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# DRAG CHARACTERISTICS OF RIBBONS

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## ABSTRACT

An extensive experimental program has been conducted to determine the aerodynamic characteristics of grenade ribbon stabilizers. Data have been acquired from vertical and horizontal wind tunnel tests, free-flight drop tests, free-flight gun tests, and flight dispense tests. This paper summarizes the aerodynamic results from these tests (in particular the drag characteristics), and discusses the recent program developments. Design charts that significantly extend the data presented by Hoerner for the drag of flags is presented.

## NOMENCLATURE

Symbols:

| | |
|---|---|
| AoA | Angle-of-attack, degrees. |
| $C_D$ | Drag coefficient |
| D | Reference length, inches |
| L | Ribbon loop/streamer length, inches |
| S | Reference area, sq. in. |
| T | Ribbon thickness, inches |
| W | Ribbon width, inches |

## FORWARD

An effort has been undertaken to reduce the hazardous dud rate of rocket-dispensed grenades to less than 1 percent. As a part of this effort, the current study was initiated as a low cost solution to this problem. The objective being to eliminate side impact, the largest single cause of hazardous duds. *Figure 1* shows a typical grenade configuration with a typical ribbon stabilizer unfurled.

Following dispense the grenades experience large oscillatory motion until the ribbon stabilizer is deployed. After the stabilizer is deployed, the grenade motion quickly damps out and slows to terminal velocity. Once the grenade has reached terminal velocity it should not experience any moderate or large oscillatory motion (small, moderate, and large oscillatory angles shall be defined later in the paper). Wind tunnel test results indicate that there are four distinct modes of flight. These flight modes have been identified, are defined in detail in references 1 and 2, and are summarized herein. Based upon the findings of these documents, further enhancements to the ribbon were made and tested. Several candidate ribbon configurations were selected for further testing based on their superior stability at terminal velocities.

## INTRODUCTION

A wind tunnel test of an instrumented full-scale ribbon stabilized grenade has been conducted at the Auburn University Low Speed Wind Tunnel. The grenade currently employs a 6.25x0.75x0.017-inch nylon ribbon loop to provide aerodynamic stability and arming. The primary objective of this test was to determine and characterize the parameters that affect the grenade's dynamic stability at terminal flight velocities. To accomplish this objective, numerous ribbon configurations have been fabricated that systematically vary ribbon parameters.

For selected configurations, the high subsonic and supersonic drag profile was extracted via Doppler radar tracking data and a 3-degree-of-freedom simulation of the grenade flight. These tests were conducted at Eglin AFB, and in addition to the radar data, detailed weight measurements of the individual grenades and atmospheric data were acquired. The terminal velocity drag results obtained at Eglin were found to be consistent with previous drop test results of the current grenade.

## WIND TUNNEL TEST SUMMARY

An extensive wind tunnel test program was conducted to characterize the ribbon parameters that affect the aerodynamic performance of ribbon stabilizers. This test program has been discussed in detail in references 1 and 2.

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Furthermore this test series is an extension of earlier work on ribbon stabilizers as documented in references 3 and 4.

The wind tunnel test program was conducted at the low speed facility located at Auburn University and obtained aerodynamic coefficients in the terminal velocity range (freestream velocity was varied from 90 to 150 ft/sec). The wind tunnel model and associated test hardware used in this series is presented in *Figure 2*. A special purpose 4-component balance was designed and fabricated by Modern Machine and Tool Company (MMT) to fit inside the grenade body. This balance measures axial force, side force, yawing moment, and pitching moment. The remainder of the test hardware were designed and fabricated by Dynetics, Inc. An angular displacement transducer located in the upper strut measured the yaw position of the grenade. An A/C powered solenoid, located in the lower strut, was used to release the grenade from its initial position once the tunnel was on condition. Linear bearings and ball joints were incorporated into the design to allow the upper and lower support legs to be adjusted to eliminate any possible binding that may be introduced during the installation.

A typical dynamic run consisted of the grenade being locked at an initial yaw angle, with the ribbon stabilizer unfurled. After the tunnel was on condition, the data acquisition system (DAS) was started and the grenade was released and allowed to rotate freely in the yaw plane of the tunnel. The DAS acquired data at a rate of 1000 hertz for a minimum of 10 seconds. For a few selected configurations data were acquired for a 60 second duration. A number of static runs were also obtained, during which the grenade was held at a constant yaw-angle throughout the run.

## EGLIN GRENADE TEST SUMMARY

Multiple tests of various ribbon designs were conducted at the Eglin Air Force Base test range B-71 over a two-year period beginning in November 1999. The various ribbon designs were installed on a typical cylindrical inert grenade. The test articles were launched with initial velocities from approximately 280 to over 600 m/s, and in some cases the test articles were preconditioned prior to launch with selected temperature from -30°C to 60°C. Of the various configurations tested at Eglin, only the three most promising candidates are presented here.

The Eglin tests were designed to accomplish several things. Primary to this paper, the test articles were tracked with a Weibel Doppler radar to obtain velocity and deceleration data. Other objectives included assessment of the impact angle, assessment of slider-lock ejection and ribbon deployment, and fuze arming function. The drag characteristics of the test articles were "backed-out" of the radar data by using a three-degree-of-freedom simulation of the grenade flight. The two main drawbacks of this test are the high in-tube launch acceleration and the speed of testing. Approximately 60 to 80 shots could be comfortably made each day, depending on weather and equipment breakdowns. The muzzle velocity was limited to about 600 m/s with the available tube length, powder charges, and sabot designs. During the launch, grenade fuze damage was experienced with muzzle velocity above 600 m/s.

Prior to the test, an identification number was placed on each test article as it was assembled. After assembly, each test article was weighed and the ribbon folded to the pre-launch condition. A spreadsheet was built for each test that identified all of the pertinent information for each test article. These data included the test article number and any modification, test article mass, day and approximate time of launch, gunpowder charge, conditioned temperature if any, and all anomalies that were noticed during the test.

Each grenade was tracked with a low-power, stationary Doppler velocity radar and a Weibel Doppler tracking radar, both located at the gun site. These radars were initially aimed down the firing direction. The reference time of firing was determined at the gun muzzle by an installed sensor that detected the time for test article exit from the gun muzzle. *Figure 3* shows the 40-mm gun and location of the radars at Eglin.

The impact angle was measured from the impression left by the grenade impact on the target area asphalt. The status of the arming function was recorded for each grenade upon location in the target impact area. This was recorded along with any remarks worthy of note regarding the general physical and mechanical condition of the recovered grenade. Finally, the ground impact angle was measured in two planes.

Eglin Air Force Base Range B-71 has an elevation of approximately 35 m above sea level. Two surface stations recorded meteorological conditions at 10-minute intervals. This data consisted of wind speed and direction, barometric pressure, temperature, and humidity. All available data were considered during the drag analysis.

## RESULTS AND ANALYSIS

### Classification of Grenade Oscillations

*Reference 2* presents the grenade yaw-angle versus time for all of the free-yaw runs acquired during the Auburn test series. A review of these data indicates that the stabilizer configuration can produce a number of different flight characteristics. These flight characteristics have been classified into four distinct categories and are summarized in *Table 1*.

*Table 1. Grenade Flight Characteristics*

| Type | Description of Flight Characteristics |
|---|---|
| 1 | Large initial oscillations damp quickly to near zero angles, and the remaining grenade oscillations are at small angles. |
| 2 | Large initial oscillations damp quickly to near zero angles, however, the grenade continues to oscillate at moderate angles with an occasional spike to large angles. |
| 3 | After release, the grenade oscillates at large angles about zero. |
| 4 | Large initial oscillations damp, however, the grenade may trim at and oscillate about some non-zero angle. |
| Note: | ***Large angles*** are considered to be greater than 20 degrees. ***Moderate angles*** are considered to range from 10 to 20 degrees. ***Small angles*** are considered to be less than 10 degrees. |

Even with these definitions, classification of the oscillations is still very subjective. It was determined early on in the testing that it was necessary to acquire multiple runs per configuration to confidently confirm that a configuration exhibited Type-1 oscillations.

The grenade body-alone drag coefficient was determined to be approximately 1.00 from wind tunnel test results of the grenade fixed at zero degrees AoA.

### Ribbon Drag Characteristics

In his discussion of the drag of flags, Hoerner[5] points out that the flag's skin friction is only a small part of the measured drag. The larger portion of the measured drag of ribbons is attributed to the flutter of the bunting. Hoerner, referring back to Fairthorne's[6] data, indicates that there are two parameters that influence ribbon drag. These are the ribbon's (or flag's) length-to-width ratio and the weight of the fabric per unit area. Fairthorne's data were for flags with length-to-width ratios varying from 0.25 to 4.0. These data are shown in *Figure 4* (labeled Hoerner), and represent a linearly increasing function of the length-to-width ratio.

In the current investigation, ribbons (both strands and loops) with length-to-width ratios of 4 to 75 were investigated and indicate a significantly different trend than that for lower length-to-width ratios. The new ribbon data show a 90% correlation to the following power-series equation:

$$CD_{ribbon} = 0.4012 * (L/W)^{-0.639}.$$

The ribbon drag coefficient is non-dimensionalized by the total wetted area of the unfurled ribbon (both sides) and the free-stream dynamic pressure. The length-to-width ratio used in the correlation, corresponds to the loop/streamer length. These data are shown plotted with the above correlation in *Figure 4*. This figure shows data for both strand and looped ribbon configurations.

During testing, it was observed that ribbon fluttering occurred only at the ends of high length-to-width ribbons. Therefore, as the length-to-width ratio increases, a smaller percentage of the ribbon experiences fluttering oscillations and as a result the non-dimensionalized ribbon drag coefficient decreases. Also, since the fluttering is located at the end of the ribbon, longer ribbons tend to transmit smaller disturbances back to the grenade housing.

### Average Grenade Drag for Several Ribbons

*Figure 5* presents the average grenade drag as a function of Mach number for the three primary ribbon candidates. These curves are an amalgamation of many separate gun shots of each of the three configurations. A three-degree-of-freedom simulation of the grenade flight was used. Given the mass of each grenade, and the metrological conditions at firing, the 3-DOF was exercised to determine the drag coefficients that yielded the best match to the Weibel radar data. The drag curves for individual shots were then averaged to produce the curves presented in *Figure 5.* Here the grenade diameter is used as the reference length.

The higher terminal velocity drag associated with the 6.25 x 0.750-inch ribbon loop configuration is attributed to the fact that this configuration tends to have much larger oscillations at terminal speeds. As a result, the average grenade drag calculated by the simulation is accounting for the drag of grenade housing at fairly large angles-of-attack.

The longer 10-inch loop ribbon configurations have lower drag coefficients and are better stabilizers (impart less dynamics back into the grenade body) than the shorter and wider ribbon loop. As a result the average grenade drag as calculated by the 3-DOF is lower for these configurations at terminal velocities.

The higher supersonic average grenade drag associated with the 9/16-inch loop is attributed to the fact that this ribbon configuration tends to have less drag and therefore may not provide adequate damping at the higher Mach numbers.

## CONCLUSIONS

The grenade stabilizer serves two functions. It must, as the name implies, stabilize the grenade, and secondly it must arm the grenade (by unscrewing the arming screw). If the stabilizer does not provide adequate drag, then the grenade body will trim at non-zero yaw angles. Analysis indicates that the zero-yaw drag coefficient must be greater than 1.50 for the given configuration to consistently trim to zero-yaw without any alternate trim points. If the stabilizer produces excessive flagging dynamics, then these dynamics will be translated to the grenade producing large oscillatory motion and a high number of side impacts.

Ribbon flagging is a significant contributor to over-all ribbon drag. The 0.750-inch width ribbon produces considerably more drag than the 0.500-inch width ribbon. However, this added drag comes with the price of added ribbon dynamics. The dynamic flagging oscillations of the 0.750-inch ribbon tend to destabilize the grenade and appear to outweigh the benefits of higher drag.

A power-series equation describing ribbon drag for looped and single/double streamer configurations is presented herein. This equation has a 90% correlation to all test data acquired during an extensive low-speed wind tunnel test. The correlation is valid over a range of ribbon length-to-width ratios ranging from 4 to 75.

Ballistic tests of the grenade with various ribbon configurations provided an excellent set of data that could be used to calculate average grenade drag. Drag results from these tests were in agreement with terminal velocity drag data obtained from the low-speed wind tunnel, and drop tests.

## REFERENCES

(1) Auman, L.M., et.. al., "Aerodynamic Characteristics of Ribbon Stabilized Grenades", AIAA Paper 2000-0270, Presented at the 38 Aerospace Sciences Meeting & Exhibit, Reno, NV, January 2000.

(2) Auman, L.M., "Free-Yaw Characteristics of Ribbon Stabilized Grenades", U.S. Army Aviation and Missile Command Technical Report TR-RD-SS-99-16, October 1999.

(3) Dahlke, C.W., "Aerodynamic and Flight Dynamics of Ribbon Stabilized M42 Grenade", U.S. Aviation and Missile Command Technical Report T-79-84, Redstone Arsenal, AL, September 1979.

(4) Dahlke, C.W., "Aerodynamic and Flight Dynamics of Ribbon Stabilized Grenades", AIAA 17th Aerospace Sciences Meeting, New Orleans, LA, January 1979.

(5) Hoerner, S.F. "Fluid-Dynamic Drag" Published by Author, 1965.

(6) Fairthorne, "Drag of Flags", Aeronautics Research Council, ARC RM 1345, 1931.

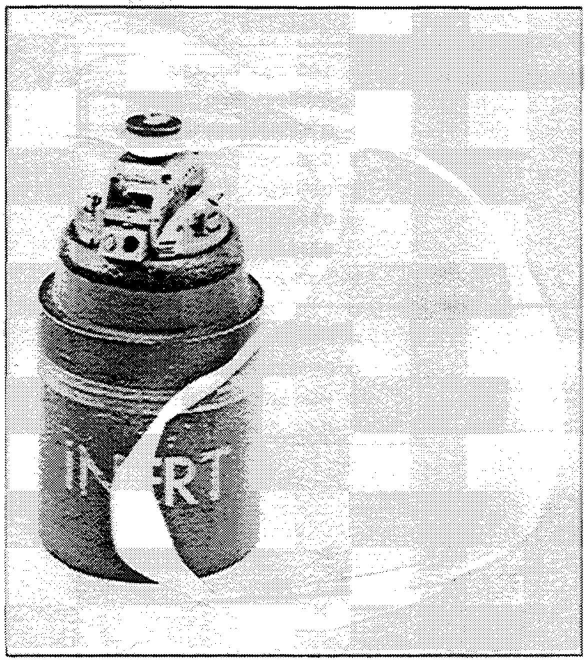

*Figure 1. Typical ribbon stabilized grenade*

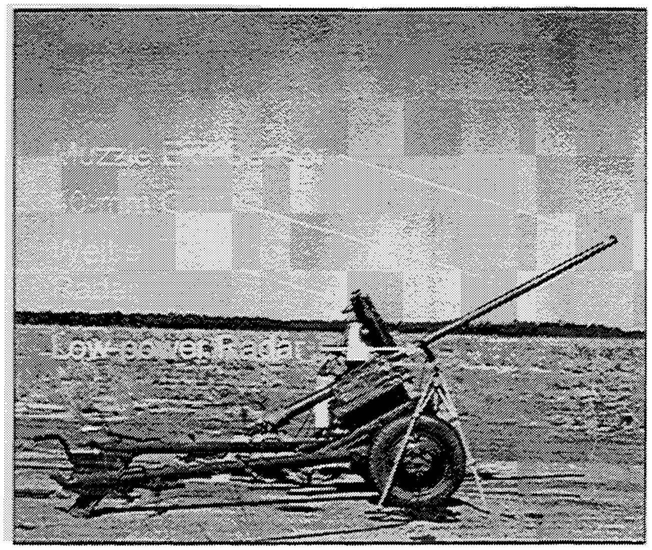


*Figure 3. 40-mm gun at Eglin AFB.*

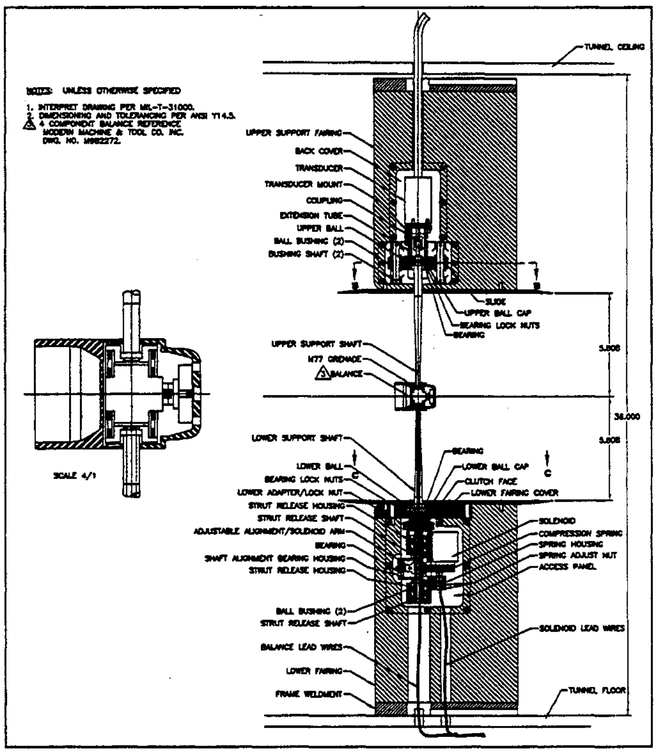


*Figure 2. Wind Tunnel model grenade test fixture.*

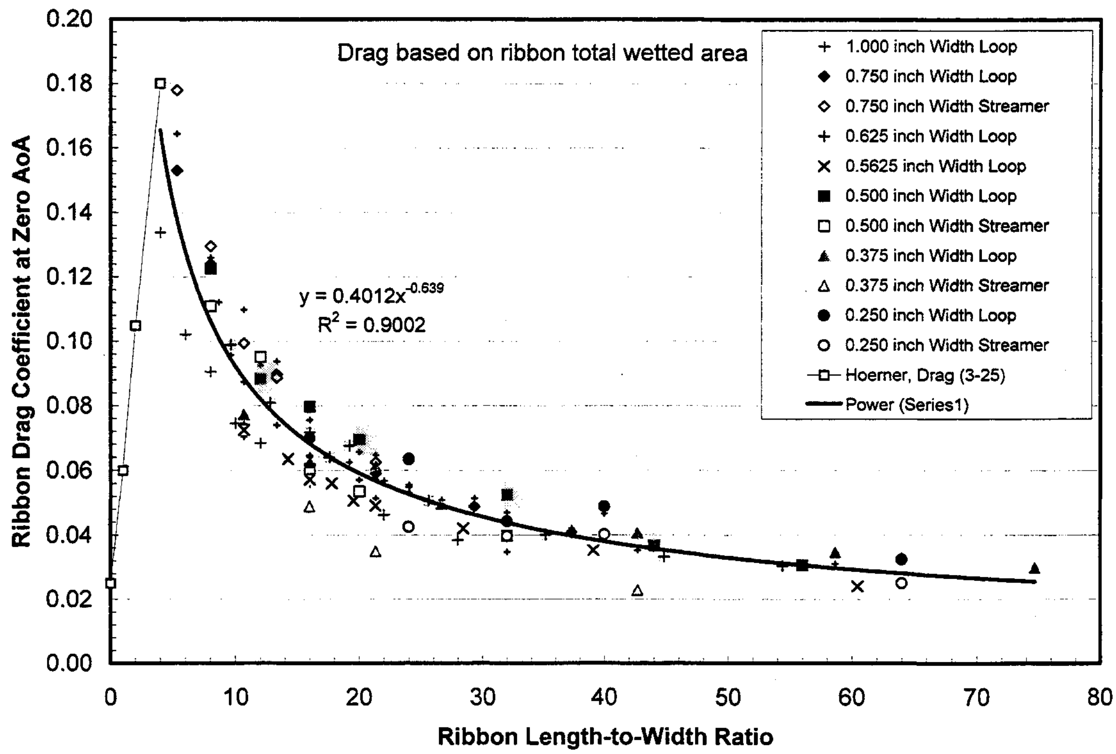


Figure 4. Loop ribbon drag as a function of ribbon length-to-width

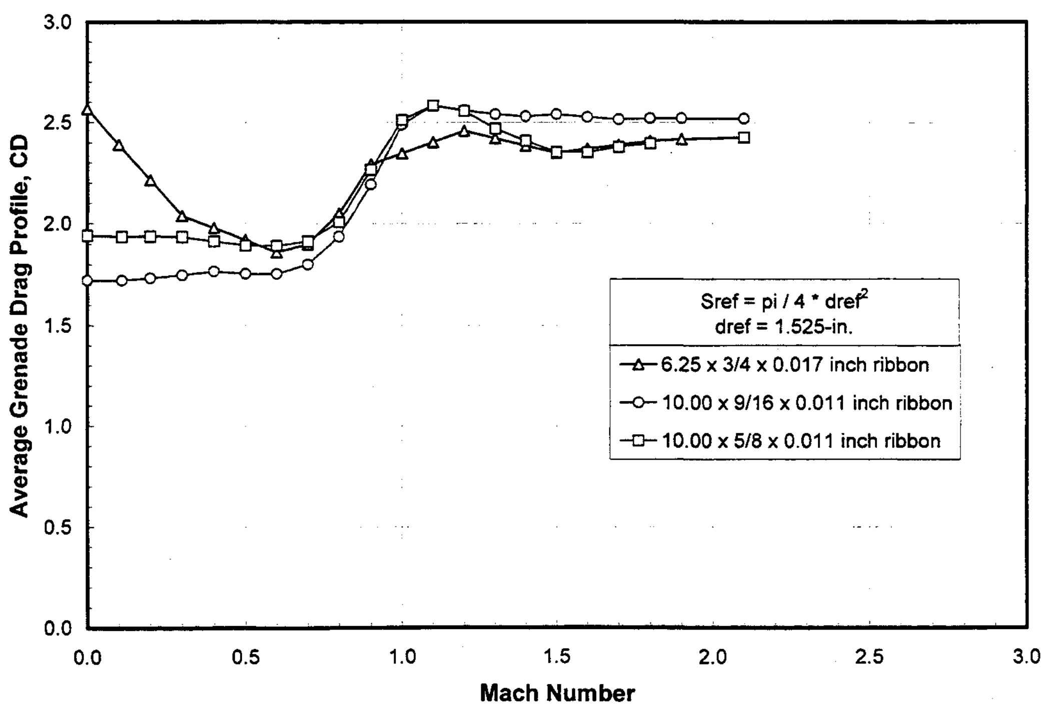


Figure 5. Average grenade drag as a function of Mach number