EXPERIMENTAL MAGNUS CHARACTERISTICS OF SEVERAL BALLISTIC PROJECTILES WITH VARIOUS BOATTAIL ANGLES AND LENGTHS AT MACH NUMBERS 1.5, 2.0, AND 2.5

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APPROVAL STATEMENT

This technical report has been reviewed and is approved.

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An experimental investigation was conducted to determine the effects of boattail angle, the boattail length, and the base diameter on the Magnus-force and moment characteristics of spin-stabilized projectiles. The models were tested at Mach numbers 1.5, 2.0, and 2.5 over an angle-of-attack range from -2 to 8 deg. Data were obtained at length Reynolds numbers of $2.44 \times 10^6$, $9.60 \times 10^6$, and $17.53 \times 10^6$, and for spin parameter $(pd/2V_0)$ values.
20. ABSTRACT (Continued)

of 0.024 to about 0.270 radians. Results are presented showing the effects of spin, Mach number, angle of attack, boattail geometry, and Reynolds number. The results show that increasing the boattail length or angle decreased \( C_{N\alpha} \), and increased the magnitude of \( C_{m\alpha} \), \( C_{y\alpha} \), and \( C_{n\alpha} \).
The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), for the Naval Weapons Laboratory (NWL) under sponsorship of the Air Force Armament Laboratory (AFATL), AFSC, under Program Element 62602F, Project 2547. AFATL project monitor was Mr. E. Sears. The results presented herein were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee. The tests were conducted on March 22, 25, and 26, 1974, under ARO Project No. VA427. The final data package was completed on April 26, 1974, and the manuscript (ARO Control No. ARO-VKF-TR-74-48) was submitted for publication on June 17, 1974.
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1.0 INTRODUCTION

This test was conducted as part of a continuing investigation (Refs. 1 and 2) by the Naval Weapons Laboratory (NWL) on development work of ballistic shells. Since these projectiles are statically unstable, they must be spin-stabilized. The spin velocity required to stabilize the projectiles tends to induce Magnus effects, which can lead to dynamic instabilities. Both of these factors will influence the flight path. This test was initiated to determine the effects of boattail angle, boattail length, and base diameter on the Magnus-force and moment characteristics of projectiles. Data were obtained at Mach numbers 1.5, 2.0, and 2.5 at a Reynolds number (based on a model length of 28.662 in.) of $9.6 \times 10^6$. Some additional data were obtained at $M_\infty = 2$ for Reynolds numbers of $2.4 \times 10^6$ and $17.5 \times 10^6$. The angle of attack was varied from -2 to 8 deg., and values of the spin parameter ($p d / 2 V_\infty$) ranged from 0.02 to about 0.27 radians.

2.0 APPARATUS AND PROCEDURE

2.1 TEST ARTICLES AND TEST MECHANISM

The aluminum models (Figs. 1 and 2) were supplied by NWL and were similar to the ones tested in Ref. 2. The models consisted of one common nose section and ten afterbody sections with various boattail lengths and angles as well as various base diameters. All of the models were dynamically balanced in roll at VKF so that there would be no vibrational loads on the balance.

The models were mounted on the Magnus-force test mechanism shown in Fig. 3. Basically, the Magnus-force test mechanism has a sting-mounted, water-jacketed, four-component balance with a shell mounted on ball bearings over the water jacket. A two-stage, air-driven turbine is mounted inside the model mounting shell at a fixed axial position near the forward end of the sting. The turbine is used to spin the model to some desired speed and then is disengaged with an air-operated sliding clutch to allow the model to spin freely on the ball bearings. It is estimated that the turbine will produce a starting torque of 50 in.-lb and a developed torque of approximately 100 in.-lb. The mechanism is designed to operate under normal-force loads up to 500 lb and axial-force loads of 125 lb and for a maximum spin rate of approximately 25,000 rpm.
2.2 TEST FACILITY

Supersonic Wind Tunnel (A) is a continuous, closed-circuit, variable density wind tunnel with an automatically driven flexible-plate-type nozzle and a 40- by 40-in. test section. The tunnel can be operated at Mach numbers from 1.5 to 6 at maximum stagnation pressures from 29 to 200 psia, respectively, and stagnation temperatures up to 750°R \( (M_\infty = 6) \). Minimum operating pressures range from about one-tenth to one-twentieth of the maximum at each Mach number. In most instances, Mach number changes may be made without stopping the tunnel flow. The model can be injected into the tunnel for a test run and then retracted for model changes without stopping the tunnel flow.

2.3 INSTRUMENTATION

Tunnel A stilling chamber pressure is measured with a 150-psid transducer referenced to a near vacuum and having full-scale calibrated ranges of 10, 50, and 150 psi. Based on periodic comparisons with secondary standards, the precision of this transducer (a band which includes 95 percent of the residuals) is estimated to be within \( \pm 0.5 \) percent of the measured pressure. The stilling chamber temperature is measured with a copper-constantan thermocouple to a precision of \( \pm 2°R \) based on the thermocouple wire manufacturer's specifications.

Model forces and moments were measured with the VKF four-component, moment-type, strain-gage balance shown in Fig. 4. The small outrigger side beams of the balance, with semiconductor strain gages, were used to obtain the sensitivity required to measure small side loads while maintaining adequate balance stiffness for the larger pitch loads. When a yawing moment is imposed on the balance, secondary bending moments are induced in the side beams. Thus, the outrigger beams act as mechanical amplifiers, and a normal-force to side-force capability ratio of 20 was achieved for a 500-lb normal-force loading. Before testing, static loads in each plane and combined static loads were applied to the balance, simulating the range of model loads anticipated for the test. The uncertainties shown in Table 1 represent the bands for 95 percent of the measurement residuals based on differences between the applied loads and the corresponding values calculated from the final data reduction equations.

The transfer distance to the model moment reference was measured with a precision of \( \pm 0.005 \) in.
The rotational speed of the model was computed from the electrical pulses produced by a ring with reflective surfaces passing an internally mounted infrared-emitting diode and phototransistor. This tachometer system could measure spin rates form 0 to 25,000 rpm.

2.4 TEST PROCEDURE

The model was positioned at the desired attitude with the tunnel pitch mechanism and then spun with the turbine. When the desired spin rate was achieved, the nitrogen to the turbine was shut off, the clutch was disengaged, and data were recorded as the model spin rate decayed. Model spin rates were monitored using the internally mounted tachometer described in Section 2.3.

3.0 TEST CONDITIONS AND DATA PRECISION

3.1 TEST CONDITIONS

A summary of the configurations tested is presented in Table 2, and the nominal wind tunnel test parameters at which the data were obtained are presented in Table 3. The "x" in Table 2 indicates that Magnus data were obtained for $\alpha = -2$ to 8 deg.

3.2 DATA PRECISION

Uncertainties (bands which include 95 percent of the calibration data) in the basic tunnel parameters, $p_o$, $T_o$, and $M_\infty$, were estimated from repeat calibrations of the instrumentation and from the repeatability and uniformity of the test section flow during tunnel calibrations. These uncertainties were then used to estimate uncertainties in other free-stream properties, using the Taylor series method of error propagation. Listed in Table 4 are the uncertainties in the basic wind tunnel parameters at which most of the data were obtained.

Measurements of the model attitude in pitch including the model-balance deflection are precise within $\pm 0.05$ deg, based on repeat calibrations. The rpm precision is estimated to be $\pm 5$ rpm.
The basic uncertainties listed in Section 2.3 were combined with uncertainties in the tunnel parameters (Table 4), assuming a Taylor series error propagation, to estimate the precision of the aerodynamic coefficients. The uncertainties shown in Tables 5 and 6 are those that were computed for the test conditions at which most of the data were obtained ($Re \approx 4 \times 10^6/\text{ft}$) and are near the maximum aerodynamic loads.

It should be noted that the data repeatability, which is a measure of the random-type errors, was generally within the maximum propagated uncertainties quoted.

4.0 RESULTS AND DISCUSSION

These tests were conducted primarily to determine the effect of varying the boattail geometry of ballistic shell configurations on their Magnus-force and moment characteristics at supersonic Mach numbers. Data were obtained at Mach numbers 1.5, 2.0, and 2.5 for angles of attack from -2 to 8 deg. The spin rate parameter ($pd/2V_\alpha$) ranged from 0.024 to 0.270 radians.

The variations of normal force ($C_N$) and pitching moment ($C_m$) with angle of attack are presented in Figs. 5 through 7. Since gun-launched projectiles are spin-stabilized, they are all statically unstable, as expected. Both $C_N$ and $C_m$ are essentially linear functions of angle of attack for angles up to 4 deg. For all configurations, $C_N$ increased and $C_m$ decreased with increasing Mach number indicating a rearward shift in the center of pressure. The results presented in Fig. 6 show that varying the Reynolds number at Mach number 2 had no effect on the values of $C_N$ and $C_m$ of Configuration 3. Figure 7 shows the variations of $C_{N\alpha}$ and $C_{m\alpha}$ with Mach number. As was shown in Fig. 5, $C_{N\alpha}$ increases and $C_{m\alpha}$ decreases with increasing Mach number. The results also show that as the boattail length or angle increased, in effect decreasing the projectile planform area aft of the moment reference, $C_{N\alpha}$ decreased and $C_{m\alpha}$ increased as would be expected.

Figure 8 presents the typical variation of side force ($C_y$) and yawing moment ($C_n$) with $pd/2V_\alpha$ for Configuration 3 at Mach number 1.5. The data typify the type of data, the amount of scatter, and the number of points that were obtained as the model spin rate changed. The data presented hereafter in this report show a computer fairing through the data.
points (a third-degree, least-squares curve fit) instead of a symbol for each data point. The complete $C_Y$ and $C_n$ versus $pd/2V_\infty$ results are presented in Figs. 9 through 18. Generally, the results indicate that both $C_Y$ and $C_n$ are nonlinear with $pd/2V_\infty$ at the higher angles of attack ($\alpha > 4$ deg) and higher spin rates ($pd/2V_\infty > 0.15$). In addition, the usual negative $C_Y$ and positive $C_n$ for positive values of $pd/2V_\infty$ and $\alpha$ were obtained for all configurations.

To examine the effects of angle of attack, the linear portion of the data (slopes of $C_Y$ and $C_n$ versus $pd/2V_\infty$ for $pd/2V_\infty < 0.1$) will be used. Figure 19 presents the variations of $C_{Yp}$ and $C_{np}$ with angle of attack. The results show that the magnitudes of both $C_{Yp}$ and $C_{np}$ generally increase continuously with angle of attack. The only exception to this was Configuration 7 at Mach number 1.5 and $\alpha \approx 6$ deg, where $C_{np}$ showed a considerable decrease. In addition, the magnitude of both parameters decreased with increasing Mach number.

The effects of Reynolds number on $C_{Yp}$ and $C_{np}$ for Configuration 3 at Mach number 2.0 are presented in Fig. 20. The results show that for Reynolds numbers of $4.0 \times 10^6/ft$ and $7.3 \times 10^6/ft$ there was little difference in the parameters. However, for the low Reynolds number ($1 \times 10^6/ft$) the magnitude of both parameters increased. This is probably the result of the laminar boundary layer in the boattail region at the low Reynolds number. For the other test conditions the boundary layer was turbulent.

The variations of $C_{YP\alpha}$ and $C_{np\alpha}$ with Mach number are presented in Fig. 21. Generally, the magnitude of each parameter is either nearly constant or decreases with increasing Mach number. Increasing the boattail angle and maintaining a constant boattail length (Fig. 21a) increased the magnitude of $C_{YP\alpha}$ and $C_{np\alpha}$ except at $M_\infty = 2.5$ where $C_{np\alpha}$ was not appreciably affected. Increasing the boattail length and maintaining a constant angle (Fig. 21b) produced magnitude increases in both $C_{YP\alpha}$ and $C_{np\alpha}$. At $M_\infty = 1.5$ the largest increase in magnitude was produced by increasing the boattail length from 0.5 calibers to 1.0 caliber, while at $M_\infty = 2.0$ and 2.5 the largest increase occurred as the length increased from 1.0 caliber to 1.35 calibers. The effects of increasing the boattail length and maintaining a constant base diameter are shown in Fig. 21c. Generally, the magnitude of $C_{YP\alpha}$ and $C_{np\alpha}$ increased as the boattail length increased.
5.0 CONCLUDING REMARKS

An experimental investigation was conducted to determine the effects of boattail geometry changes on the Magnus-force and moment characteristics of ballistic shells at supersonic Mach numbers. The tests were conducted at Mach numbers 1.5, 2.0, and 2.5 for an angle-of-attack range from -2 to 8 deg. Results obtained at spin parameter \((pd/2V_\infty)\) values up to 0.270 are summarized as follows:

1. All configurations were statically unstable.
2. \(C_{N_\alpha}\) increased and \(C_{m_\alpha}\) decreased with increasing Mach number.
3. Increasing the boattail length or angle decreased \(C_{N_\alpha}\) and increased \(C_{m_\alpha}\).
4. Both \(C_y\) and \(C_n\) were nonlinear with \(pd/2V_\infty\) at the higher angles of attack \((\alpha > 4\ \text{deg})\) and higher spin rates \((pd/2V_\infty > 0.15)\).
5. \(C_y\) was negative and \(C_n\) was positive for positive values of \(pd/2V_\infty\) and \(\alpha\).
6. Generally, the magnitude of \(C_{y_p}\) and \(C_{n_p}\) increased with \(\alpha\) and were linear up to about 2.5 deg.
7. Decreasing the Reynolds number from \(4 \times 10^6/\text{ft}\) to \(1 \times 10^6/\text{ft}\) increased the magnitude of \(C_{y_p}\) and \(C_{n_p}\).
8. Increasing the boattail length or angle generally increased the magnitude of \(C_{y_p\alpha}\) and \(C_{n_p\alpha}\).

REFERENCES

a. Tunnel A installation (configuration 3)

Figure 1. Model photographs.
b. Boattail configurations
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b. Concluded

Figure 1. Concluded.
Figure 2. Model details.
Figure 3. Magnus-force test mechanism.
Figure 4. Balance details.
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a. Configuration 0
b. Configuration 1
Figure 5. Continued.
c. Configuration 2
Figure 5. Continued.
d. Configuration 3
Figure 5. Continued.
Figure 5. Continued.

e. Configuration 4
f. Configuration 5
Figure 5. Continued.
g. Configuration 6

Figure 5. Continued.
h. Configuration 7
Figure 5. Continued.
i. Configuration 8
Figure 5. Continued.
j. Configuration 9
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Figure 7. Continued.
c. Effect of boattail length with a constant base diameter

Figure 7. Concluded.
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a. $M_\infty = 1.5$
b. \( M_\infty = 2.0 \)

Figure 9. Continued.
Figure 9. Concluded.

\( c. \ M_\infty = 2.5 \)

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Figure 10. Variation of $C_Y$ and $C_n$ with $pd/2V_\infty$ for configuration 1, $Re_\infty = 9.6 \times 10^6$.

a. $M_\infty = 1.5$
Figure 10. Continued.

b. $M_\infty = 2.0$

Figure 10.
c. $M_\infty = 2.5$

Figure 10. Concluded.
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a. $M_\infty = 1.5$
Figure 11. Continued.

b. $M_\infty = 2.0$
c. \( M_\infty = 2.5 \)

Figure 11. Concluded.
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a. $M_\infty = 1.5$
Figure 12. Continued.

b. $M_\infty = 2.0$

Figure 12. Continued.
c. $M_\infty = 2.5$

Figure 12. Concluded.
Figure 13. Variation of $C_Y$ and $C_n$ with $pd/2V_\infty$ for configuration 4, $Re_\infty = 9.6 \times 10^6$. 

a. $M_\infty = 1.5$
Figure 13. Continued.

b. $M_\infty = 2.0$

Figure 13. Continued.
Figure 13. Concluded.

c. $M_\infty = 2.5$

Figure 13. Concluded.
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a. $M_\infty = 1.5$
b. $M_a = 2.0$

Figure 14. Continued.
Figure 14. Concluded.

c. $M = 2.5$

Figure 14. Concluded.
Figure 15. Variation of $C_Y$ and $C_n$ with $pd/2V_{\infty}$ for configuration 6, $Re_g = 9.6 \times 10^6$. 

a. $M_\infty = 1.5$
Figure 15. Continued.

b. $M_\infty = 2.0$

SYM $\alpha$, deg

- $-2.17$
- $-0.03$
- $1.07$
- $2.10$
- $4.28$
- $6.43$
- $8.55$

$C_n$ vs $pd/2V_\infty$
c. $M_\infty = 2.5$

Figure 15. Concluded.
Figure 16. Variation of $C_Y$ and $C_n$ with $pd/2V_\infty$ for configuration 7, $Re_l = 9.6 \times 10^6$.

a. $M_\infty = 1.5$
Figure 16. Continued.

b. \( M_\infty = 2.0 \)

Figure 16. Continued.
Figure 16. Concluded.

c. $M_a = 2.5$

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Figure 17. Variation of $C_Y$ and $C_n$ with $pd/2V_\infty$ for configuration 8, $Re_y = 9.6 \times 10^6$. 

a. $M_\infty = 1.5$
SYM α, deg

- 2.14
- 0.01
1.05
2.17
4.28
6.48
8.64

b. \( M_\infty = 2.0 \)

Figure 17. Continued.
Figure 17. Concluded.

c. $M_\infty = 2.5$

Figure 17. Concluded.
Figure 18. Variation of $C_Y$ and $C_n$ with $pd/2V_\infty$ for configuration 9, $Re_\infty = 9.6 \times 10^6$. 

a. $M_\infty = 1.5$
b. $M_\infty = 2.0$

Figure 18. Continued.
Figure 18. Concluded.
a. Configuration 0

Figure 19. Variation of $C_{Y_p}$ and $C_{n_p}$ with angle of attack, $Re = 9.6 \times 10^6$. 
b. Configuration 1
Figure 19. Continued.
c. Configuration 2

Figure 19. Continued.
d. Configuration 3
Figure 19. Continued.
e. Configuration 4

Figure 19. Continued.
Figure 19. Continued.

f. Configuration 5
Figure 19. Continued.

Configuration 6

$C_{ay}$, rad$^{-1}$

$C_{az}$, rad$^{-1}$

$\theta$, deg
h. Configuration 7
Figure 19. Continued.
i. Configuration 8
Figure 19. Continued.
j. Configuration 9
Figure 19. Concluded.
Figure 20. Effect of Reynolds number variation on $C_{Y_p}$ and $C_{n_p}$, at $M_\infty = 2$, configuration 3.
<table>
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<tr>
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<td>2</td>
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<td>1.0</td>
<td>0.83</td>
</tr>
<tr>
<td>◇</td>
<td>3</td>
<td>7.5</td>
<td>1.0</td>
<td>0.74</td>
</tr>
</tbody>
</table>

![Diagram of $C_{Y_{p\alpha}}$ and $C_{n_{p\alpha}}$ vs Mach number](image)

- Effect of boattail angle with a constant boattail length

Figure 21. Variation of $C_{Y_{p\alpha}}$ and $C_{n_{p\alpha}}$ with Mach number, $Re_{\infty} = 9.6 \times 10^6$. 

75
b. Effect of boattail length with a constant boattail angle
Figure 21. Continued.
c. Effect of boattail length with a constant base diameter

Figure 21. Concluded.
Table 1. Balance Uncertainty

<table>
<thead>
<tr>
<th>Balance Component</th>
<th>Design Load</th>
<th>Range of Static Loads</th>
<th>Measurement Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal force, lb</td>
<td>500</td>
<td>±150</td>
<td>±0.05</td>
</tr>
<tr>
<td>Pitching moment*, in.-lb</td>
<td>2500</td>
<td>±240</td>
<td>±0.30</td>
</tr>
<tr>
<td>Side force, lb</td>
<td>25</td>
<td>± 14</td>
<td>±0.03</td>
</tr>
<tr>
<td>Yawing moment*, in.-lb</td>
<td>125</td>
<td>± 70</td>
<td>±0.08</td>
</tr>
</tbody>
</table>

*About balance forward moment bridge

Table 2. Test Summary

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Boattail Length ($f_{BT}$), calibers</th>
<th>Boattail Angle ($\theta_{BT}$), deg</th>
<th>Base Diameter ($db$), calibers</th>
<th>$M_\infty$($Re = 4 \times 10^6$/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1,0000</td>
<td>x</td>
</tr>
<tr>
<td>1</td>
<td>1.00</td>
<td>2.5</td>
<td>0.9126</td>
<td>x</td>
</tr>
<tr>
<td>2</td>
<td>1.00</td>
<td>5.0</td>
<td>0.8249</td>
<td>x</td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
<td>7.5</td>
<td>0.7366</td>
<td>x</td>
</tr>
<tr>
<td>4</td>
<td>0.50</td>
<td>5.0</td>
<td>0.9124</td>
<td>x</td>
</tr>
<tr>
<td>5</td>
<td>1.35</td>
<td>5.0</td>
<td>0.7637</td>
<td>x</td>
</tr>
<tr>
<td>6</td>
<td>1.70</td>
<td>5.0</td>
<td>0.7024</td>
<td>x</td>
</tr>
<tr>
<td>7</td>
<td>0.45</td>
<td>18.4</td>
<td>0.7000</td>
<td>x</td>
</tr>
<tr>
<td>8</td>
<td>0.85</td>
<td>10.0</td>
<td>0.7000</td>
<td>x</td>
</tr>
<tr>
<td>9</td>
<td>1.25</td>
<td>6.9</td>
<td>0.7000</td>
<td>x</td>
</tr>
</tbody>
</table>

*Also tested at $Re = 1 \times 10^6$/ft and $7.3 \times 10^6$/ft

Table 3. Wind Tunnel Test Parameters

<table>
<thead>
<tr>
<th>$M_\infty$</th>
<th>$P_o$, psia</th>
<th>$T_o$, °R</th>
<th>$q_m$, psia</th>
<th>$V_m$, ft/sec</th>
<th>$Re \times 10^{-6}$, ft$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50</td>
<td>13.6</td>
<td>560</td>
<td>5.84</td>
<td>1444</td>
<td>3.95</td>
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<tr>
<td>1.99</td>
<td>4.2</td>
<td>564</td>
<td>1.51</td>
<td>1731</td>
<td>1.02</td>
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<tr>
<td>2.00</td>
<td>16.5</td>
<td>560</td>
<td>5.91</td>
<td>1729</td>
<td>4.02</td>
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<tr>
<td>2.01</td>
<td>30.8</td>
<td>567</td>
<td>10.95</td>
<td>1745</td>
<td>7.34</td>
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<tr>
<td>2.50</td>
<td>21.0</td>
<td>560</td>
<td>5.38</td>
<td>1933</td>
<td>4.02</td>
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</tbody>
</table>
Table 4. Wind Tunnel Parameter Precision

<table>
<thead>
<tr>
<th>$M_a$</th>
<th>$M_o$</th>
<th>$P_o$</th>
<th>$T_o$</th>
<th>$q_o$</th>
<th>$V_m$</th>
<th>Re</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>±0.7</td>
<td>±0.50</td>
<td>±0.36</td>
<td>±0.52</td>
<td>±0.51</td>
<td>±0.73</td>
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<tr>
<td>2.0</td>
<td>±0.5</td>
<td>±0.50</td>
<td>±0.36</td>
<td>±0.75</td>
<td>±0.33</td>
<td>±0.83</td>
</tr>
<tr>
<td>2.5</td>
<td>±0.3</td>
<td>±0.50</td>
<td>±0.36</td>
<td>±0.78</td>
<td>±0.23</td>
<td>±0.83</td>
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</table>

Table 5. Coefficient Precision

<table>
<thead>
<tr>
<th>$M_a$</th>
<th>$\alpha$, deg</th>
<th>$C_N$</th>
<th>$C_m$</th>
<th>$C_Y$</th>
<th>$C_n$</th>
<th>$C_{Y, rad^{-1}}$</th>
<th>$C_{n, rad^{-1}}$</th>
<th>$pd/2V_m$*</th>
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</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0</td>
<td>±0.00036</td>
<td>±0.00040</td>
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<td>±0.00011</td>
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<td>±0.51</td>
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<tr>
<td></td>
<td>2</td>
<td>±0.00052</td>
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<td>±0.00022</td>
<td>±0.00012</td>
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<td>±0.0007</td>
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<tr>
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<td>±0.00085</td>
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<td>±0.00014</td>
<td>±0.0017</td>
<td>±0.0010</td>
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<tr>
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<td>8</td>
<td>±0.00230</td>
<td>±0.00340</td>
<td>±0.00037</td>
<td>±0.00030</td>
<td>±0.0022</td>
<td>±0.0018</td>
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<tr>
<td>2.0</td>
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<td>±0.00036</td>
<td>±0.00039</td>
<td>±0.00021</td>
<td>±0.00010</td>
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<td>---</td>
<td>±0.33</td>
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<tr>
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</tr>
<tr>
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<td>±0.00225</td>
<td>±0.00024</td>
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<td>±0.0020</td>
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<td>±0.00033</td>
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<td>±0.0022</td>
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<td>±0.00380</td>
<td>±0.00034</td>
<td>±0.00026</td>
<td>±0.0022</td>
<td>±0.0017</td>
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</table>

Table 6. Derivative Coefficient Precision

<table>
<thead>
<tr>
<th>$M_a$</th>
<th>$C_{N, \alpha}$, deg$^{-1}$</th>
<th>$C_{m, \alpha}$, deg$^{-1}$</th>
<th>$C_{Y, p\alpha}$, rad$^{-2}$</th>
<th>$C_{n, p\alpha}$, rad$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>±0.00061</td>
<td>±0.00140</td>
<td>±0.034</td>
<td>±0.030</td>
</tr>
<tr>
<td>2.0</td>
<td>±0.00073</td>
<td>±0.00133</td>
<td>±0.036</td>
<td>±0.031</td>
</tr>
<tr>
<td>2.5</td>
<td>±0.00080</td>
<td>±0.00122</td>
<td>±0.049</td>
<td>±0.036</td>
</tr>
</tbody>
</table>
**NOMENCLATURE**

A  
Reference area, model maximum cross-sectional area, 23.715 in.$^2$

$C_m$  
Pitching-moment coefficient, pitching moment/$q_\alpha Ad$

$C_m\alpha$  
Pitching-moment coefficient derivative at $\alpha = 0$, $\partial C_m / \partial \alpha$, per deg

$C_N$  
Normal-force coefficient, normal force/$q_\alpha A$

$C_N\alpha$  
Normal-force coefficient derivative at $\alpha = 0$, $\partial C_N / \partial \alpha$, per deg

$C_n$  
Yawing (Magnus)-moment coefficient, yawing moment/$q_\alpha Ad$  
(see Fig. 2)

$C_{np}$  
Magnus-moment spin derivative coefficient for $(pd/2V_\alpha) < 0.1$, $\partial C_n / \partial (pd/2V_\alpha)$, per radian

$C_{np\alpha}$  
Magnus-moment coefficient derivative at $\alpha = 0$, $\partial^2 C_n / \partial (pd/2V_\alpha) \partial \alpha$, per radian$^2$

$C_Y$  
Side (Magnus)-force coefficient, side force/$q_\alpha A$  
(see Fig. 2)

$C_Yp$  
Magnus-force spin derivative coefficient for $(pd/2V_\alpha) < 0.1$, $\partial C_Y / \partial (pd/2V_\alpha)$, per radian

$C_Yp\alpha$  
Magnus-force coefficient derivative at $\alpha = 0$, $\partial^2 C_Y / \partial (pd/2V_\alpha) \partial \alpha$, per radian$^2$

d  
Reference diameter, model maximum diameter, 5.495 in.

$d_B$  
Base diameter, calibers (note: one caliber = 5.495 in.)

$l$  
Model length, 28.662 in.

$l_{BT}$  
Boattail length, calibers (note: one caliber = 5.495 in.)

$l_c$  
Length of cylindrical section, calibers  
(note: one caliber = 5.495 in.)

$M_\infty$  
Free-stream Mach number

$p$  
Model spin rate (positive, clockwise viewing from the base), radians/sec

$P_0$  
Tunnel stilling chamber pressure, psia
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pd/2V_\infty$</td>
<td>Spin parameter, radians</td>
</tr>
<tr>
<td>$q_\infty$</td>
<td>Free-stream dynamic pressure, psia</td>
</tr>
<tr>
<td>$Re$</td>
<td>Free-stream unit Reynolds number, ft$^{-1}$</td>
</tr>
<tr>
<td>$Re_f$</td>
<td>Free-stream Reynolds number based on model length</td>
</tr>
<tr>
<td>$T_0$</td>
<td>Tunnel stilling chamber temperature, °R</td>
</tr>
<tr>
<td>$V_\infty$</td>
<td>Free-stream velocity, ft/sec</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Angle of attack, deg</td>
</tr>
<tr>
<td>$\delta_{BT}$</td>
<td>Boattail angle, deg</td>
</tr>
</tbody>
</table>