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AEROBALLISTIC ANALYSIS OF ERB/TIGER II
AERODYNAMIC TEST UNIT ATU-2
(SLA R715032)

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ABSTRACT

The results of the first drop test of the 13.3-in-diameter ERB/TIGER II are documented. The test unit, designated Aerodynamic Test Unit-2 (ATU-2), was dropped on August 25, 1977, at the Sandia National Laboratories Tonopah Test Range from an Air Force F-4 Aircraft. Nominal release conditions were an altitude of 20,000 ft mean sea level and Mach 0.8. The purpose of the test was to obtain free-flight vehicle characteristics including the effect of the free-floating rollers, to evaluate release and separation characteristics of the 13.3-in-diameter vehicle, and to evaluate the performance of the recovery system. Modifications to the mathematical model for the vehicle that yield better agreement between simulation and flight test results are presented. The system is also described.

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NOMENCLATURE

a	Vector of parameters
C_l	Rolling moment coefficient, $L/\bar{q}sd$
C_{l_δ}	$\partial C_l / \partial \delta$; Rolleron roll moment effectiveness,
C_{l_p}	$\partial C_l / \partial (pd/2V)$ Roll damping due to roll rate,
C_{l_q}	$\partial C_l / \partial (qd/2V)$ Roll damping due to pitch rate,
C_{l_r}	$\partial C_l / \partial (rd/2V)$ Roll damping due to yaw rate,
C_m	Pitching moment coefficient, $M/\bar{q}sd$
C_{m_δ}	$\partial C_m / \partial \delta$; Rolleron pitching moment effectiveness,
C_{m_q}	$\partial C_m / \partial (qd/2V)$ Pitch damping due to pitch rate,
C_n	Yawing moment coefficient, $N/\bar{q}sd$
C_{n_δ}	$\partial C_n / \partial \delta$; Rolleron yawing moment effectiveness,
C_x	X-axis force coefficient, $F_x/\bar{q}s$
C_y	Y-axis force coefficient, $F_y/\bar{q}s$
C_{y_δ}	$\partial C_y / \partial \delta$; Rolleron force effectiveness,
C_{y_r}	$\partial C_y / \partial (rd/2V)$
C_z	Z-axis force coefficient, $F_z/\bar{q}s$
C_{z_δ}	$\partial C_z / \partial \delta$; Rolleron force effectiveness,

NOMENCLATURE (cont)

C_{z_q}	$\partial C_z / \partial (qd/2V)$
C_{n_r}	$\partial C_n / \partial (rd/2V)$ Yaw damping due to yaw rate,
d	Reference length, body diameter (ft)
F_x, F_y, F_z	Aerodynamic forces in X,Y,Z body axes (lb)
G	Least-squares performance index
h	Vector of point constraints
K_a, K_h	Scalar weighting constants
L,M,N	Aerodynamic moments in X,Y,Z body axes (lb-ft)
l	Dimension of vector of point constraints
M_n	Mach number
m	Dimension of measurement vector
p,q,r	Body angular rates in X,Y,Z body axes (rad/s)
p'	Dimension of parameter vector
q'	Dimension of control vector
$\bar{q}$	Dynamic pressure $1/2 \rho V^2$
S	Reference area, $\pi d^2/4$ (ft ²)
t	Time (s)

NOMENCLATURE (cont)

u	Control vector
V	Total airspeed (ft/s)
W_a, W_h, W_I	Weighting matrices
x	State vector
y	Simulated measurement vector
z	Actual measurement vector
X, Y, Z	Body axes
α	Pitch-plane angle-of-attack (rad)
β	Yaw-plane angle-of-attack (rad)
δ_i	Deflection of i-th rolleron ($i = 1, 2, 3, 4$) (rad)
δ_y	Pitch canard deflection (rad)
δ_z	Yaw canard deflection (rad)
η	Measurement noise
θ_E	Euler pitch angle (rad)
θ_{MARS}	MARS platform pitch gimbal angle (rad)
ξ	Total angle-of-attack (rad)
ρ	Atmospheric density (slug/ft ³)
ϕ_A	Aerodynamic roll angle (rad)
ϕ_E	Euler roll angle (rad)
ϕ_{MARS}	MARS platform roll angle (rad)
ψ_E	Euler yaw angle (rad)
ψ_{MARS}	MARS platform yaw angle (rad)

AEROBALLISTIC ANALYSIS OF ERB/TIGER II
AERODYNAMIC TEST UNIT ATU-2 (SLA R715032)

Introduction

The Tactical Inertially-Guided Extended Range Bomb (TIGER) program, also referred to as Extended Range Bomb (ERB) and Return-To-Target Bomb (RTTB), is an exploratory development program designed to demonstrate the feasibility of improving the performance and deliverability of an existing bomb by the addition of an inertial guidance and control module and a solid propellant rocket motor for added range and maneuverability.

The program has been structured around two similar vehicles that differ primarily in body diameter. The first three flight tests (aerodynamic test unit 1 (ATU-1)¹⁻³ and flight test units 1 and 2 (FTU-1, FTU-24) were conducted with the 16.5-in. vehicle. This report documents the first flight test of the 13.3-in-diameter aerodynamic test unit (ATU-2).

The return-to-target flight of FTU-2 exhibited substantial rolling and pitching motion;⁵ it was suggested⁶ that this was due to the variation with aerodynamic roll angle of the aerodynamic characteristics upon which the autopilot had been designed and to the destabilizing effects of floating rollerons. Consequently, the first flight of the 13.3-in. TIGER II vehicle (ATU-2) was designed to assess the effect of rollerons and the validity of the wind tunnel aerodynamic data. Vehicle control was performed open loop (without autopilot stabilization) by step canard deflections selected to yield first a positive angle-of-attack, α , and angle-of-sideslip, β , followed by a negative α and β . Rollerons in the x-z body plane were fixed at zero deflection while those in the x-y plane were free to move. It was anticipated that differences in pitch and yaw stability caused by the rollerons would be shown by differing trim angles in the two planes.

The data obtained from ATU-2 were analyzed to develop modifications to the vehicle mathematical model to more accurately reproduce the actual vehicle flight characteristics. The results of these analyses form the major portion of this report. The remainder of the report is composed of system description.

ATU-2 Test Objectives

This test was the first drop test of the 13.3-in-diameter TIGER II vehicle. The objectives of the test were to

- Obtain free-flight aerodynamic characteristics including the effect of free-floating rollerons.
- Evaluate release and separation characteristics of the 13.3-in-diameter vehicle.
- Evaluate the performance of the recovery system.

Description of Test Unit (ATU-2)

Aerodynamic Design

The TIGER II external shape (Figure 1) consists of a sphere-cone nose section equipped with two pairs of canards for pitch and yaw control, a cylindrical center section, and a truncated-ogive afterbody equipped with four tail surfaces. The tail surfaces or fins were designed to be stowed during carriage and to be deployed after release, but were fixed in their open position for the flight test. A partial list of TIGER physical characteristics⁷ is given below. A discussion of the ERB/TIGER II design is contained in Reference 8.

Vehicle length	157.3 in.
Reference diameter	13.3 in.
Weight	847.8 lb
Center of mass	70.37 in.

Pitch moment of inertia	297.97 slug-ft ²
Yaw moment of inertia	297.97 slug-ft ²
Roll moment of inertia	5.2881 slug-ft ²

NOTE: LUGS AND UMBILICAL ARE ROTATED 45° ABOUT LONGITUDINAL AXIS FOR CLARITY

Figure 1. TIGER II Outboard Profile

The TIGER II digital control system computes inertial acceleration commands and then resolves these into the canard axes for implementation. Control system computation rate and actuator requirements are directly related to the maximum roll rate to be encountered during flight. Therefore, it was necessary to maintain the roll rate at a level compatible with the nominal control system capabilities.

Cruciform vehicles, especially those that are canard-controlled, exhibit particularly nonlinear roll behavior which is caused by the variability of the flow over the aft surfaces due to body attitude and forward surface deflections. The complexity of the roll moment induced by attitude and control deflection precluded a roll control system based on

differential canard deflections. Therefore, rollerons⁹ of the type used on the AIM-9 Sidewinder air-to-air missile series were selected to maintain acceptable roll rates by providing additional roll damping while avoiding the additional complexity of controllable roll control surfaces and associated actuators.

The rollerons (Figure 2) are small, movable aerodynamic surfaces mounted at the tips of the tail fins. A vaned wheel is partially enclosed within the rolleron in such a way that the relative wind will cause it to spin with its spin axis perpendicular to the rolleron surface. Vehicle roll rate causes precessional torque to be developed about the rolleron hinge line, and the resultant rolleron deflection relative to the tail fin is in the direction to provide an aerodynamic moment to resist roll rate. Added pitch and yaw damping are also obtained because the swept-back hinge line allows pitch and yaw rate components to generate additional precessional torques.

Figure 2. Rolleron Description

Trajectory Analysis

General Description

The ATU-2 trajectory was determined from film records obtained from four Contraves cinetheodolite tracking stations.¹⁰

The vehicle was allowed to fall for 8 s after release before the programmed canard deflection sequence was started. Approximately 20 s of data were obtained during the canard sequence; payload separation occurred 30 s after release. Flight test data are presented in the appendix.

Meteorological Data

Atmospheric data were obtained by means of a radiosonde balloon that was released in the general test area at 1703 hr PDT. The measured atmospheric density (Figure A-1), speed-of-sound (Figure A-2), and winds (Figure A-3 and A-4) were used¹⁰ to compute dynamic pressure and Mach number from Contraves cinetheodolite estimates of altitude and velocity. The atmospheric wind data have been rotated so that the x-component coincides with the flight path heading at launch and y is positive to the right. The atmospheric density and speed-of-sound for the standard atmospheric model that was used in the TIGER II systems development simulations are shown in Figures A-5 and A-6 for comparison.

Trajectory Data

The optically reduced trajectory data¹⁰ are presented in Figures A-7 through A-10. The dynamic pressure, velocity, and Mach number include the effects of speed-of-sound, density, and wind variation with altitude as measured via the radiosonde balloon. These data were used in combination with the telemetry flight test data¹¹ to perform the aerodynamic analyses contained in this report.

Rolleron Behavior

The determination of the effect of rollerons upon the overall aerodynamic stability of the vehicle was one of the objectives of this test. The initial wind tunnel tests^{12,13} were performed with a model

precluded direct evaluation of the effects of rolleron deflection upon vehicle aerodynamics. Furthermore, examination of rolleron hinge moment characteristics from AIM-9 Sidewinder missile aerodynamics⁹ indicated that in the absence of body angular rates the rollerons would trim at deflections approximately one-half the vehicle angle-of-attack. For example, an AIM-9 angle-of-attack of 10° (nose up) would cause the horizontal axis rollerons to trim trailing-edge up at $\sim 5^\circ$. This would produce a decrease in nose down pitching moment and a corresponding decrease in static stability. Estimates of this reduction in stability were initially obtained during the consideration of the 16.5-in. vehicle by removing the rolleron surface area from the tail and performing tests¹⁴ in the SLA Trisonic Wind Tunnel (TWT). Additional wind tunnel tests¹⁵ were also run in the CALSPAN transonic facility for the 13.3-in. vehicle in which the simulated rolleron surfaces were allowed to float freely about their hinge lines. The simulated rollerons were fabricated to approximate the actual surfaces in area and did not contain movable wheels; no gyroscopic effects were measured. During this test the rollerons were observed to float to significantly higher angles than had been suggested by the AIM-9 hinge moment data.

The higher rolleron trim angles are caused by the placement of the rollerons so that the hinge line is nearer the tail leading edge (Figure 3) for the ERB/TIGER II than for the AIM-9.⁹ In fact, the rolleron forms the leading edge of the tail fin tip. The increased suction near the leading edge of the swept tail surface causes a larger hinge moment and increases the floating tendency. Analysis of the CALSPAN data (digital and film) revealed that the rollerons floated to approximately three times the test angle-of-attack.¹⁶

Since the nominal return-to-target maneuver requires approximately a 10° angle-of-attack, the canard deflections were programmed for this flight to produce accelerations and angles-of-attack of 2 g and 10° , respectively. Therefore, large rolleron deflection angles were expected to occur.

Release and Recovery

The vehicle was released from an F-4 aircraft, and the separation was accomplished as expected. The recovery system performed as expected, and the vehicle forebody was recovered successfully.

Figure 3. TIGER II Rolleron/Tail Fin Assembly

Flight Dynamic Analysis

Flight Data

The test unit was equipped with a telemetry system which provided sufficient information² to describe the vehicle motion. The observed quantities¹¹ that were used in this analysis, along with accompanying accuracy estimates and variable ranges, are shown in Table 1. A more complete list of available telemetered quantities is included in Reference 17.

The measured canard positions are shown in Figures A-11 and A-12. The canard deflection sign convention is presented in Figure 4. These histories were pieced together by using the coarse measurements for the first 8 s and fine measurements for the remainder of the flight in order to realize the best data resolution. The "weathervaning" or floating of the canards during the first 8 s is apparent. The first 28 s of data were used in this analysis.

Axial and lateral accelerations (a_x, a_y , and a_z) are presented in Figures A-13, A-14, and A-15, respectively. The lateral accelerations were adjusted during data reduction to produce an average of 0.707 g in each axis for ~5 s before release to reduce the effects of temperature-induced bias shifts.¹⁸

Vehicle angular rates, p, q, and r, are shown in Figures A-16, A-17, and A-18, respectively. The yaw rate exhibits a slightly higher frequency than the pitch rate during the first 8 s. If all of this difference is due to the free rollerons, the ratio of static margins is given by

$$\frac{C_m a_{\text{free}}}{C_m a_{\text{fixed}}} \approx \left(\frac{8/8}{9/7.5} \right)^2 = 0.69 .$$

This agrees well with the wind tunnel results obtained with rollerons removed.¹⁴

Vehicle attitude angles, (yaw, Ψ ; pitch, θ) and roll, ϕ , are presented in figures A-19, A-20, and A-21, respectively. These angles were measured by using a Minature Attitude Reference System (MARS) platform. This roll-stabilized platform was uncaged at release, and the angles measured are therefore referenced to this orientation. Since the vehicle is carried in the x-configuration, this coincides with a 45° roll angle. Simulations performed to compare trajectory predictions were begun with $\phi = 45^\circ$. Comparisons were performed by subtracting 45° from the simulation roll angle.

Table 1

ATU-2 Onboard Instrumentation for Vehicle Dynamics

<u>Measurement</u>	<u>Samples/s</u>	<u>Accuracy</u>	<u>Range</u>
MARS roll	cont	2°	360°
MARS pitch	cont	10°	360°
MARS yaw	cont	1°	<u>+86°</u>
Roll rate			
(coarse)	20	16°/s	<u>+400°/s</u>
(fine)	cont	8°/s	<u>+200°/s</u>
Pitch rate			
(coarse)	20	8°/s	<u>+200°/s</u>
(fine)	cont	4°/s	<u>+100°/s</u>
Yaw rate			
(coarse)	20	8°/s	<u>+200°/s</u>
(fine)	cont	4°/s	<u>+100°/s</u>
Axial acceleration (x-axis)	40	0.4 g	<u>+5g</u>
Lateral acceleration (y-axis)	40	0.4 g	<u>+5g</u>
Lateral acceleration (z-axis)	40	0.4 g	<u>+5g</u>
Y-canard position			
(coarse)	20	0.5°	<u>+15°</u>
(fine)	20	0.1°	<u>+5°</u>
Z-canard position			
(coarse)	20	0.5°	<u>+15°</u>
(fine)	20	0.1°	<u>+ 5°</u>
Rolleron position 2			
(coarse)	20	0.6°	<u>+30°</u>
(fine)	20	0.4°	<u>+10°</u>
Rolleron position 4			
(coarse)	20	0.6°	<u>+30°</u>
(fine)	20	0.4°	<u>+10°</u>

Figure 4. Canard Deflection Sign Convention

Rolleron deflection time histories are shown in Figures A-22 and A-23. The rolleron deflections tend to follow the z -acceleration (Figure A-15), as expected, because of the dependence of acceleration on angle-of-attack. The positive sign convention (Figure 5) for rollerons 2 and 4 is trailing edge down and up, respectively. The amount of differential deflection is obtained by adding the two deflections and during the two periods of nearly constant deflection is approximately

1°	$10 < t < 18 \text{ s}$
5°	$22 < t < 30 \text{ s}.$

This behavior was not expected because comparison of the roll rate direction and magnitude during these time periods reveals that¹⁹

- The differential deflection during the first period is neither significant nor sufficient to reduce the roll rate
- During the second period the deflection is in the wrong direction and is apparently in response to a smaller roll rate than in the first period.

Figure 5. Rolleron Deflection Sign Convention

Subsequent analysis²⁰ of rolleron behavior on ATU-2, FTU-3, and FTU-4 flight tests revealed that this unexpected motion can be attributed to the rollerons' tendency to respond strongly to local angle-of-attack. The local angle-of-attack is a complex function of body angle-of-attack, aerodynamic roll angle, and canard position; it can vary significantly for opposing elements of a rolleron pair. Therefore, for this flight the rollerons were responding more to local angle-of-attack than to roll rate.

Estimation of Model Parameters

A six-degree-of-freedom model for the TIGER II vehicle was parameterized in terms of initial vehicle state conditions, aerodynamic coefficients, inertial properties, center-of-mass location, and measurement biases and scale factors. Combinations of these parameters were estimated by using a nonlinear weighted-least-squares method based on the Square Root Variable Metric (SRVM) function minimization algorithm developed by Williamson.²¹ The parameter vector was chosen to minimize the cost function composed of the weighted sum of the squares of the residuals that existed between observed and simulated measurements. The cost function also included quadratic forms composed of point constraints and of deviations of the parameters from nominal values. The degree of agreement in a particular measurement was adjusted by modifying the weighting factor associated with that component of the cost function. Nominal weighting factors were chosen based on the accuracy estimates listed in the TM data list¹⁷ (Table 1). The mathematical formulation of the cost function, G , is given below.

$$G = \left(\frac{1}{t_f - t_o} \right) \int_{t_o}^{t_f} \left\{ \left[z(t) - y(t) \right]^T W_I \left[z(t) - y(t) \right] \right\} dt$$
$$+ K_a (a - a_o)^T W_a (a - a_o) + K_h (h - h_c)^T W_h (h - h_c).$$

<u>Description</u>	<u>Dimension</u>
$\dot{x}(t) = f(x, u, a, t)$	n - dimensional state vector
$y(t) = g(x, u, t)$	m - dimensional vector of simulated observation
$z(t) = y(t) + \eta(t)$	m - dimensional observation vector
$h = h(x, u, a, t)$	l - dimensional vector of point constraints
a	p - dimensional vector of parameters to be estimated

η	m - dimensional vector of measurement noise
u	q - dimensional control vector
W_a	p x p - diagonal matrix of weighting coefficients
W_I	m x m - diagonal matrix of weighting coefficients
W_h	l x l - diagonal matrix of weighting coefficients
K_a, K_h	scalar constants

Aerodynamic Model

The nominal aerodynamic model for the systems development simulation of the TIGER II vehicle was based on wind tunnel data that had been obtained with fixed rollerons.¹²⁻¹³ These data were placed in tabular form and interpolated as a function of total angle-of-attack, ξ ; aerodynamic roll angle, ϕ_A ; Mach number, M_n ; and canard deflections, δ_y and δ_z .

The aerodynamic force and moment models (Figure 6) for the parameter estimation were based on this tabular model with additional coefficients added to account for the effects of the rollerons and dynamic coupling. The relationships expressing these models are given below:

$$C_x = C_{x_{Table}}(\xi, M_n, \phi_A, \delta_y, \delta_z) + C_{x_{Bias}}$$

$$C_y = C_{y_{Table}}(\xi, M_n, \phi_A, \delta_y, \delta_z) + C_{y_{Bias}} + C_{y_{\delta}}(\delta_1 - \delta_3) + C_{y_r} \frac{rd}{2V}$$

$$C_z = C_{z_{Table}}(\xi, M_n, \phi_A, \delta_y, \delta_z) + C_{z_{Bias}} + C_{z_{\delta}}(\delta_4 - \delta_2) + C_{z_q} \frac{qd}{2V}$$

$$C_{\ell} = C_{\ell_{Table}}(\xi, M_n, \phi_A, \delta_y, \delta_z) + C_{\ell_{Bias}} + C_{\ell_{\delta}}(\delta_1 + \delta_2 + \delta_3 + \delta_4)$$

$$+ C_{\ell_p} \frac{pd}{2V} + C_{\ell_q} \frac{qd}{2V} + C_{\ell_r} \frac{rd}{2V}$$

$$C_m = C_{m_{Table}}(\xi, M_n, \phi_A, \delta_y, \delta_z) + C_{m_{Bias}} + C_{m_q} \frac{qd}{2V} + C_{m_{\delta}}(\delta_4 - \delta_2)$$

$$C_n = C_{n_{Table}}(\xi, M_n, \phi_A, \delta_y, \delta_z) + C_{n_{Bias}} + C_{n_r} \frac{rd}{2V} + C_{n_{\delta}}(\delta_3 - \delta_1)$$

A characteristic of data fitting techniques is that they compensate for unmodeled behavior by adjusting the available parameters. Therefore, errors in the basic aerodynamic model will affect the estimates of the effects of the rollersons. Thus, care must be exercised in using estimates for parameters when the basic trajectory is significantly different (e.g., higher Mach number, different angle-of-attack range, etc).

Simulation of Flight Measurements

The accelerations were measured by accelerometers that were not located at the vehicle center-of-mass. Therefore, the simulated accelerations of the center-of-mass were corrected for position to generate simulated accelerometer measurements by using the following:

$$\bar{a}_p = \bar{a}_{cm} + \bar{\omega} \times (\bar{\omega} \times \bar{r}_{p/cm}) + \dot{\bar{\omega}} \times \bar{r}_{p/cm},$$

or in scalar form

$$a_{p_x} = a_{cm_x} - \Delta x(q^2 + r^2) + \Delta y(p\dot{q} - \dot{r}) + \Delta z(pr + \dot{q})$$

$$a_{p_y} = a_{cm_y} + \Delta x(p\dot{q} + \dot{r}) - \Delta y(p^2 + r^2) + \Delta z(qr - \dot{p})$$

$$a_{p_z} = a_{cm_z} + \Delta x(pr - \dot{q}) + \Delta y(qr + \dot{p}) - \Delta z(p^2 + q^2)$$

where

$$\Delta x = x_p - x_{cm}$$

$$\Delta y = y_p - y_{cm}$$

$$\Delta z = z_p - z_{cm}$$

In addition, the MARS platform gimbal arrangement does not allow direct measurement of both yaw and pitch Euler angles. For the platform orientation used on ATU-2 the relationships between MARS angles and body Euler angles are as follows:²²

$$\psi_{MARS} = \psi_E$$

$$\Theta_{MARS} = \tan^{-1} (\tan(\Theta_E) / \cos(\psi_E))$$

$$\Phi_{MARS} = \Phi_E$$

where the Euler rotation sequence is (yaw, ψ_E ; pitch, Θ_E ; roll, Φ_E).

Figure 6. Force and Moment Sign Convention

Velocity and dynamic pressure measurements were simulated by adding in the effect of wind and atmospheric density variations in the same way as in Reference 10.

Parameter Estimation Results

When preflight simulation results were compared with flight test data, 19 significant differences were observed between the predicted and observed motions. Lateral center-of-mass offset was demonstrated to be a possible source for the difference in roll-rate behavior.

The vehicle model was parameterized to attempt to quantify the effects of inaccurately known vehicle characteristics upon the observed

differences in motion. The results of estimating various vehicle parameters during the period 9 to 26 s after release are presented in this section. The simulated data obtained by using the parameter estimates are compared with the flight data in Figures 7 through 16. During this time segment, the angle-of-attack and angle-of-sideslip are predicted to go through two periods of near constant value (Figures 17 and 18). The aerodynamic roll angle changes from 45° to -135° (Figure 19). The difficulty encountered in consistently predicting rolleron position required using measured rather than simulated rolleron deflection as "control" input. In the initial stages of parameter convergence, measured roll rate was also used as input instead of the computed value to improve the stability of the process. Good agreement between measured and simulated data is achieved. The parameters and their values that were estimated are given in Table 2.

Estimates of the effects of rollerons were also available¹⁶ from wind tunnel data and are included in Table 2. The estimates from the flight test indicate that the rollerons were less effective in roll than was indicated by the wind tunnel data. However, since only two rollerons were free to move on ATU-2 any loss of effectiveness caused by wake interference would cause a large percentage error in total rolling moment that could have been partially hidden if all four rollerons were active as in the wind tunnel test. The wind tunnel estimates of $C_{z\delta}$ and $C_{m\delta}$ were derived from rolling moment and are not direct measurements.

Figure 7. Comparison of Measured and Simulated Altitude Histories

Figure 8. Comparison of Measured and Simulated X-Axis Acceleration Histories

Figure 9. Comparison of Measured and Simulated Y-Axis Acceleration Histories

Figure 10. Comparison of Measured and Simulated Z-Axis Acceleration Histories

Figure 11. Comparison of Measured and Simulated Body Roll Rate Histories

Figure 12. Comparison of Measured and Simulated Body Pitch Rate Histories

Figure 13. Comparison of Measured and Simulated Body Yaw Rate Histories

Figure 14. Comparison of Measured and Simulated MARS Yaw Angle Histories

Figure 15. Comparison of Measured and Simulated MARS Pitch Angle Histories

Figure 16. Comparison of Measured and Simulated MARS Roll Angle Histories

Figure 17. Angle-of-Attack History Generated by Simulated Trajectory

Figure 18. Angle-of-Sideslip History Generated by Simulated Trajectory

Figure 19. Aerodynamic Roll Angle History Reconstructed From Lateral Acceleration Measurements

Table 2

Comparison of Flight Test and Wind Tunnel Estimates

<u>Parameter</u>	<u>Flight Test Estimates</u>	<u>Wind Tunnel Estimates</u> ¹⁶
Δx_{cm}	0.022367 ft	
Δy_{cm}	-0.00544 ft	
Δz_{cm}	-0.01829 ft	
I_{x_y}	-0.21912 slug-ft ²	
I_{x_z}	0.21651 slug-ft ²	
I_{y_z}	1.4018 slug-ft ²	
$C_{z_q}(-C_{y_r})$	221.4	
C_{l_p}	4.57	
$C_{m_q}(C_{n_r})$	2034.0 (about nose)	
C_{l_δ}	0.0696 rad ⁻¹	0.19 rad ⁻¹
C_{z_δ}	0.2809 rad ⁻¹	0.16 rad ⁻¹
C_{m_δ}	2.8935 rad ⁻¹ (about nose)	1.597 rad ⁻¹

Conclusions

Based on the preceding analysis, the following conclusions were reached.

- The rolleron have a destabilizing effect upon vehicle pitch and yaw stability as evidenced by the differing pitch and yaw frequencies.
- The tabular wind tunnel data are sufficiently accurate to predict behavior for the flight conditions of ATU-2 if rolleron and center-of-mass offset effects are included.
- Rolleron models that ignore the effects of wake interference do not accurately predict rolleron motion.
- Parameter estimates were obtained for dynamic derivatives which improved the agreement between flight and simulation results.
- The small rolleron deflections in response to roll rate (~100 deg/s) indicate the need to reevaluate the rolleron/tail fin configuration to minimize rolleron deflection sensitivity to local angle-of-attack and improve roll damping effectiveness.
- Release and separation characteristics of the vehicle were as expected.
- The recovery system performed as expected.

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APPENDIX

ATU-2 Flight Test Data

Figure A-1 Variation of Atmospheric Density With Altitude (ATU-2)

Figure A-2 Variation of Speed of Sound With Altitude (ATU-2)

Figure A-3 Variation of Downrange Wind Speed
With Altitude (ATU-2)

Figure A-4 Variation of Crossrange Wind Speed With Altitude (ATU-2)

Figure A-5 Variation of Density With Altitude (Standard Atmosphere)

Figure A-6 Variation of Speed of Sound With Altitude (Standard Atmosphere)

Figure A-7 Altitude vs Time From Release

ERB/TIGER II ATU-2 (R715032)

Figure A-8 Velocity vs Time From Release

Figure A-9 Mach Number vs Time From Release

Figure A-10 Dynamic Pressure vs Time From Release

Figure A-11 Pitch Canard Deflection (δ_y) vs Time From Release

Figure A-12 Yaw Canard Deflection (δ_z) vs Time From Release

Figure A-13 Body X-Axis Acceleration vs Time From Release

Figure A-14 Body Y-Axis Acceleration vs Time From Release

Figure A-15 Body Z-Axis Acceleration vs Time From Release

Figure A-16 Body Roll-Rate vs Time From Release

Figure A-17 Body Pitch-Rate vs Time From Release

Figure A-18 Body Yaw-Rate vs Time From Release

Figure A-19 MARS Yaw Angle vs Time From Release

Figure A-20 MARS Pitch Angle vs Time From Release

Figure A-21 MARS Roll Angle vs Time From Release

Figure A-22 Deflection of Roller 2 vs Time From Release

Figure A-23 Deflection of Rolleron 4 vs Time From Release

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