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FREE-FLIGHT WIND TUNNEL TESTS OF TOMAHAWK AND SANDHAWK MISSILE MODELS AT MACH NUMBER 8

A. R. Wallace

ARO, Inc.

February 1969

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NOTICES

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A. R. Wallace
ARO, Inc.

FOREWORD

The work reported herein was done at the request of the Atomic Energy Commission (AEC) for the Sandia Corporation, Albuquerque, New Mexico, under Program Area 921D.

The results of tests presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Contract F40600-69-C-0001. The test was conducted on September 25 and 26, 1968, under ARO Project No. VB1838. The manuscript was submitted for publication on December 23, 1968.

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ABSTRACT

Free-flight tests of two slender, finned missile models (Tomahawk and Sandhawk) were conducted in Tunnel B of the von Kármán Gas Dynamics Facility to obtain dynamic stability characteristics. The models were launched into the wind tunnel flow using various combinations of initial pitch angle and spin rate. The resulting free-flight oscillation was photographed by orthogonal high-speed motion-picture cameras. The free-stream conditions were nominally Mach number 8 and Reynolds number 1.8×10^6, based on model length. Pitch and yaw angle measurements are presented for one typical run.

CONTENTS

APPENDIXES

NOMENCLATURE

I_X	Axial moment of inertia, slugs-ft^2
I_Y	Transverse moment of inertia, slugs-ft^2
M_∞	Free-stream Mach number
p_o	Stilling chamber total pressure, psia
p_∞	Free-stream static pressure, psia
q_∞	Free-stream dynamic pressure, psia
Re_∞	Free-stream unit Reynolds number, ft^{-1}
T_o	Stilling chamber total temperature, °R
T_∞	Free-stream temperature, °R
t	Time, sec
V_∞	Free-stream velocity, ft/sec
X_{cg}	Distance from nose to center of gravity, in.
θ	Angle of pitch, deg
ρ_∞	Free-stream density, slugs/ft^3
ψ	Angle of yaw, deg

SECTION I
INTRODUCTION

The Tomahawk and Sandhawk missiles are sounding rockets which are fired from the surface of the earth to above the sensible atmosphere. As pointed out in Ref. 1, about a third of the Tomahawk missiles developed a severe, divergent, coning motion which began after burnout. Analysis showed that these were not cases of roll-pitch lockin, nor were they the type of instability that would result from a time varying (decreasing) dynamic pressure. Other possible causes such as missile flexibility, Magnus effects, and asymmetrical vortices have been considered, but no completely satisfactory explanation has been found.

The interpretation of the dynamic instabilities of the Tomahawk vehicles certainly requires knowing the level of the damping-in-pitch derivatives. The high fineness ratio (23.25) of the vehicle would not allow meaningful sting-supported, dynamic stability tests to be conducted in a wind tunnel. This led Millard and Stone (Ref. 2) of the Sandia Corporation to devise a transverse rod-type dynamic balance which they used to obtain dynamic stability data on a Tomahawk model at Mach number 7.3. This balance, which is described in detail in Ref. 2 and termed the "strap rig", consists of a relatively thin strap located in the plane of the model oscillation and extending from the model to the top and bottom of the tunnel. The model was allowed to rotate by using a ball-bearing-type pivot.

The present wind tunnel test was initiated in order to obtain support-interference-free data for comparison with the data from the strap rig used by Sandia (Ref. 2). In addition to testing the Tomahawk configuration, models of the Sandhawk sounding rocket were also tested. During the present tests, the models were thrusted upstream into free flight by a pneumatic launcher. Orthogonal views of the flight were made with high-speed motion-picture cameras. The primary advantage of the free-flight test is the complete elimination of any support interference. The test was conducted in the 50-in.-diam test section of the hypersonic tunnel (Gas Dynamic Wind Tunnel, Hypersonic (B)) of the von Kármán Gas Dynamics Facility (VKF). The free-stream Mach number was 7.99, and the free-stream Reynolds number was 1.8×10^6 based on model length.

SECTION II
APPARATUS

2.1 WIND TUNNEL

Tunnel B is a continuous, closed-circuit, variable density wind tunnel with an axisymmetric contoured nozzle and a 50-in.-diam test section. The tunnel can be operated at a nominal Mach number of 6 or 8 at stagnation pressures from 20 to 300 and 50 to 900 psia, respectively, at stagnation temperatures up to 1350°R. The model launcher may be injected into the tunnel for a test run and then retracted without interrupting the tunnel flow. A description of the tunnel may be found in Ref. 3.

2.2 MODELS

The models (Figs. 1 and 2, Appendix I) were supplied by the Sandia Corporation and were made of magnesium and Mallory® for the highest possible ratio of mass to moment of inertia and still be consistent with required strength and rigidity. The model scales were chosen as a compromise between obtaining maximum length Reynolds number and maximum viewing time in the upstream window. To obtain the maximum viewing time for free-flight models, a certain ratio of drag/weight is required. While the optimum could not always be achieved, especially for the high drag condition at the larger angles of attack, the optimum ratio was approached by adding a tungsten alloy (Mallory) slug near the center of gravity, thus increasing the weight with only a slight increase in moment of inertia. The model weights and moments of inertia are given in Table I (Appendix II). A number of dummy models, which were crude, inexpensive models made at VKF of Lexan® and aluminum, were used to evaluate the model deflector (see Section 2.3). The dummy model runs account for the runs missing from Table II, which gives the measured and calculated wind tunnel conditions.

2.3 MODEL LAUNCHER

The model was launched upstream with a velocity from 30 to 40 ft/sec by the pneumatic launcher. The launcher has a high volume pressure reservoir allowing the launching process to take place at nearly constant pressure and acceleration. A detailed description of the launcher is given in Ref. 4. For the present test, however, the launch was considerably more complex because of the high fineness ratio of the model and the requirement for a high rate of spin. Preliminary studies of mechanisms which would spin and support a slender model at angle of attack during the launch acceleration and then provide a clean release appeared quite complicated. It was thought that a simpler approach would be to launch the model spinning at zero angle of attack and, after release, deflect it with an oblique shock.

The model deflection equipment as finally developed (Fig. 3) consisted of a flat plate 12 in. wide extending about 15 in. ahead of the model. It was about 2 in. below the centerline of the model and launcher piston. This plate provided two methods for deflecting the model and thus initiating model oscillation. One method consisted of air jets (Fig. 3) originating from a transverse row of holes (19, 0.063-in.-diam holes spanning 2 in.). The second method for deflecting the model was to attach a wedge on the leading edge of the plate (see Figs. 3 and 4). The two-dimensional shock generated by the wedge produced almost the same effect on the model as the jet. A family of wedges was used primarily because of the greater simplicity of operation.

For about one third of the runs, a spin adapter (Fig. 5a) was installed and the model spun to from 4000 to 5000 rpm before being launched. The spin adapter is similar to the nonspin adapter (Fig. 5b) except that it is larger to contain ball bearings and has turbine buckets milled on the rear face. High pressure air from two diametrically opposed nozzles (see Fig. 5b) acted on the turbine buckets to rotate the model and adapter. By painting the turbine buckets alternatingly white and black, they also served to measure rotational speed at launch with a photoelectric cell and light source system (Fig. 5a). The model adapters also included cylindrical mandrels which protruded into the hollow base of the model.

2.4 PHOTOGRAPHY

The model trajectory in the upstream windows was photographed with high-speed motion-picture cameras at approximately 4000 frames per second. The horizontal view was obtained through the standard tunnel shadowgraph system supplied by the Sandia Corporation. In both systems, parabolic mirrors provided parallel light through the test section. Both high-speed motion-picture films had 1000-Hz timing marks and an event marker, for time correlation. Selected frames from the two cameras have been reproduced in Fig. 6.

In addition, a Polaroid® sequence camera was used to obtain a series of eight pictures during the run to assist in selecting the launch parameters for subsequent runs.

SECTION III
PROCEDURE

The model was installed with the launcher in the test section tank by simply pushing it onto the mandrel of the launcher adapter. The launcher was sequenced into the firing mode, and the tank was evacuated. If the run required spinup, the turbine air pressure was then applied until the required rpm was reached. The launcher was then injected into the tunnel and the launch initiated.

When the model launch switch was closed, the following sequence of events automatically took place.

Time, sec	Event
0	Launch switch closed, cameras start, lights on
1.00	Signal to launcher
1.30	Signal to film event timer and Polaroid camera
1.37	Approximate release time
1.50 to 1.75	Approximate data span

After these events took place, the launcher was retracted into the tank, another model installed, and the run cycle repeated.

The Sandia Corporation has the primary responsibility for reducing and analyzing the data. However, some of the data were manually read from the film and are shown in Figs. 7 and 8 to illustrate the type and quality of data. The length of time for the data was limited to the viewing time. Some portions of the data have more scatter than others because of periods of time when only a portion of the model was in view.

REFERENCES

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2. Millard, W. A. and Stone, G. W. "The Pitch-Damping Characteristics of the Sandia Tomahawk Rocket Configuration." Sandia Laboratory, SC-RR-66-690, July 1967.

3. Test Facilities Handbook (Seventh Edition). "von Kármán Gas Dynamics Facility, Vol. 4." Arnold Engineering Development Center, July 1968.

4. Ward, L. K., Hodapp, A. E., Jr., and Choate, R. H. "Description of a Model Launcher and Techniques Used for Obtaining Model Free-Flight Measurements in the VKF Continuous Flow Wind Tunnels at Mach Numbers from 1.5 through 10." AEDC-TR-66-112 (AD487477), August 1966.

APPENDIXES

I. ILLUSTRATIONS
II. TABLES

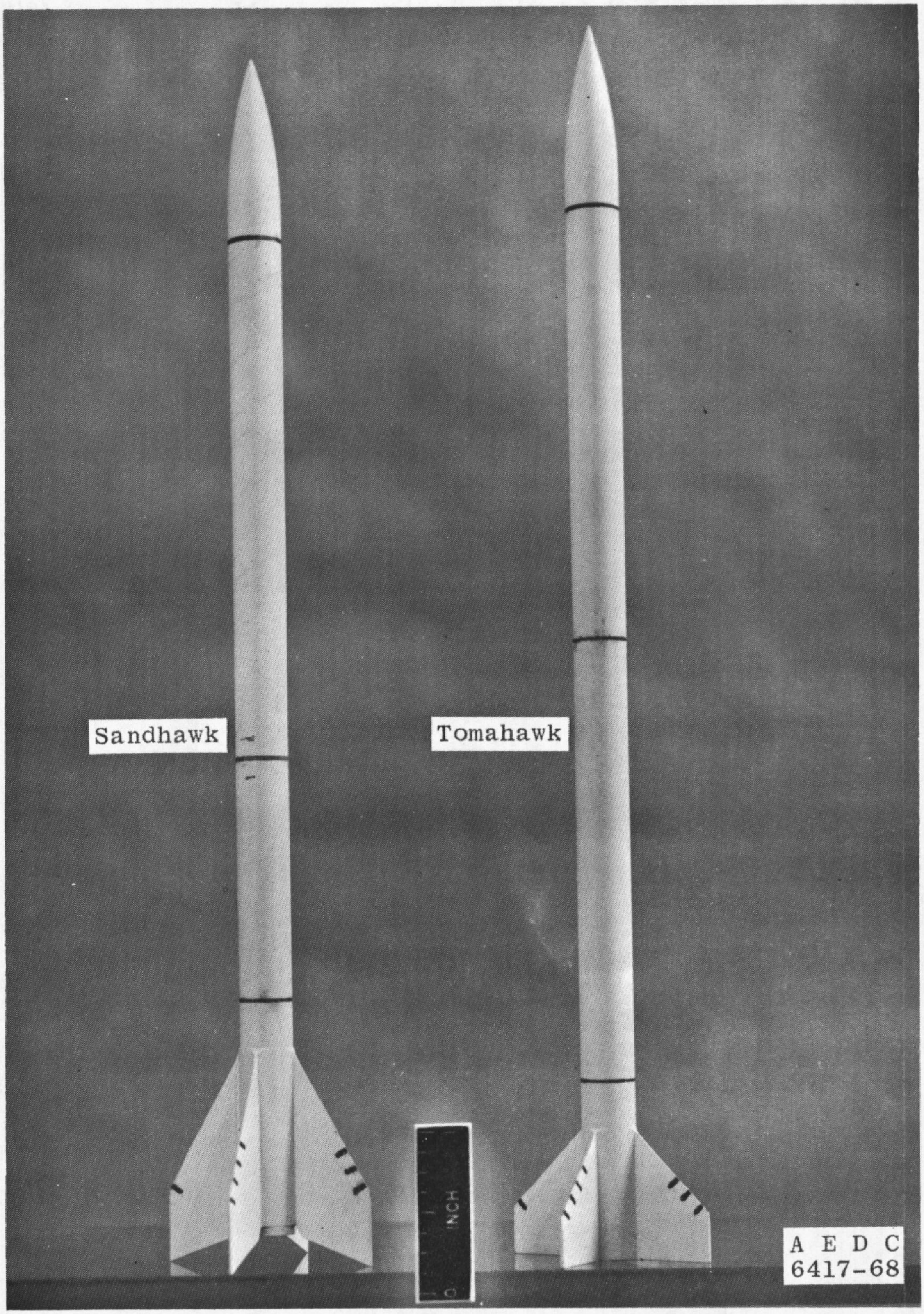


Fig. 1 Photograph of the Sandhawk and Tomahawk Free-Flight Wind Tunnel Models

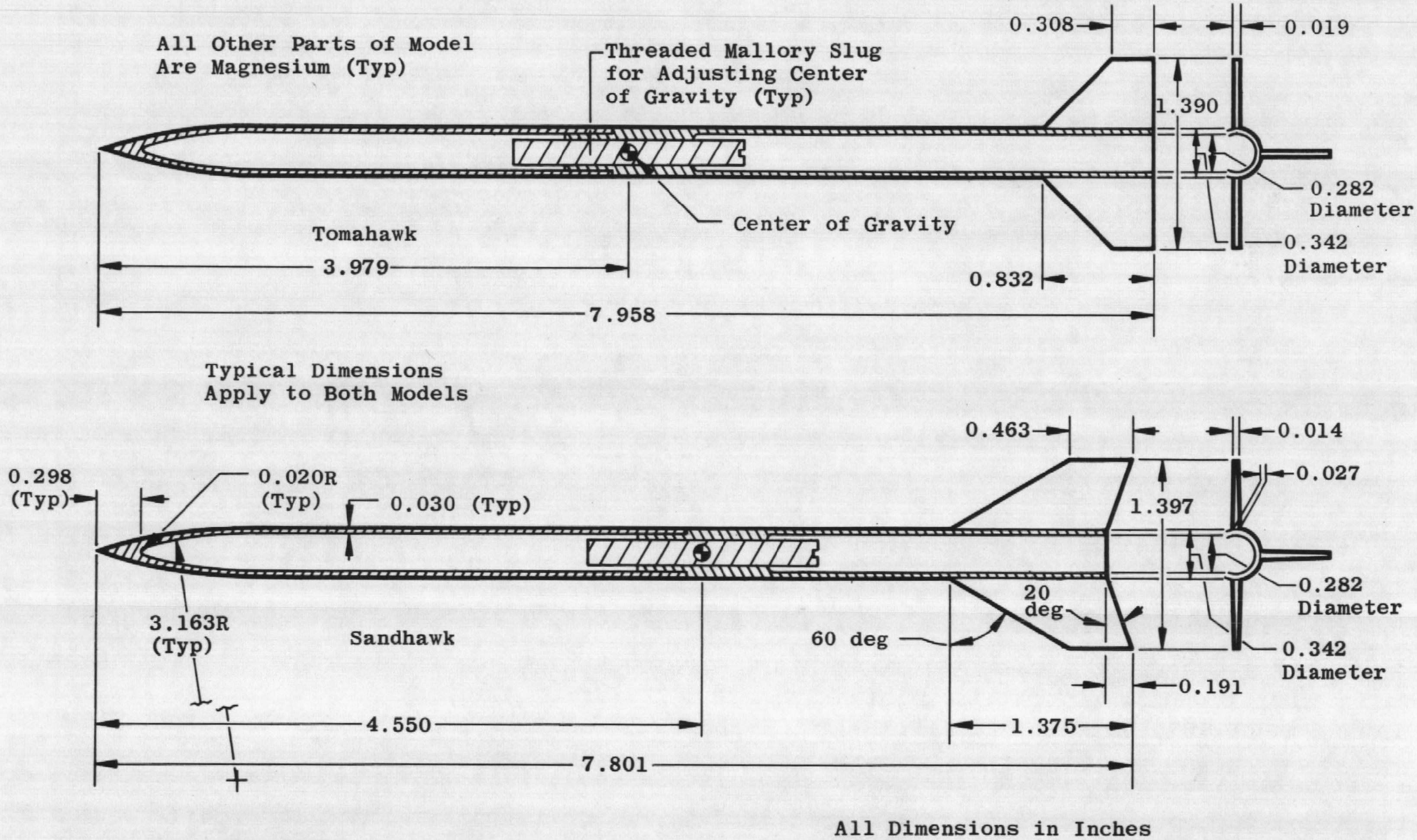


Fig. 2 Section and Rear Views of Tomahawk and Sandhawk Free-Flight Models

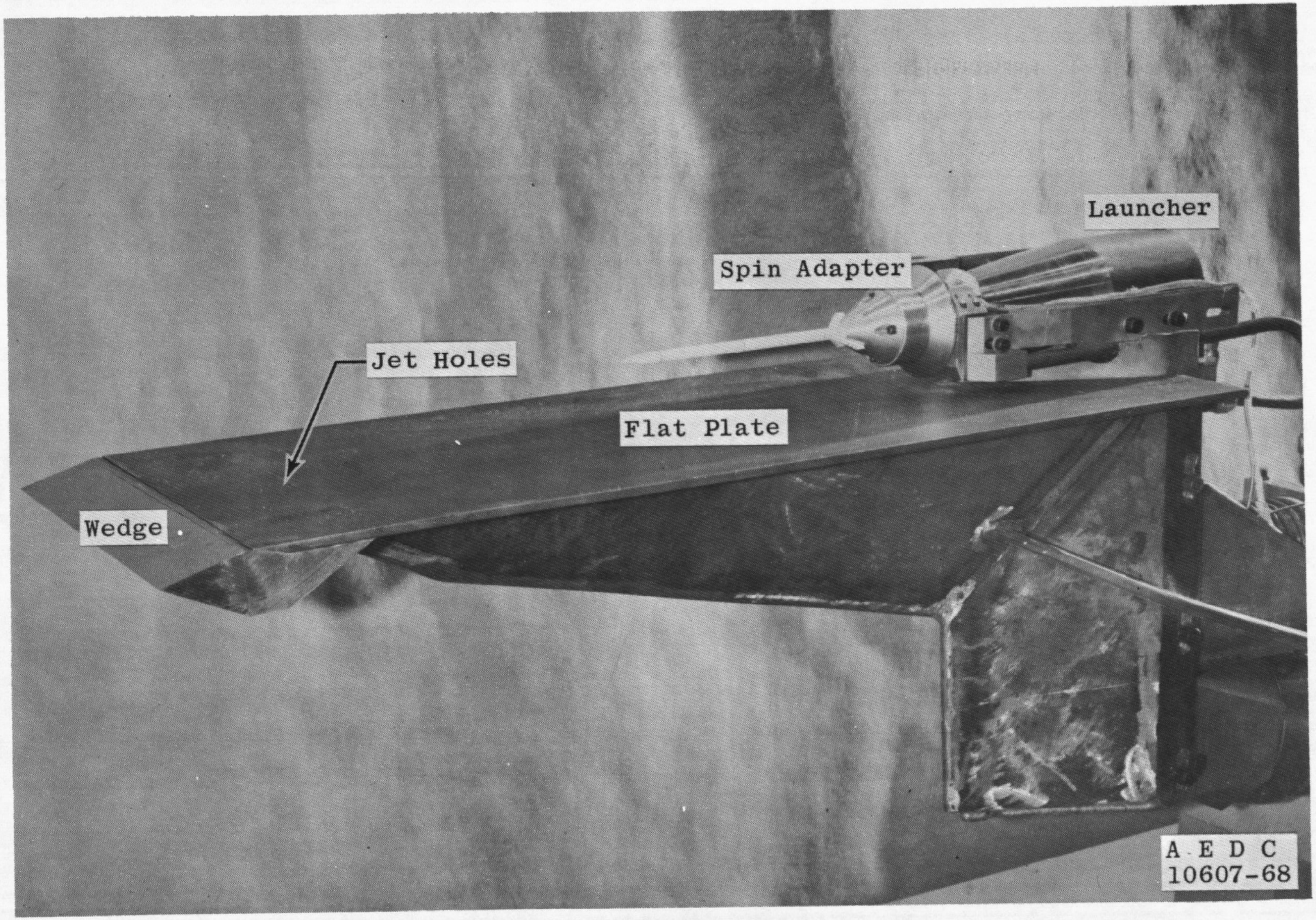


Fig. 3 Photograph of the Model Launcher and Deflector System

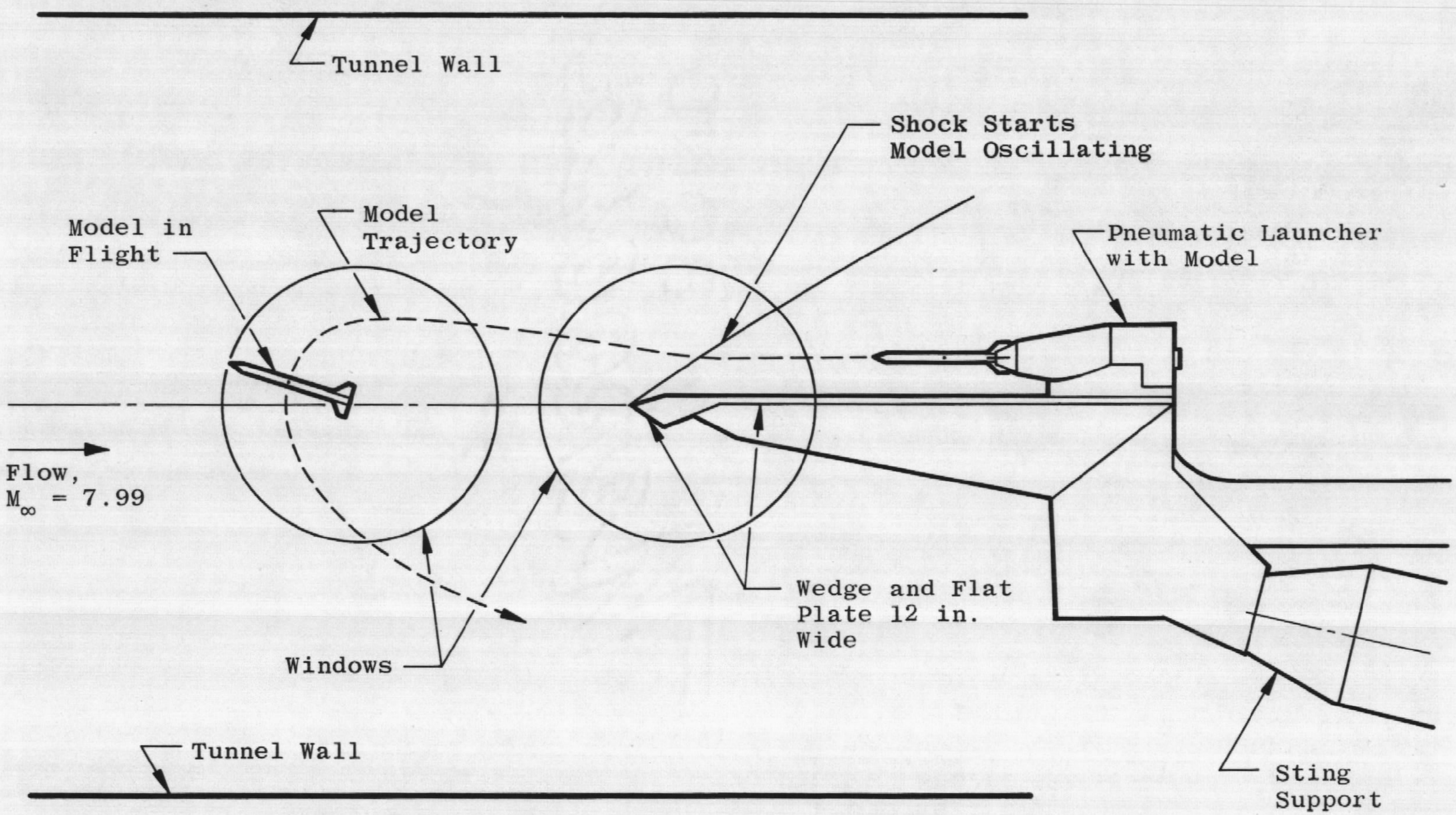
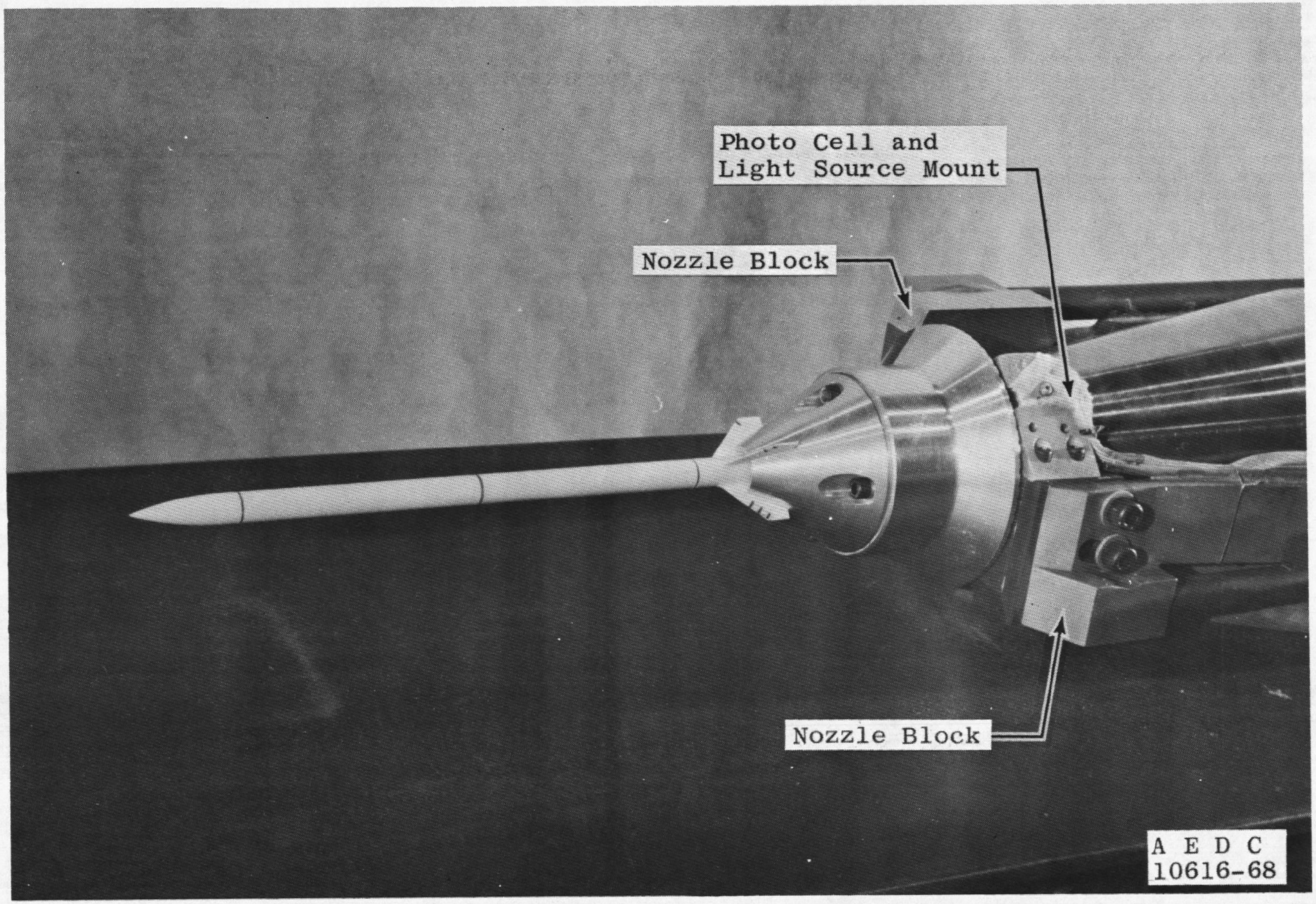
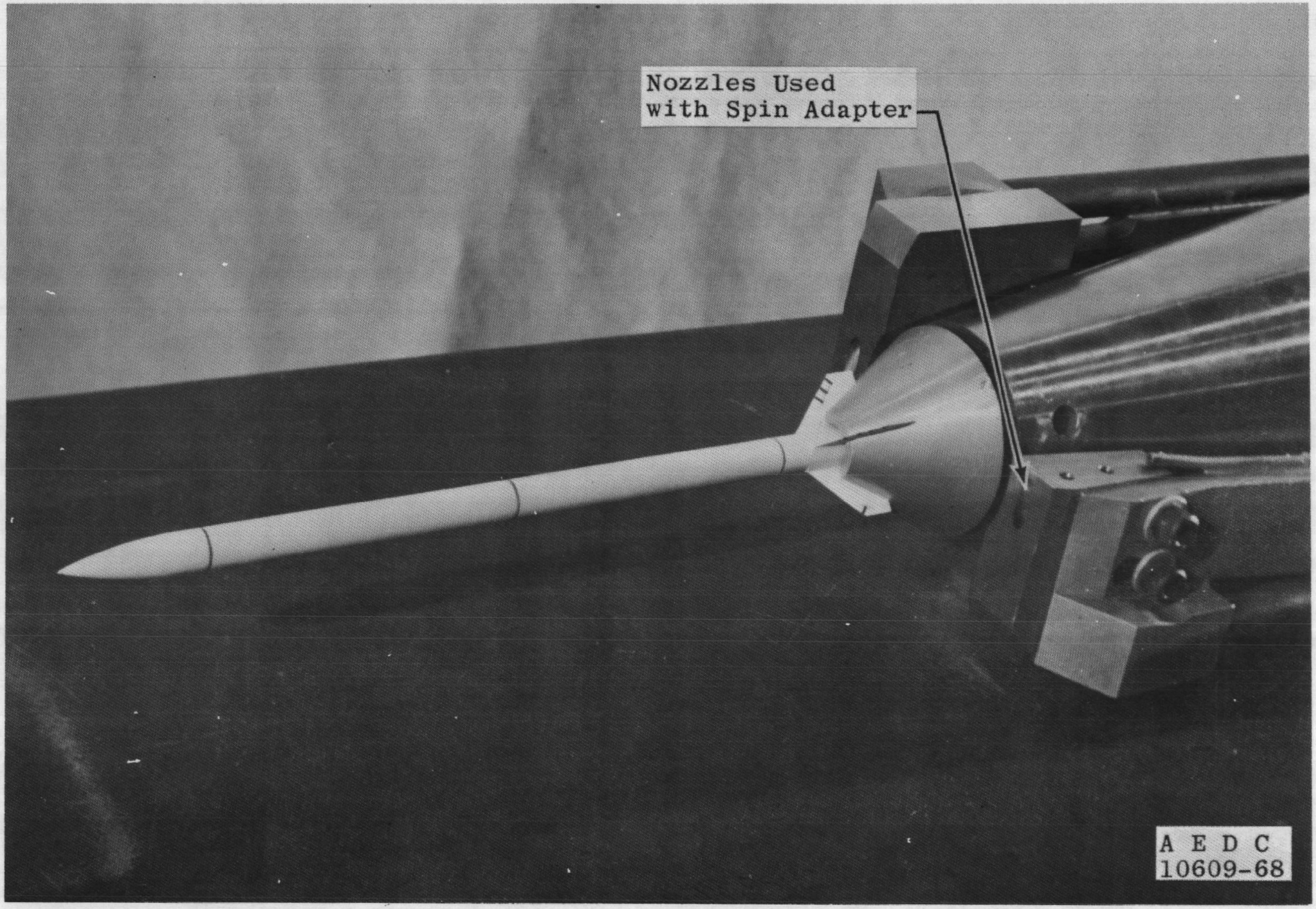


Fig. 4 Sketch Showing Model Flight in Tunnel B



a. Spin Adapter

Fig. 5 Model Adapters for the Launcher



b. Nonspin Adapter

Fig. 5 Concluded

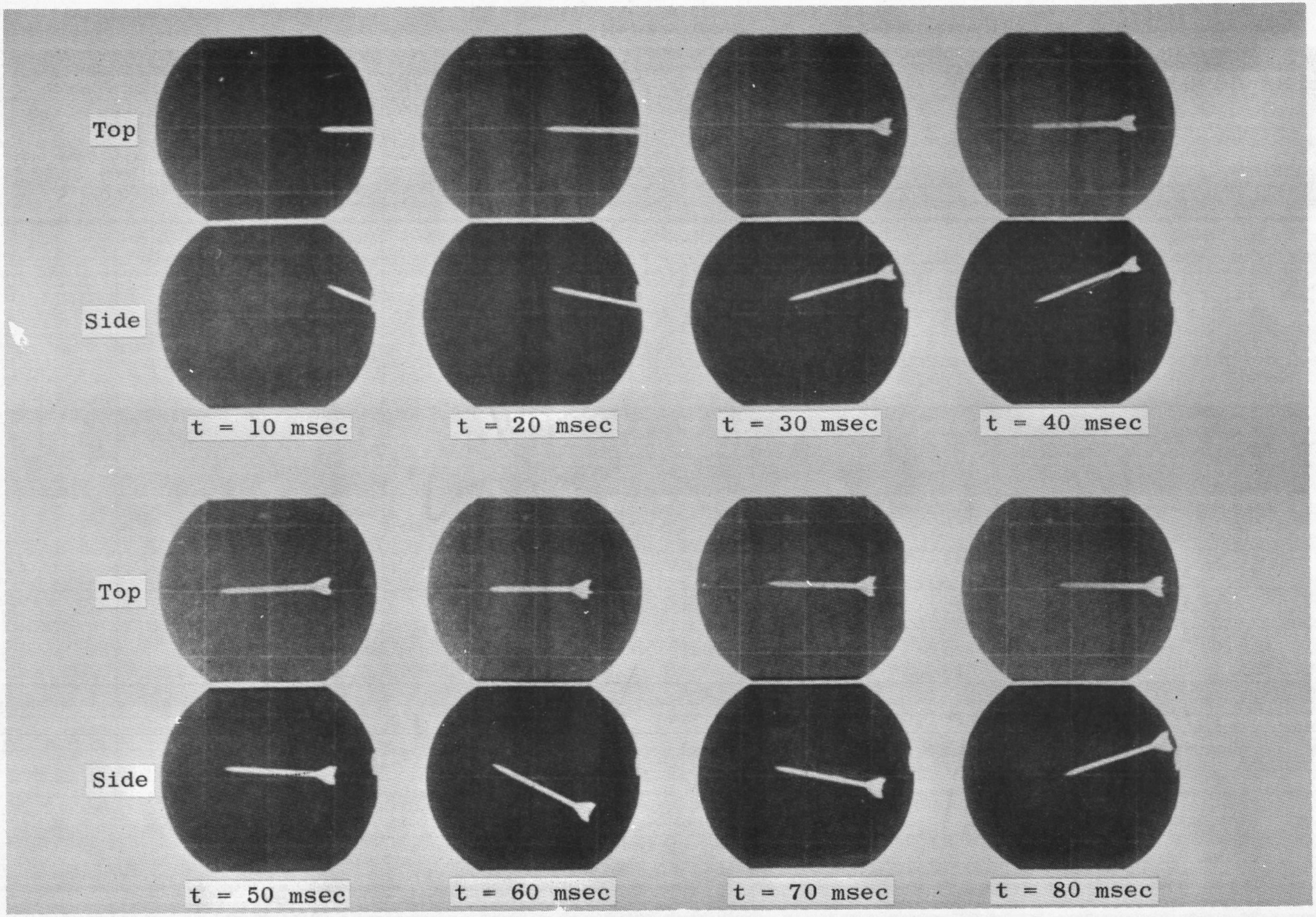


Fig. 6 Sequence Photographs of Free Flight of Sandhawk Missile Model in Tunnel B at M_∞ = 8

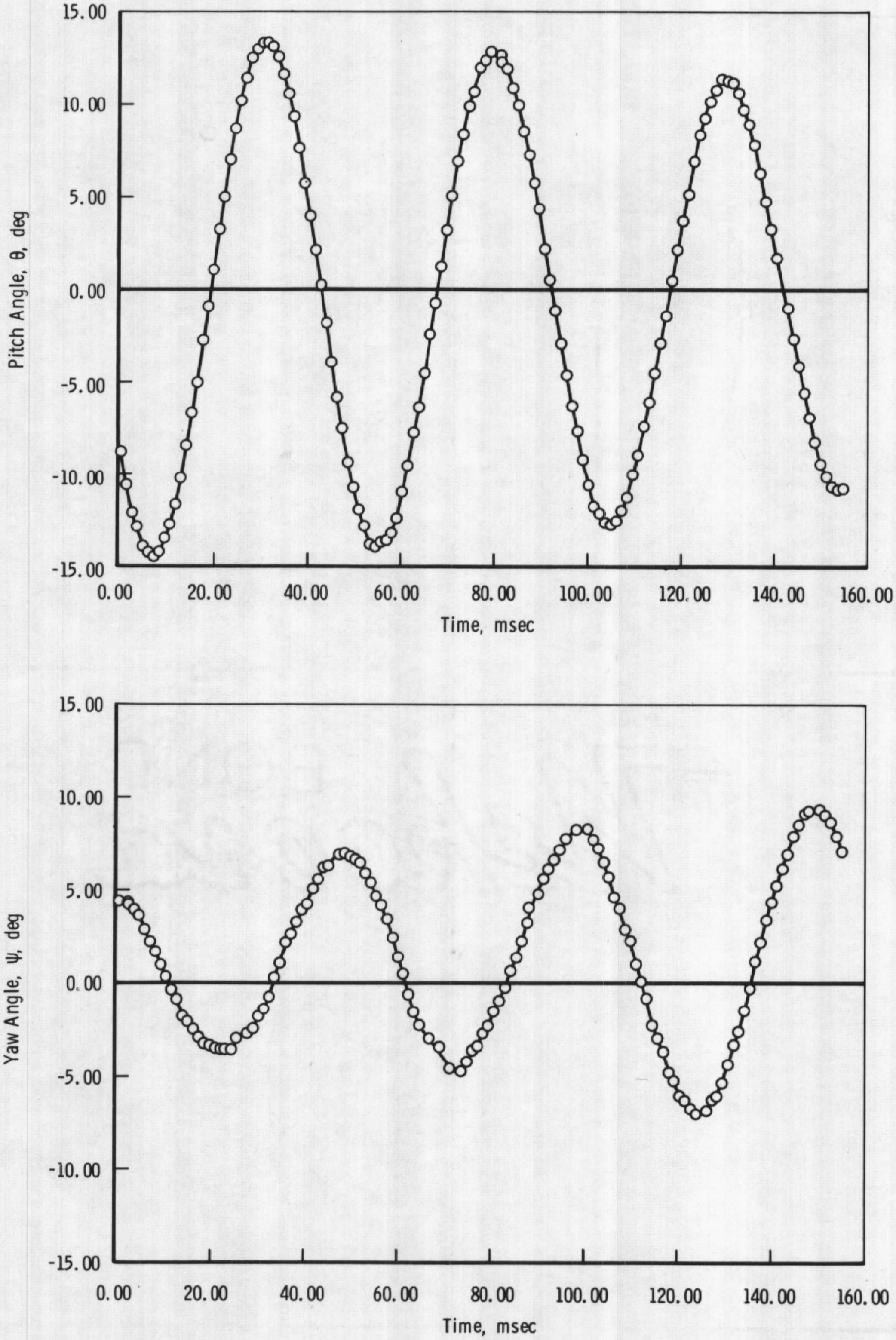


Fig. 7 Model Pitching and Yawing Oscillation as a Function of Time (Run 4, Tomahawk Model No. 10)

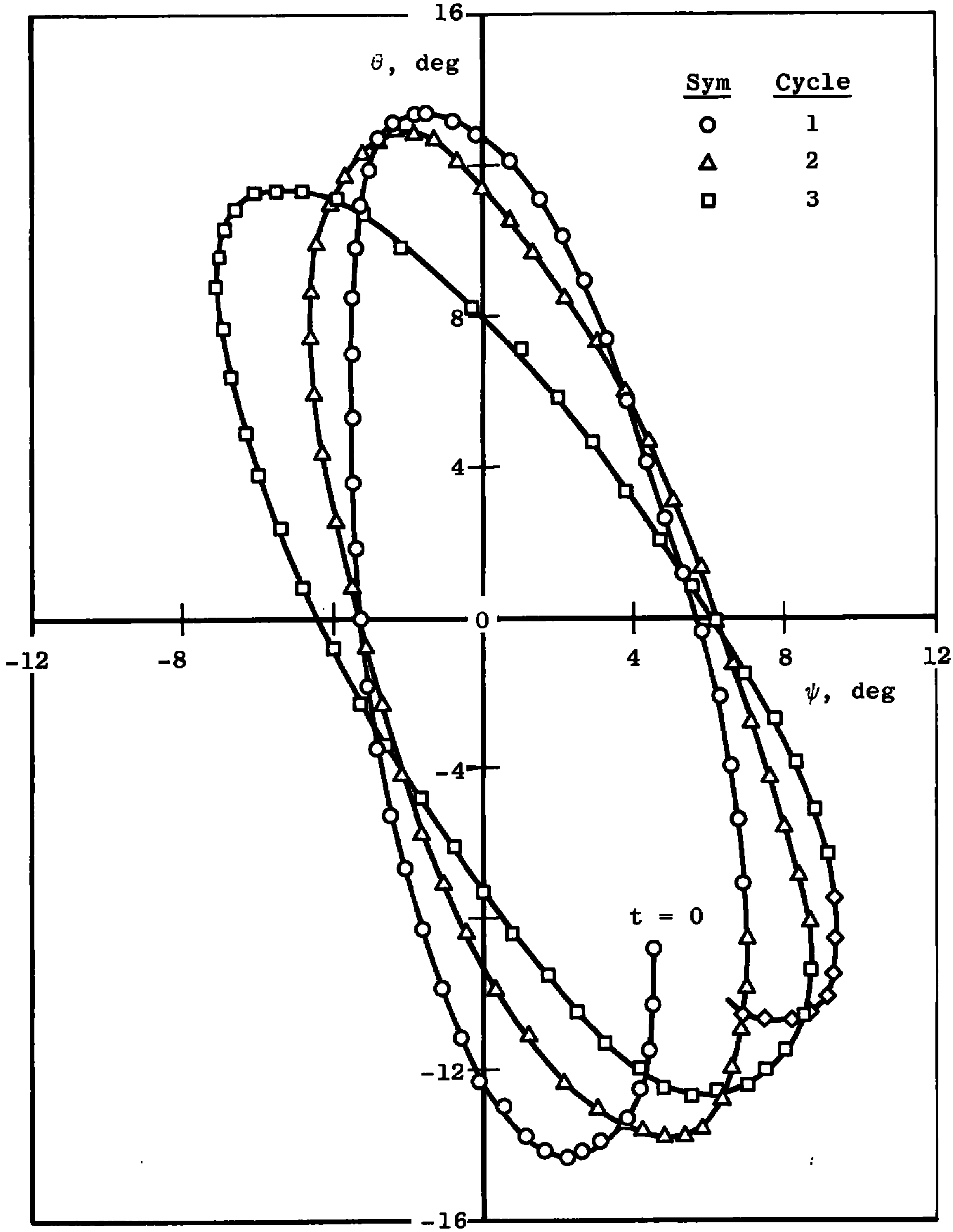


Fig. 8 Model Motion in Pitch-Yaw Plane (Run 4, Tomahawk Model No. 10)

TABLE I
PHYSICAL CHARACTERISTICS OF MODELS

Tomahawk				
Model Length = 7.958 in.				
Model No.	Weight, lb x 10^2	X_{cg} from Nose, in.	I_Y, slug-ft^2 x 10^5	I_X, slug-ft^2 x 10^7
2	2.47	4.00	2.43	1.56
3	2.50	4.00	2.42	1.56
4	2.48	4.00	2.41	1.52
5	2.51	4.00	2.44	1.56
6	3.35	4.00	2.23	1.67
7	3.34	4.00	2.26	1.67
9	3.36	3.99	2.26	1.66
10	3.40	4.01	2.30	1.70
11	3.61	3.98	2.27	1.74
12	3.65	4.00	2.28	1.72
13	3.63	3.98	2.25	1.68
14	3.67	3.98	2.30	1.76
15	3.62	3.98	2.30	1.71
17	3.37	4.00	2.23	1.65
18	3.74	3.96	2.38	1.83

Sandhawk				
Model Length = 7.801 in.				
Model No.	Weight, lb x 10^2	X_{cg} from Nose, in.	I_Y, slug-ft^2 x 10^5	I_X, slug-ft^2 x 10^7
1	2.62	4.55	1.94	1.90
2	2.60	4.55	1.96	1.90
3	2.60	4.56	1.95	1.80
4	2.61	4.57	1.95	1.82
5	2.60	4.56	1.96	1.85
6	3.38	4.55	1.98	2.01
7	3.43	4.55	1.95	2.01
8	3.42	4.53	1.96	1.95
9	3.42	4.52	1.96	1.93
10	3.44	4.53	1.98	1.97
11	3.66	4.53	1.95	1.95
12	3.64	4.53	1.95	1.95
13	3.69	4.52	1.98	1.97
14	3.66	4.56	1.96	1.97
15	3.69	4.56	1.97	1.98
17	3.44	4.56	2.00	1.95
18	3.64	4.55	1.99	2.07

TABLE II
WIND TUNNEL PARAMETERS

Run	Model No.	M_∞	p_o, psia	T_o, °R	q_∞, psia	V_∞, ft/sec	ρ_∞, slugs/ft^3 x 10^5	Re_∞, 1/ft x 10^{-6}	p_∞, psia x 10^2	T_∞, °R
4	T-10	7.99	600	1310	2.77	3820	5.48	2.73	6.20	95
7	T-18	7.99	599	1320	2.76	3830	5.44	2.71	6.19	96
11	T-15	7.99	594	1310	2.74	3820	5.42	2.70	6.13	95
13	S-11	7.99	601	1310	2.77	3820	5.48	2.73	6.21	95
15	S-17	7.99	597	1310	2.76	3820	5.45	2.72	6.17	95
19	T-17	7.99	598	1310	2.76	3820	5.46	2.72	6.18	95
20	S-10	7.99	600	1310	2.77	3820	5.48	2.73	6.20	95
22	T-6	7.99	601	1320	2.77	3830	5.44	2.70	6.20	96
23	S-6	7.99	599	1320	2.76	3830	5.42	2.70	6.18	96
24	T-7	7.99	600	1320	2.77	3830	5.45	2.71	6.20	96
25	S-7	7.99	603	1320	2.78	3830	5.48	2.73	6.23	96
26	S-1	7.99	602	1320	2.78	3830	5.47	2.72	6.22	96
28	S-2	7.99	602	1320	2.78	3830	5.46	2.72	6.22	96
29	T-2	7.99	602	1320	2.78	3830	5.47	2.72	6.22	96
30	T-3	7.99	599	1320	2.76	3830	5.44	2.71	6.19	96
31	S-12	7.99	602	1310	2.78	3820	5.48	2.73	6.22	95
32	S-13	7.99	602	1310	2.78	3820	5.47	2.73	6.21	95
33	T-11	7.99	601	1310	2.77	3820	5.47	2.72	6.21	95
34	T-12	7.99	597	1310	2.75	3820	5.43	2.70	6.16	95
35	T-13	7.99	597	1310	2.76	3820	5.44	2.71	6.17	95
36	T-14	7.99	596	1310	2.75	3820	5.43	2.71	6.16	95
37	S-14	7.99	598	1310	2.76	3820	5.44	2.71	6.17	95
38	S-15	7.99	600	1310	2.77	3820	5.46	2.72	6.19	95
39	S-8	7.99	598	1310	2.76	3820	5.45	2.72	6.18	95
40	S-9	7.99	602	1310	2.78	3820	5.48	2.73	6.22	95
41	S-18	7.99	601	1310	2.77	3820	5.47	2.73	6.20	95
42	T-9	7.99	599	1310	2.76	3820	5.46	2.72	6.19	95
43	S-3	7.99	600	1310	2.77	3820	5.47	2.73	6.20	95
44	T-4	7.99	602	1310	2.78	3820	5.50	2.75	6.22	95
45	T-5	7.99	602	1310	2.78	3820	5.50	2.74	6.22	95
46	S-4	7.99	602	1310	2.78	3820	5.50	2.75	6.22	95
47	S-5	7.99	602	1310	2.78	3820	5.49	2.74	6.21	95

Model Code: T = Tomahawk, S = Sandhawk

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
missile models						
wind tunnel models						
free-flight trajectories						
stability						
hypersonic flow						

1. Missiles -- Tomahawk
2 " -- Sandhawk.
3 " -- Free flight testing
4 " -- Stability
5 " -- Hypersonic flow

1-12