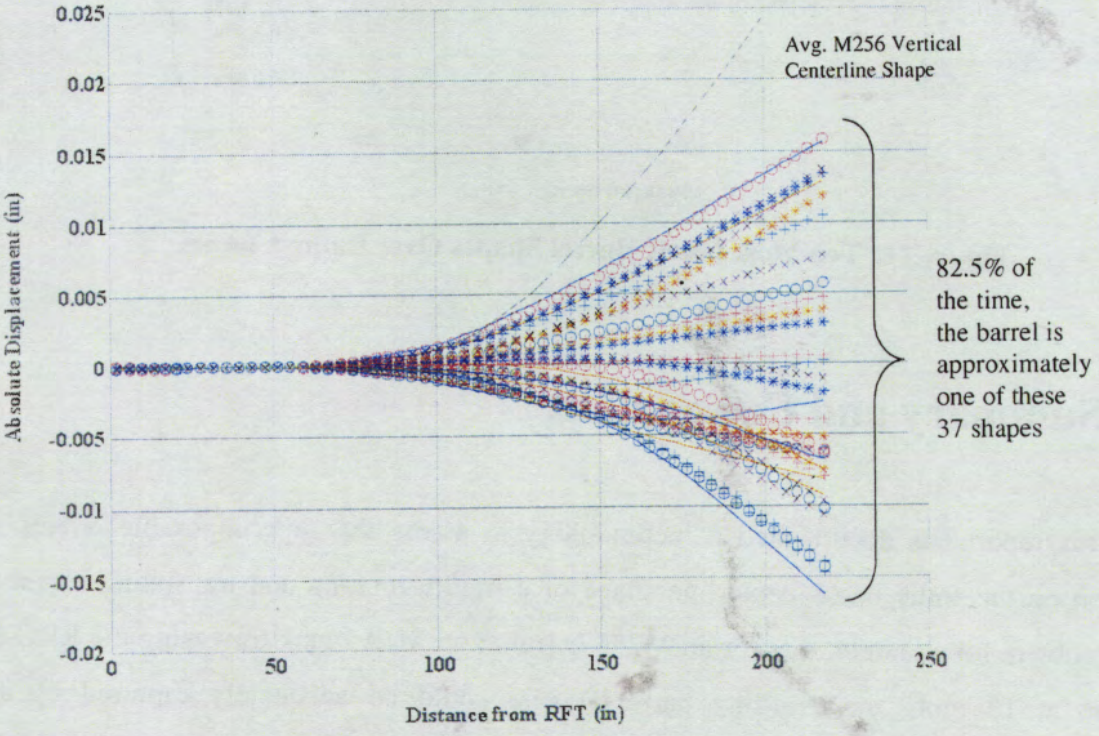


Figure 12. Comparison of Most Likely Bump Course Barrel Shapes With the Average Manufactured Shape for an M256 Barrel.

5. References

Bornstein, J., I. Celmins, P. Plostins, and E. M. Schmidt. "Techniques for the Measurement of Tank Cannon Jump." BRL-MR-3715, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, December 1988.

Bundy, M. "The Regional Nature of Aerodynamic Jump." ARL-TR-1872, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, January 1999.

Guidos, B. J. Private communications on the repeatability of M256 gun dynamics. U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, October 1999.

Held, B. J., D. W. Webb, and E. M. Schmidt. "Temperature Dependent Jump of the 120-mm M256 Tank Cannon." BRL-MR-3927, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, December 1991.

Wilkerson, S. "Possible Effects of Gun Tube Straightness on Dispersion." ARL-TR-767, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, June 1995.

Wilkerson, S. Private communications on the average measured centerline profile for the M256 120-mm barrel. U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, October 1998.

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