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# A Thin Strap Support for the Measurement of the Dynamic Stability Characteristics of High-Fineness-Ratio, Wind-Tunnel Models

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**A transverse support system that appears to have minimal support interference effects has been developed for use in dynamic stability tests of high- fineness ratio, wind-tunnel models. A thin metal strap is placed in tension between the walls of the tunnel, and the model is mounted on it in a manner which allows the model to oscillate freely in the plane of the strap. Dynamic stability tests using this rig were conducted at Mach number 7.3 on a model of the Tomahawk rocket, which has a fineness ratio of 23.3. The test results correlate reasonably well with data derived from theoretical studies, from other wind-tunnel programs, and from full-scale flight test.**

## Nomenclature

$C_m, C_{m_\alpha}$ = pitching moment coefficient and slope
$C_{m_q} + C_{m_{\dot{\alpha}}}$ = damping moment coefficient (based on $d/2V$)
$C_N, C_{N_\alpha}$ = normal force coefficient and slope
$d$ = maximum body diameter and reference length
$M$ = Mach number
$Re$ = Reynolds number based on body length
$S$ = body cross-sectional area and reference area
$V$ = velocity
$\alpha$ = angle of attack
$\phi$ = angle of roll (zero when fins in + position)

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## Introduction

The measurement of the dynamic stability characteristics of high-fineness-ratio shapes in a wind tunnel by means of the free oscillation technique using a fixed support has long been a problem. A sting supporting the model will in general not allow sufficient oscillation amplitude. A transverse support system interferes with the flowfield over the model. The type of transverse support generally used is a rod installed perpendicular to the model's plane of oscillation. Interference effects in this case could be significant on the aftersection of a finned model oscillating through the support wake.

A transverse support system that appears to have minimal support interference is a strap placed in tension in the pitch plane of the model (Fig. 1). Because the strap is not subjected to large bending loads, it can be made extremely thin, and its wake will be small. This report describes the test apparatus and presents the results of an investigation of the dynamic stability characteristics of a model of the Tomahawk sounding rocket.

## Experimental Equipment

The Sandia Hypersonic Wind Tunnel[1] is an intermittent, blowdown-to-vacuum tunnel with an 18-in.-diam test section. The air is heated by a pebble bed heater. Nominal conditions for this test program were: Mach number 7.3; Reynolds number $1.16 \times 10^6$ based on model length; stagnation pressure 186 psia; and stagnation temperature 1550°R. The last two properties were recorded approximately every 0.6 sec during the tunnel operation. These data were used to determine an average dynamic pressure and flow velocity for each tunnel run.

The pivot section of the aluminum model contained two Fafnir ball bearings that rotated about a hub located at the center of the transverse support. The model was free to rotate ±20°‡ in the pitch plane. To insure that the model was balanced at the 50% (pivot) point, a movable brass weight was located in the nose section. The moment of inertia of the model about the pivot point was 0.00148 slug-ft². This was determined using a trifilar pendulum.

The strap was made of 0.015-in.-thick Inconel X-750 alloy and tapered in width from 0.70 in. at the test section wall to 0.50 in. at the tunnel centerline. To compensate for its thermal expansion during a test, the strap was prestressed to 42,000 psi. For the conditions of this test, the strap was heated to ~1000°F during a run. At this temperature, its stress decreased to 38,000 psi. A hub around which the model would rotate was resistance-welded to the center of the strap.

The model was deflected using a burn wire that extended through the test section and attached to a metal tang located at the rear of the model (Fig. 1). By pulling on one end of the burn wire, the model could be rotated to a predetermined initial angle of attack. A charged capacitor bank was then discharged through the burn wire, causing the wire to break at the tang. The wind loads were sufficient to cause the broken wires to bend back and lie along the side of the test section, allowing the model to pitch free of any interference from the wires. The model motion was recorded on 16-mm film using a Milliken camera, the framing speed of which can be varied from 64 to 400 frames/sec.

## Test Procedure and Data Analysis

Pretest calculations using the static data obtained by Reece[2] and shown in Fig. 2 indicated that the model would oscillate at ~5–6 Hz. Past experience with the numerical analysis of oscillatory data indicated that approximately 20 data points per cycle were necessary to obtain good statistical estimates of the static and dynamic stability parameters. Therefore, a framing speed of 200 frames/sec was chosen to record the oscillatory data. A clock, capable of reading a hundredth of a second, was positioned to appear in each frame beside the model (Fig. 3). Because of shadows on the far wall of the test section, the edge of the model was obscured at times, and direct measurment of $\alpha$ was not practical. Therefore, it was decided to measure the Cartesian coordinates of the fin tips and to calculate $\alpha$ from these Cartesian measurements. The photographic data were measured for every camera frame at those times when the model was near its maximum or peak amplitudes, and for every other frame when the model was between peaks. The measurements were punched onto data processing cards using a Benson Lerner Model S film reader. Runs were made for angles of attack varying from 9° to 15° at model release. Figure 3 presents two frames from a run, and Fig. 4 shows $\alpha(t)$ for a typical run.

Any analysis of experimental, oscillatory data requires an initial fundamental assumption regarding the form of the governing equations of motion. The simplest assumption possible is that of a linear dynamic system. This basic assumption has been used successfully in the analysis of experimental data and, in fact, has been very useful in the analysis of nonlinear systems, as evidenced by the work of Nicolaides et al.[3] Although the application of the linear theory to the planar oscillatory data with an amplitude of ±15° is not readily justifiable in view of the nonlinear characteristics shown in Fig. 2, it was felt that it could be employed successfully if only a few cycles of data were analyzed at one time. Two techniques using the linear theory were used: the log decrement method[4] and the least-squares numerical method with differential corrections;[5] both methods yielded comparable results.

The damping due to friction in the bearings was estimated by a bench test in which a weight approximately equal to the drag was suspended from the bearing and allowed to oscillate freely. The tare damping so determined was only about 3% of the aerodynamic damping. Moreover, in the actual tunnel test, the model oscillation frequency was about three times higher than during the tare test, and the rig was subjected to

‡ The maximum amplitude of oscillation in this test was 15°.

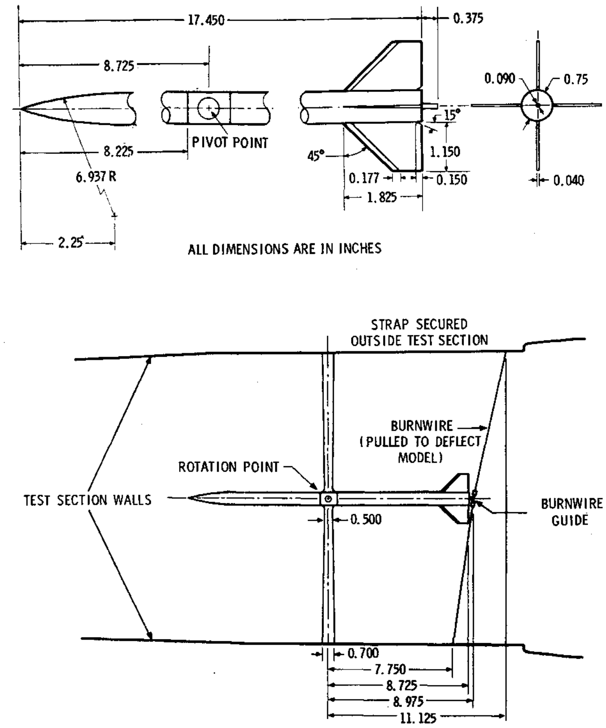


**Fig. 1 Tomahawk model and strap rig installation.**

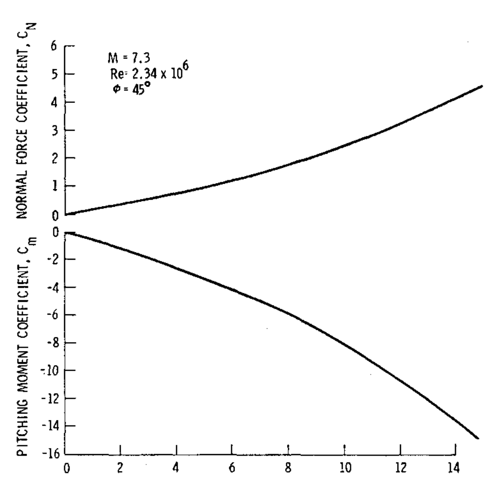


**Fig. 2 Basic normal force and pitching moment characteristics of the Tomahawk configuration (from Ref. 2).**

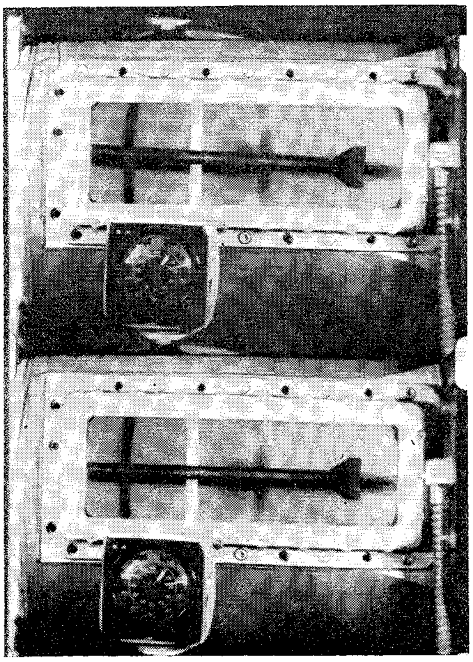

Fig. 3 Typical photographic data obtained on the Tomahawk model.

a large spectrum of vibrational frequencies; both effects would tend to reduce the tare damping determined in the bench test. No attempt was made, therefore, to make corrections for tare damping in the data reduction program.

An attempt was made to determine the effect of the wake from the strap on the measured dynamic stability characteristics of the Tomahawk model. Roache[6] estimated the strap wake thickness using data obtained by Batt[7] and showed that the wake thickness at the aft end of the model could vary from 0.23-in. for a completely laminar wake to 0.42-in.for a wake with a conservative estimate of transition to turbulent at 4.5-in. downstream of the strap. The distance between the fins at the root chord is approximately 0.5 in.; therefore, one may conclude that negligible wake-fin interference would occur for the fins positioned in the 45° roll configuration. This appeared to be substantiated in the testing program when a small yawing motion (in addition to the pitching motion) observed with the fins in the zero roll position was eliminated with the fins in the 45° roll position. All strap rig data presented in this report are for the 45° roll angle configuration.

A calculation of the $C_{m_q}$ contributed by that portion of the afterbody blanketed by the strap wake was made according to the following equation given by Nicolaides,[8]

$$C_{m_q} = (-2/Sd)\iint C_{N_\alpha} x^2 dx dy$$

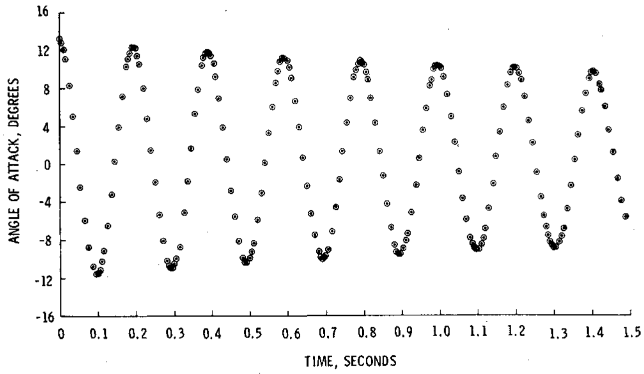


**Fig. 4 Typical amplitude/time history.**

where $x$ and $y$ are the coordinates of the exposed area. The width of the strap wake was assumed to grow linearly in the downstream direction from zero width at the strap to 0.42-in. in width at the rear of the model. The $C_{N\alpha}$ over the aft portion of the Tomahawk without the strap wake was determined by the technique of Muraca[9] to be constant and equal to 0.015 deg$^{-1}$. Integration of the above equation then showed that the portion of the body oscillating in the wake comprises only 2.5% of the total damping of the model. If it is further assumed that the average dynamic pressure in the strap wake is approximately one-half the true value, the total damping coefficients measured are only in error by about 1% due to strap wake effects.

## Results

Figure 5 compares damping moment coefficient data from the strap rig test with theoretical curves and data from other experimental investigations. The strap rig data appear to be independent of oscillation amplitude within the scatter of the data; the mean value of $C_{m_q} + C_{m_{\dot\alpha}}$ is approximately $-2500$ rad$^{-1}$. The theoretical value of $C_{m_q} + C_{m_{\dot\alpha}}$ shown at $\alpha = 0$ was determined using the method of Sacks,[10,11] which relates the damping moment coefficient to the static lift coefficient. In actuality, this damping moment coefficient is semiempirical, rather than theoretical, since existing normal force data[2] on the Tomahawk were used in the calculation. Good agreement with the strap rigid data is noted.

The theoretical variation of $C_{m_q} + C_{m_{\dot\alpha}}$ with $\alpha$ was determined using the Hypersonic Arbitrary-Body Program (HAB)[12] and integrating the resulting "local" values to obtain "effective" values.§ Fair agreement with the test data is indicated, although the theory does predict a slight increase (negatively) in $C_{m_q} + C_{m_{\dot\alpha}}$ as $\alpha$ is increased.

One of the two sets of other experimental data shown in Fig. 5 was obtained from a Mach 8.0 wind-tunnel free-flight test[14] conducted in tunnel B at Arnold Engineering Development Center (AEDC) (see Appendix; it will be reported in detail by Hunter[15]). The free-flight models were only deflected in pitch, so generally exhibited near-planar oscillatory motion. The data were converted to the strap rig test Mach number of 7.3 using the $(M^2 - 1)^{-1/2}$ method.¶ Excluding the one point at low amplitude of oscillation (±5°), the $C_{m_q} + C_{m_{\dot\alpha}}$ determined by the wind-tunnel free-flight technique correlates well with the strap rig data. Essentially no variation with oscillation amplitude is again noted. The extraordinary data point showing a value of $C_{m_q} + C_{m_{\dot\alpha}}$ of $+2660$ rad$^{-1}$, at an oscillation amplitude of 5°, was at the time of this writing still unexplained.

The second set of other experimental data was obtained from a full-scale flight test. These data were analyzed by Nicolaides et al.[3] using the WOBBLE program.[16] Since the flight Mach number was near 3.7, the results were converted to the wind tunnel test Mach number of 7.3 using the $(M^2 -$

§ When the magnitude of the damping or pitching moment derivative increases with increasing $\alpha$, as it does for the present configuration (Fig. 2), the effective $C_{m_q} + C_{m_{\dot\alpha}}$ or $C_{m_\alpha}$ obtained from a linear analysis of dynamic test data will be less than those coefficients determined from theoretical calculations, forced oscillation tests, or static tests at an $\alpha$ equal to the oscillation amplitude. An estimate of these effective coefficients was obtained using the nonlinear values in the single-degree-of-freedom equation of motion, and numerically integrating this equation.[13] The effective values of $C_{m_q} + C_{m_{\dot\alpha}}$ and $C_{m_\alpha}$ were then determined by applying the linear solution (with varying frequency) to the resulting oscillatory motions. These effective values are presented in Fig. 5 as "integrated data."

¶ Static moment data at $\alpha \simeq 0$ on the Tomahawk at $2.0 < M < 7.3$ have been found to vary approximately as $(M^2 - 1)^{-1/2}$. It was assumed that this would also be the case with the damping moment. The $(M^2 - 1)^{-1/2}$ relationship should deteriorate with increasing $\alpha$, however, because of nonlinear effects.

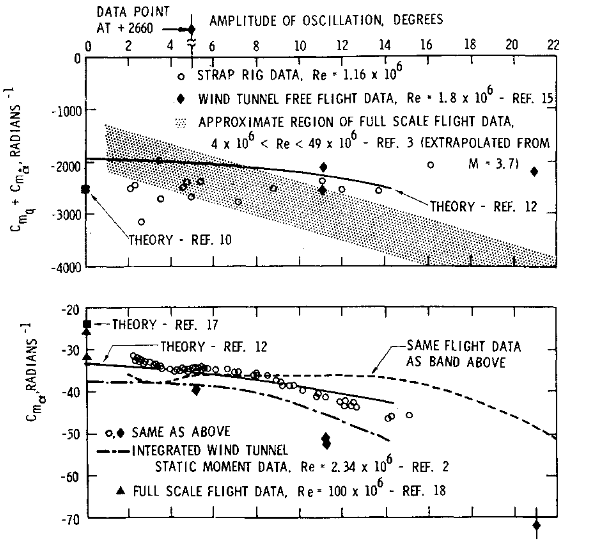


**Fig. 5 Damping moment coefficient and pitching moment coefficient slope of the Tomahawk at Mach number 7.3.**

$1)^{-1/2}$ method. As can be seen in Fig. 5, the $C_{m_q} + C_{m_{\dot\alpha}}$ derived from the strap rig lies within the region of full scale data at moderate angles of attack ($4° < \alpha < 10°$). However, the strap rig data indicate essentially constant $C_{m_q} + C_{m_{\dot\alpha}}$, whereas the full-scale data indicate an increasing (negatively) $C_{m_q} + C_{m_{\dot\alpha}}$ with $\alpha$. It should be remembered that the motion in the wind tunnel was planar, whereas in full-scale flight it was elliptical. Some variation between the trends of full-scale and strap rig data are to be expected because of nonlinear effects. For an increasing (negatively) $C_{m_q} + C_{m_{\dot\alpha}}$ with $\alpha$, the $C_{m_q} + C_{m_{\dot\alpha}}$ derived from a linear analysis of planar motion would be less negative at a given oscillation amplitude than the $C_{m_q} + C_{m_{\dot\alpha}}$ derived from a linear analysis of nonplanar motion.

Figure 5 also summarizes the data on Tomahawk pitching moment curve slope. In addition to the data obtained from the strap rig test, there are values of $C_{m_\alpha}$ determined from theory,[12,17] a wind-tunnel static force test[2] (see footnote §), a wind-tunnel free-flight test,[15] and full-scale flight tests.[3,18] The full-scale data of Ref. 18 were for $\alpha \simeq 0$ and at a comparable $M$. The full-scale data of Ref. 3, as mentioned previously, were for $M \simeq 3.7$ and hence were adjusted by the $(M^2 - 1)^{-1/2}$ method. The wind-tunnel free-flight data of Ref. 15 were also adjusted by the $(M^2 - 1)^{-1/2}$ method.

It can be seen in Fig. 5 that there is good agreement between the strap rig data and the integrated (see footnote §) theoretical $C_{m_\alpha}$ vs $\alpha$ determined by the HAB Program. It can also be seen in Fig. 5 that there is fair agreement between the various experimentally determined values of $C_{m_\alpha}$ at amplitudes of oscillation up to $\sim 10°$. At higher angles, however, the agreement is less satisfactory; the strap rig data lie between the full-scale flight data and the integrated wind-tunnel static moment data. The wind-tunnel free-flight tests yielded the largest (negative) values of $C_{m_\alpha}$.

At high angles, the $C_{m_\alpha}$ determined from the nonplanar full-scale flight motion were less negative than the $C_{m_\alpha}$ obtained from the planar motion in the strap rig test. This is inconsistent with a static moment coefficient slope which increases with increasing $\alpha$. However, the full-scale data were grossly extrapolated (M = 3.7 to 7.3) by the $(M^2 - 1)^{-1/2}$ method, and hence these extrapolated data are particularly suspect at the large $\alpha$'s. Further studies will be required to resolve these problems. *Re* effects should be considered. Ward[19] has shown a marked effect of boundary-layer transition on the stability characteristics of conical shapes. In the case of very-high-fineness-ratio rocket shapes, it is known that transition is very sensitive to $\alpha$, and that the lee-side flowfield can become very complex.[20]

## Concluding Remarks

The strap rig, a low interference transverse support system, has been developed to obtain dynamic stability data on high-fineness-ratio, wind-tunnel models. It has been used to determine the dynamic stability characteristics of the Tomahawk rocket configuration (fineness ratio 23.3) at a Mach number of 7.3. The test results agreed reasonably well with data derived from theoretical studies, from other wind tunnel programs, and from full-scale flight tests. Further investigations are recommended to determine the extent of the rig's capabilities.

## Appendix: AEDC Tunnel B Free-Flight Test

Tunnel B at the Arnold Engineering Development Center, 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 may be injected into the tunnel for a test run and then retracted for model cooling or model changes without interrupting the tunnel flow.

The size of the Tomahawk models used in the free flight test (Fig. 6) was chosen as a compromise of maximum *Re* (length) and maximum viewing time in the tunnel upstream window. The models were made of magnesium for the lowest possible moment of inertia consistent with required strength and rigidity. 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 $\alpha$'s, the optimum ratio was approached by adding a tungsten alloy slug around the center of gravity, thus increasing the weight with only a slight increase in moment of inertia for the pitch and yaw axes.

The model was launched upstream with a velocity of 30–40 fps by the pneumatic launcher.[21] The launcher has a pressure reservoir with a volume of almost two orders of magnitude greater than the piston volume; therefore, the launching process takes place at nearly constant pressure and accelera-

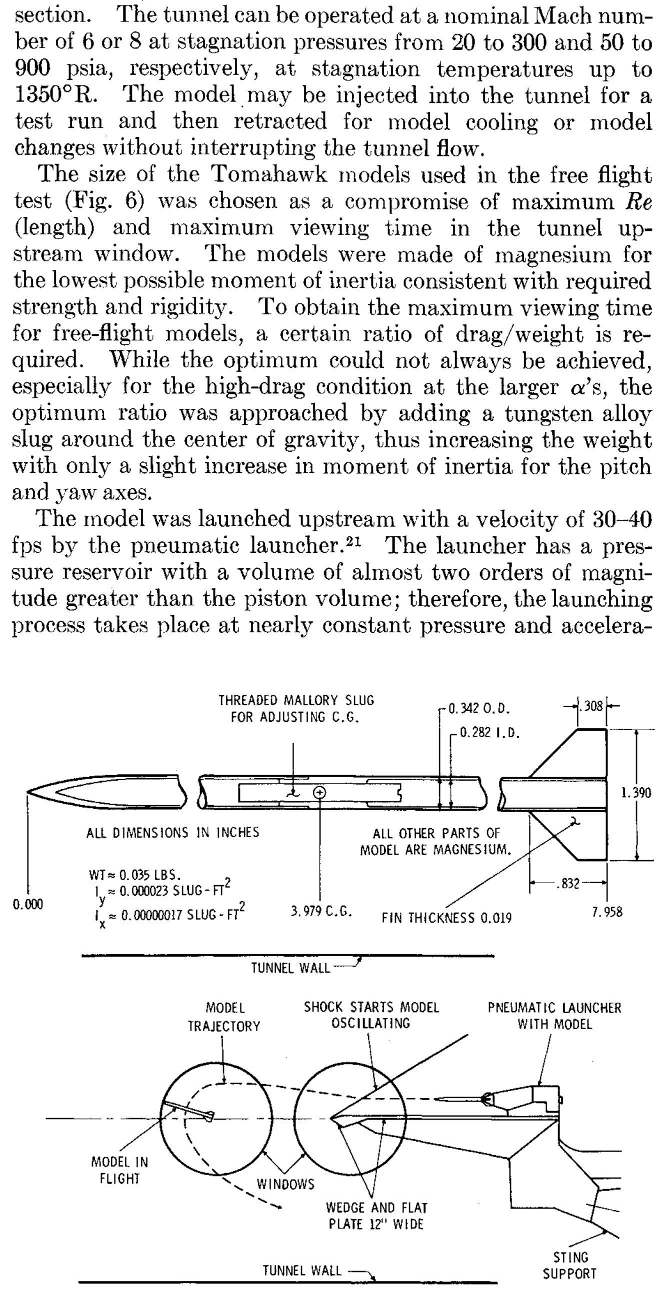


**Fig. 6 The Tomahawk model and sketch of a flight in AEDC tunnel B.**

tion. For the present test, however, the launch was considerably more complex because of the high fineness-ratio of the model and the requirement, in some runs, for a high rate of spin. Preliminary studies indicated that mechanisms which would spin and support a slender model at angle of attack during the launch acceleration and then provide a clean release would be quite complicated. It was thought that a simpler approach would be to launch the model at $\alpha = 0$ and, after release, deflect it with a jet or a shock. This latter method was found to work well.

The deflector consisted of a flat plate 12 in. wide mounted about 2 in. below the centerline of the model and launcher piston. The plate extended about 15 in. ahead of the model. It had a sharp leading edge, was flat on top and angled from beneath to minimize the shock above. This plate provided two methods for initiating model oscillation. One method consisted of air jets originating from a transverse row of holes (nineteen $\frac{1}{16}$-in.-diam holes spanning 2 in.). The jets were placed so as to strike the nose of the model immediately after release from the launcher. As the model passed over the jets, the nose was forced up, but the tail was forced up much more. This resulted in an oscillation of the model about its transverse axis. The second method for starting the model to oscillate was to attach a wedge on the leading edge of the plate. The plane shock generated by the wedge produced almost the same effect on the model as the jet. Both methods proved satisfactory. A family of wedges was used primarily because of the greater simplicity of operation.

For some of the runs, the spin adapter was installed and the model was spun to 4000 rpm before being launched. The spin adapter is similar to the nonspin adapter except that it has been enlarged to accommodate ball bearings and has turbine buckets milled on the rear face. High-pressure air from two diametrically opposed nozzles acted on the turbine buckets to rotate the model and adapter. By painting the turbine buckets alternately white and black, they also served to measure rotational speed at launch with a photoelectric and light source system. Of course, the primary source of rotational speed data was the high-speed motion picture film.

The model trajectory in the upstream windows was photographed with high speed motion picture cameras at $\sim$4000 frames/sec. The horizontal view was obtained through the existing schlieren system and the vertical view was obtained through a new system installed especially for this test. The vertical system was front lighted to better define model roll angle. In both systems, parabolic mirrors the size of the viewing area, provided parallel light through the test section. To observe the launching characteristics, some high-speed motion pictures were also made through the existing downstream schlieren system. No knife edges were used in any of the schlieren systems, so they were actually shadowgraph-type pictures.

Each high-speed motion picture reel had dashes produced on the margin of the film by a flashing light controlled by a 1000 Hz oscillator. On the opposite margin a single long dash was produced by a light controlled by the event timer which gave an accurate time correlation between the three high-speed cameras. In addition, a Polaroid sequence camera was used to obtain a series of eight pictures during model launch and free flight to assist in selecting the launch parameters for subsequent runs. Digitized angular and position data were derived from the high-speed film. These data were reduced to aerodynamic coefficients using the WOBBLE program.[16]

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