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GROUND-BASED FACILITIES FOR EVALUATING VORTEX MINIMIZATION CONCEPTS

Joseph W. Stickle

Langley Research Center

and

Mark W. Kelly

Ames Research Center

SUMMARY

To determine the feasibility of altering the formation and decay of aircraft trailing vortexes through aerodynamic means, NASA used the test capabilities of two wind tunnels and two towing basins. This paper describes the facilities, common models, and measurement techniques that were employed in the evaluation of vortex minimization concepts.

INTRODUCTION

The initial task of the NASA Wake Vortex Alleviation Program was to evaluate the many devices and concepts that had been proposed to alter vortex formation and decay. Facilities, therefore, were a major concern because the characteristics of the vortex system must be determined from the point of generation to points far downstream, representing in scale the area of interest to a following aircraft.

The problems, measurement techniques, and scaling of Reynolds number and viscosity effects were discussed among both Government and industry researchers in preparation for the evaluation program. It was generally agreed that evaluation testing should be limited to those facilities that can recreate, in model scale, an actual vortex penetration situation. It was further agreed that the facilities should have common models, standard measurement techniques, and be capable of providing a model Reynolds number on the order of 0.5 million or greater, based on the generating model chord. The facilities selected included the 40- by 80-ft wind tunnel at NASA's Ames Research Center, the vertical/short takeoff and landing (V/STOL) wind tunnel at Langley Research Center, and the Hydronautics Ship Model Basin in Laurel, Md. In addition, the inactive 549-m long towing basin at Langley was modified with a new overhead carriage system to provide a towing system using air as the test medium in lieu of water, as used at the Hydronautics facility. The new installation was designated the Langley Vortex Research Facility. The models selected include a 0.03-scale jumbo-jet transport generating aircraft and two trailing wing models representing, in span and aspect ratio, a small jet transport and business jet. Each facility had the capability to generate a vortex system and to measure directly the induced rolling moment of the vortex on the trailing models.

This paper describes the evaluation facilities and the standard measurement technique. It will also indicate the range of test capability including other measurement and visualization techniques that have been applied to the study of wake vortexes in these facilities.

It should be noted that reference 1 describes the development of a laser velocimeter for vortex flow analysis and the use of the water towing facility at the University of California, Berkeley. Although these were not part of the standard evaluation apparatus, they both contributed significantly to improved understanding of the complex nature of the aircraft trailing vortex system during the evaluation program.

SYMBOLS

b_W wingspan of vortex generator model, m

c local wing chord, m

$\bar{c}$ average wing chord, m

X distance behind vortex generator model, m

MODEL DESCRIPTIONS

Vortex Generating Models

The generating aircraft model used in each of the facilities was a 0.03-scale jumbo jet transport, shown in figure 1. A sketch and pertinent geometric characteristics are given in figure 2. The initial model built for use in the Hydronautics Ship Model Basin was constructed of aluminum, stainless steel, and plastic. The three remaining models were molded of fiber glass, using molds constructed from the Hydronautics model. Mounting techniques varied between facilities and are discussed in subsequent facility descriptions; however, each generating model was equipped with a force balance to measure the performance impact of the vortex alleviation concepts. The generating models were equipped with two spanwise segments of triple-slotted trailing-edge flaps and full span leading-edge slats. Flap brackets were available to provide flap deflections for each of the spanwise segments.

The generating model used in the Ames 40- by 80-ft tunnel used flow-through nacelles and had no internal air ducting. The Hydronautics model had internal tubing for dye injection that can be pressurized for studies of vortex dissipation concepts with very low mass flow (2.1×10^{-4} m^3/s). For high mass flow studies, such as engine thrust effects, the Hydronautics facility incorporated an overhead scoop and centrifugal pump arrangement as shown in figure 3. Water is taken in through the scoop and pumped through' two streamlined struts positioned ahead of the model. The flow was scaled to achieve the proper momentum and ratio of exit velocity to forward speed. The thrust of each strut was set to equal 25 percent of the generating model drag at the test lift coefficient. The lateral and vertical positions of the struts were varied to investigate the effects of engine placement.

The model used in the Langley Vortex Research Facility was equipped with high-pressure air (690 kPa (100 psi)) and internal tubing to simulate the engine thrust on all four engines. Flow rates have been adjusted to provide the appropriate thrust force; however, the ratio of model jet velocity to the model forward speed is higher than that .for full scale.

The V/STOL tunnel model also is equipped with high-pressure air (690 kPa (100 psi)) that can be used to simulate thrust in the manner similar to the Vortex Research Facility model. To date, mass flow tests in the V/STOL tunnel have involved only very-low-mass injection schemes and jettype spoilers.

Following Probe Models

The probe models are illustrated in figure 4 along with pertinent geometric characteristics. Each is a straight rectangular wing having the span (0.03 scale) and aspect ratio of a current day small jet transport aircraft and a business jet. The Hydronautics probe models are constructed of aluminum, although the other probe models are constructed of balsa wood. All of the probe models were instrumented with a single-component roll balance with the exception of the Hydronautics model, which also included lift and drag force measurement.

TEST PROCEDURES

The standard test procedure involves generation of a vortex system in the ground facility and surveying the flow field at various distances downstream using the roll-balance-equipped following model as a sensor. Although it is recognized that this technique represents only one of many types of penetrations likely to occur in a real situation, it does represent one judged to be most hazardous from a pilot/control standpoint. It is also safe to assume that large reductions in the induced rolling moment will result in reductions in the severity of other upset situations. Figure 5 shows the test setup for each of the four facilities. The generating aircraft are mounted in the V/STOL and 40- by 80-ft tunnels in the most forward position of the test section, and the probe models are used to survey the vortex field at discrete downstream locations. Because the generating models in these facilities are stationary and the airstream is moving, the probe models can sense the vortex at a given position over a long period of time. Typical sample periods ranged from 10 to 40 s. Rolling-moment data in the V/STOL tunnel were sampled once per second and averaged over the sample period; data from the 40- by 80-ft tunnel were selected as only the highest peak within the sample period. Comparison of the two analysis techniques, using data from the V/STOL tunnel taken at 7.5 span lengths downstream with the large probe model, indicated approximately 10 percent higher values using the peak measurements over the averaged measurements, It would be expected that the difference measured with the smaller model, or at greater distances downstream with either model, would be greater because of the meandering of the vortex.

In the towing facilities, both models are moving and the data recording time is limited. A normal test run in the Hydronautics facility was approximately 25 s, which provides about 15 s for a single vertical survey through the vortex. In the Vortex Research Facility, the probe model is positioned prior to the run, and the sample time is approximately 2 s. In both Hydronautics and Vortex Research Facilities, the highest peak data per sample were used.

Figure 6 indicates the range of downstream distances in generating model span lengths that can be tested in the various facilities. The dark areas represent distances for which data have been obtained to date. It is worthwhile to note that figure 6 shows the test capability for the V/STOL tunnel extends well into the diffuser section. Trends of the rolling-moment data obtained in the diffuser and corrected for dynamic pressure change have been found to be in general agreement with those at comparable distances from the Vortex Research Facility and from Hydronautics. Furthermore, reference 1 supports the diffuser results by comparing measurements made inside the test section behind a 1.22-m straight wing model with measurements outside the test section, but at identical span lengths behind a 2.44-m straight wing model.

HYDRONAUTICS SHIP MODEL BASIN

The Hydronautics Ship Model Basin is a water-towing facility 95 m long and 8 m wide, with a water depth of 4 m. Two independently powered carriage systems are used to propel the vortex generating model and the following probe model. Maximum speed for conducting constant-speed runs is 6 m/s; however, the evaluation tests were conducted at a nominal 3.8 m/s, which corresponds roughly to the approach speed in span lengths per second of the full-scale aircraft. Test Reynolds number at this speed is approximately 1.0×10^6. The carriage system is shown in figure 7 for the generating model and in figure 8 for the following model. The generating model is attached with a pair of rigid faired struts that are mounted to a tilt table. The tilt table provides for a pitch attitude adjustment from -4° to 12° relative to the model fuselage reference line. Vertical positioning is provided by substituting struts of different lengths. Normal test depth is 0.79 m below the surface; however, tests have been conducted at depths of 1.70 and 2.48 m. The latter depth places the generating model just under one span length above the tank floor for investigation of vortexes in ground effect.

Lateral adjustment of the generating model is ±0.71 from the tank centerline. The following model can be adjusted from the centerline to a position 2.28 m right of the centerline, giving a total lateral survey capability of 3 m. The following model has a motor-driven vertical scan system allowing a vertical survey of 0.46 m at a maximum rate of 0.04 m/s. In full scale, this would represent a climb rate slightly less than 30 m/min.

Separation distance between the two models was determined using the time differential for the two carriages to pass a point halfway down the tow tank and the measured speed of the carriages. For all tests, a sufficient number of vertical and lateral surveys were conducted to assure that the maximum imposed rolling moment present was measured at the various downstream distances. A sample time-history of data obtained during a test run is shown in figure 9. In the rolling-moment trace, the moment level builds and decays as the following model rises through the vortex. The maximum peak for each run is considered the maximum imposed rolling moment.

Prior to the vortex evaluation program, exploratory tests were made in the Hydronautics facility using hot wire anemometers and a vortex swirl meter to define vortex characteristics.

VORTEX RESEARCH FACILITY

A sketch of the Langley Vortex Research Facility is shown in figure 10. A gasoline-powered carriage is shown mounted on the 554-m overhead track, with the vortex-generating model blade mounted beneath the carriage. The following model is located 50 m downstream of the vortex generating model (a scale distance of 1.63 km (0.88 n. mi.)) through a series of trailers to measure the rolling moment induced by the vortex of the lead model.

The test section, constructed to isolate the wake of the carriage and trailers from the model wake, is 92 m long with a 0.05-m opening along the center of the ceiling to allow the model blade mounts to pass. The exterior of the building, shown at the entrance of the test section, encloses the entire length of the track.

The overhead track extends 308 m upstream of the entrance to the covered area where each test is initiated. After the carriage is launched, the automotive drive system accelerates through first and second gear to a velocity of 31 m/s, which is held constant by a cruise control throughout the length of the covered area. At the test position, 31 m inside the covered area, smoke (vaporized kerosene) is deployed for flow visualization. (See ref. 2.) At this point, high-speed motion picture and TV cameras are used to film the motion of the vortex produced by the generating model, while the aerodynamic forces experienced by the model are recorded. After 1.6 s, the following model reaches this test point, measuring the vortex-induced roll. Caliper brakes are applied as the vehicle leaves the covered area, bringing the vehicle to a 1-g stop over the next 77 m of track.

Figure 11 illustrates data trace taken from a typical run. As the model enters the closed test section, downwash of the carriage is isolated from the vortex system and the vortex rises slightly into the path of the probe model indicated by the slight jump in rolling moment at time equal to 10 s. Thirty-one meters, or 1 s later, the test sample begins and covers the next 2 s of data. The maximum induced rolling moment is determined using the peak rolling moment during the test interval with the aid of video recording showing the position of the probe relative to the vortex core. Normal test Reynolds number in the Vortex Research Facility is 4.7×10^5.

V/STOL WIND TUNNEL

The V/STOL tunnel, located at NASA's Langley Research Center, has a test section 4.42 m high, 6.63 m wide, and 15.24 m long. (See fig. 12.) It can be operated as a closed tunnel with slotted walls, or as one or more open configurations by removing the side walls and ceiling. Tunnel speed is variable from 0 to 100 m/s (200 knots). In the vortex program, a majority of the tests were run at a free-stream dynamic pressure in the test section of 430.90 Pa, which corresponds to a velocity of 27.4 m/s. The Reynolds number based on the generating model chord was approximately 4.7×10^5. Investigations of the effect of Reynolds number on the rolling-moment data were conducted up to Reynolds numbers 1×10^6. No significant effects were detected. Blockage corrections were applied to the data by the method of reference 3. Jet-boundary corrections to the angle of attack and to the drag were applied in accordance with reference 4. Basic aerodynamic data of lift, drag, and pitching-moment coefficients for the generating model were obtained over an angle-of-attack range of -4° to $+24^{\circ}$.

The probe model was attached to a traverse mechanism capable of moving the model approximately 2 m laterally and vertically. The electric-powered traverse mechanism was positioned at various downstream distances and the flow field was surveyed. Contours of constant averaged rolling moment such as shown in figure 13 were produced. The location of single or multiple vortexes within the survey area were easily recognizable, particularly when using the smaller probe model. Other test capabilities used in the study of vortexes in the V/STOL tunnel include the three-component hot-wire anemometers and visualization techniques employing smoke and neutrally buoyant hydrogen soap bubbles.

40- BY 80-FT SUBSONIC WIND TUNNEL

The 40- by 80-ft subsonic wind tunnel is a closed-circuit wind tunnel used primarily for determining the low-speed aerodynamic characteristics of aircraft and spacecraft. The oval-shaped test section measures 12.19 m high by 24.38 m wide and is 24.38 m long. Airflow is produced by six variable-speed 12.19-m diameter fans, each powered by a 4.474 MW electric motor. Speed is continuously variable from 0 to 100 m/s (200 knots) at atmospheric pressure.

A photograph of the experimental setup for the vortex studies is shown in figure 4. The generator model is located at the forward end of the test section and the following model at the exit, The generator model is centrally located in the inlet and is attached by a single strut through a strain-gage balance to measure lift. The angle of attack of the generator is set remotely through an actuator and indicator. Downstream of the generator model 24.4 m a follower model is mounted on a single strut that can be remotely positioned vertically over a 3.05 m range and laterally over a 4.27 m range. The follower model is attached to its strut through a strain-gage balance to measure rolling moment. Full-scale range for the balance is such that adequate sensitivity would be provided for the rolling moment encountered on each model.

Figure 15 shows a typical record of rolling-moment variation with time. The source of the unsteadiness of the rolling-moment signals is the meander of the vortexes in the wind tunnel due to wind-tunnel turbulence. Earlier studies in the tunnel (ref. 5) have shown that single vortexes can move about as much as 1 m at this downstream location. The peak rolling-moment values shown on figure 15 are interpreted as corresponding to the times when the following model is alined with a vortex center. During the 38 s of data shown, the peak rolling moment was repeated three times.

The generator model was tested in both the upright and inverted positions to evaluate strut interference effects. It was found that for the conventional configurations, where the vortexes are shed primarily from the wingtip region, no strut interference could be found. However, for the configurations with the span-loading shifted inboard, in which vortexes are shed inboard of the wingtip, an inverted mounting of the generator model was required to avoid interference caused by the wake of the model mounting strut. Figure 14 shows the generator model in this inverted position.

Other test equipment used in the 40- by 80-ft tunnel for vortex study includes a hot-wire anemometer mounted on a rotating arm to survey the vortex flow field. The equipment and technique are described in reference 5.

COMPARISON OF TEST DATA

Figure 16 presents curves of lift coefficient versus angle of attack for the four generating aircraft models in their respective facilities. In each case, the generating model was in the normal landing-flap configuration and the tail incidence was set at 0^{o}. The curves indicate good agreement between facilities throughout the angle-of-attack range. A majority of the tests were conducted at a lift coefficient of 1.2 to approximate landing approach conditions and comparisons of data between facilities.

Figure 17 shows values of the induced rolling moment measured by the probe models with the generating aircraft in the normal landing flap configuration at a lift coefficient of 1.2. The data from the large probe model, figure 17(a), show a relatively consistent trend of rolling-moment coefficient with downstream distance if one neglects the data points taken in the diffuser section of the V/STOL tunnel. The data for the small probe model show a wider variation, with the V/STOL tunnel data well below that for the other facilities. The lower values of the rolling-moment coefficient may result from the data processing technique used in the V/STOL tunnel and its effect on the small model measurements.

The comparison of baseline data between facilities is intended to aid the reader in viewing results from other papers of this conference. The criterion for success of an alleviation concept was based on the ability of the concept to reduce the imposed rolling-moment coefficient at a downstream range of about 2 km (1 n. mi.) to a level that can be countered by the airplane's control system. For the small transport aircraft, the control induced rolling-moment coefficient capability is approximately 0.08; for the business jet, the value is about 0.05. If these values are applied in the Hydronautics facility, which had the highest test Reynolds number, the target alleviation at 1.9 km (1 n. mi.) represents a 32-percent reduction in rolling-moment coefficient for the large probe model and a 60-percent reduction for the small probe model. These reductions were considered in judging the effectiveness of concept in lieu of absolute values.

SUMMARY REMARKS

To determine the feasibility of alleviating the formation and decay of aircraft trailing vortexes through aerodynamic means, NASA used the test capabilities of two wind tunnels and two towing basins. The wind tunnels included the 40- by 80-ft subsonic wind tunnel at Ames Research Center and the V/STOL tunnel at Langley Research Center. An inactive towing basin at Langley (renamed the Vortex Research Facility) was converted to a high-speed (31 m/s) towing basin using air as the test medium; and a contractor's water towing facility was used, the Hydronautics Ship Model Basin, in Laurel, Md. With common models and measurement techniques employed, each facility was capable of creating a scale model vortex system and measuring the imposed rolling moment on a probe model at various downstream distances. Comparison of the lift data for the baseline generating model (landing configuration) showed good agreement between facilities.

The imposed rolling moments on the probe models from the baseline model showed relatively good agreement between facilities for the large probe model. Agreement for the small probe model was not as good. Therefore, to evaluate vortex alleviation concepts, it was necessary to consider a percentage reduction in rolling-moment coefficient for each model at each facility in lieu of an absolute target level.

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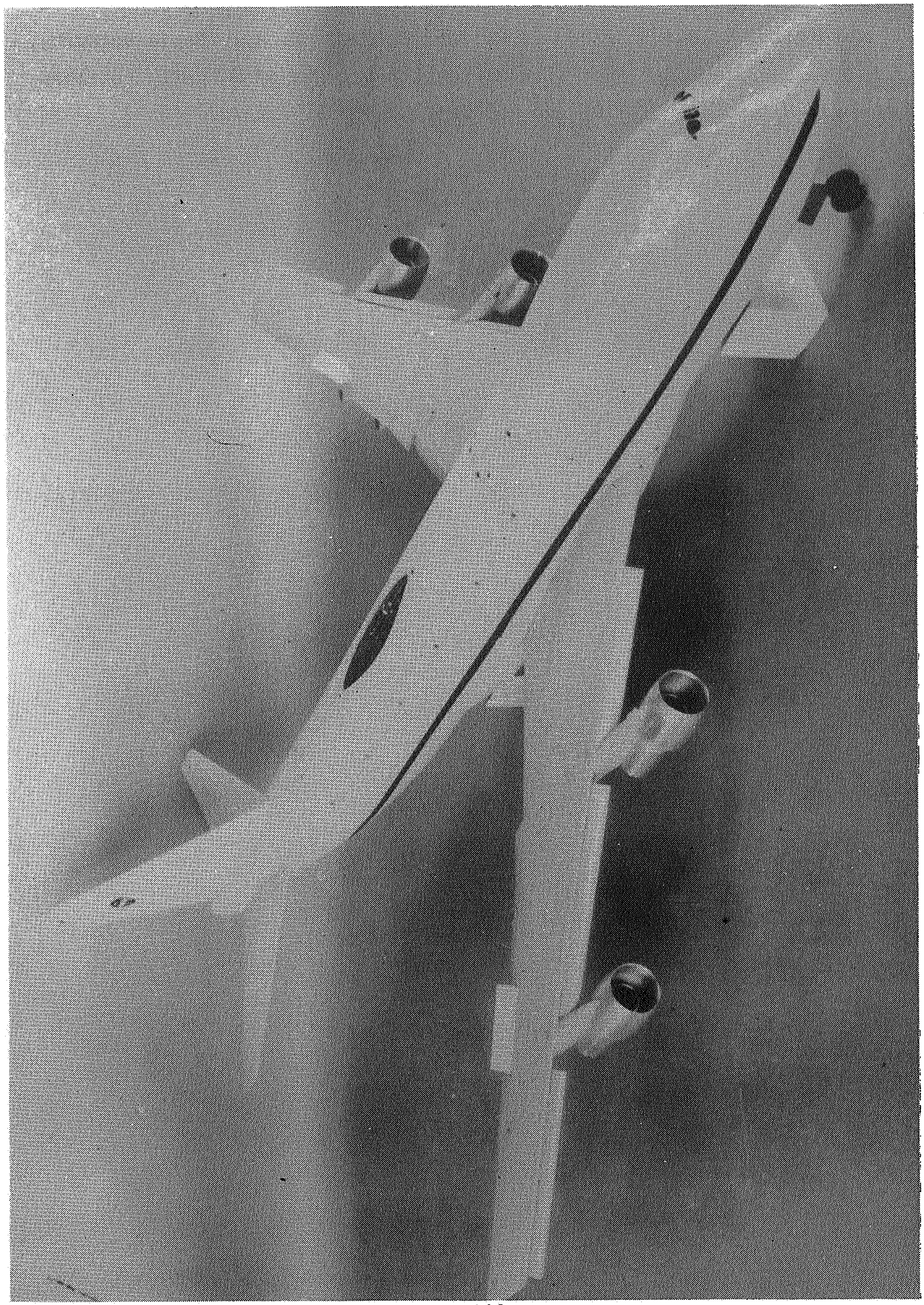
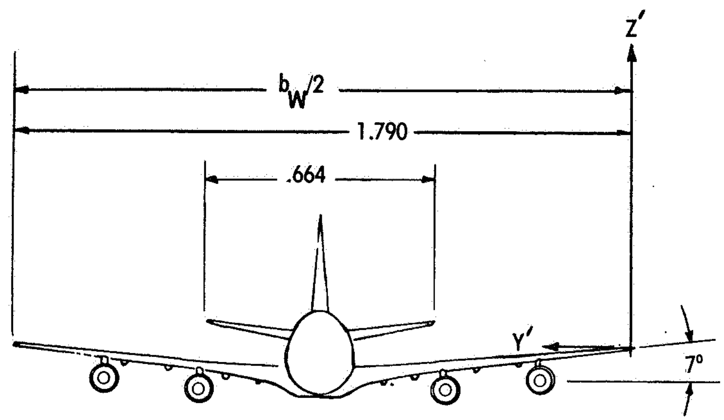


Figure 1.--Photograph of vortex generating model

Wing	
Span, m	1.79
Mean aerodynamic chord, m	0.25
Root chord, m	0.497
Tip chord, m	0.121
Sweepback at quarter chord, deg	37.5
Area, m^2	0.460
Aspect ratio	6.96
Fuselage	
Length, m	2.06
Horizontal tail	
Span, m	0.664
Area, m^2	0.123
Aspect ratio	3.6



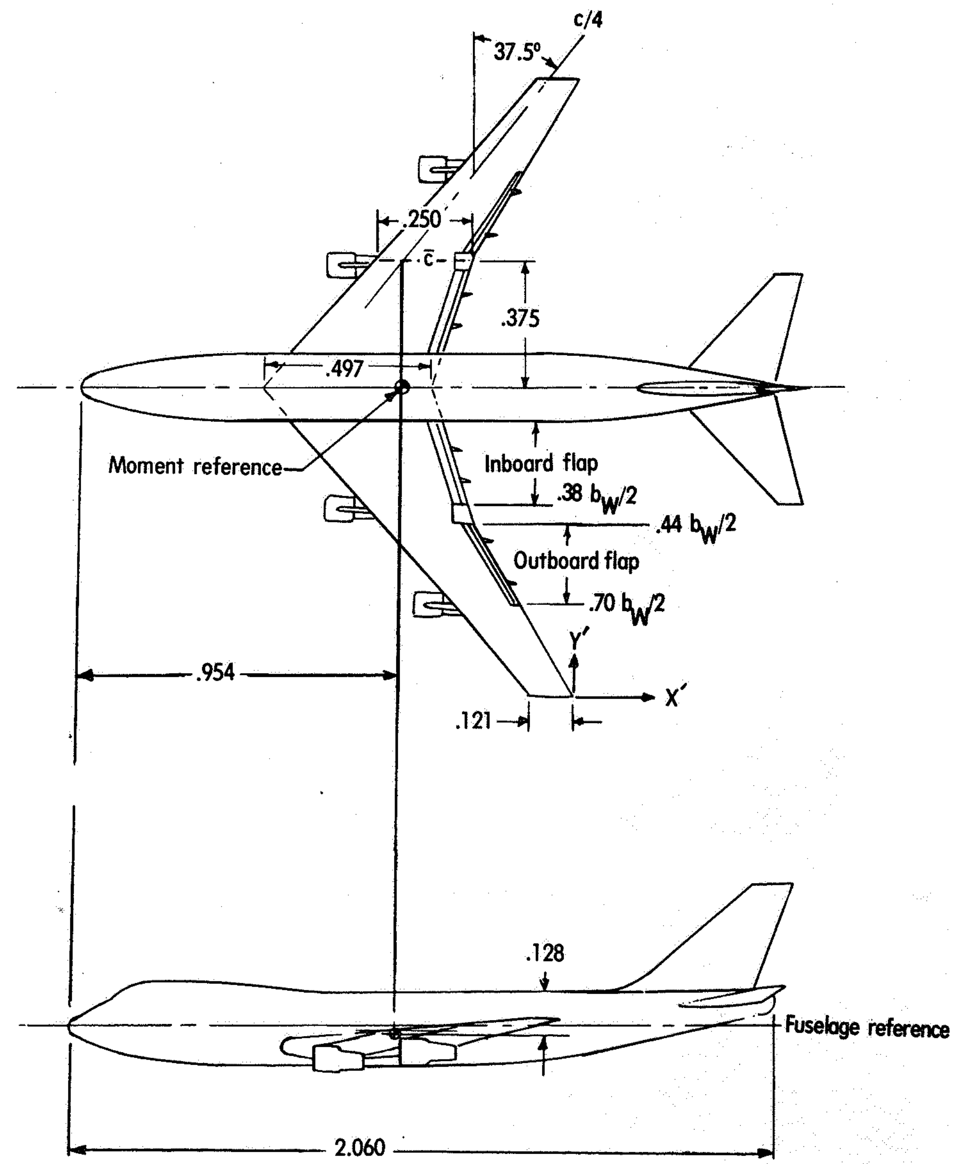


Figure 2 --Sketch and geometric characteristics of vortex generating model.

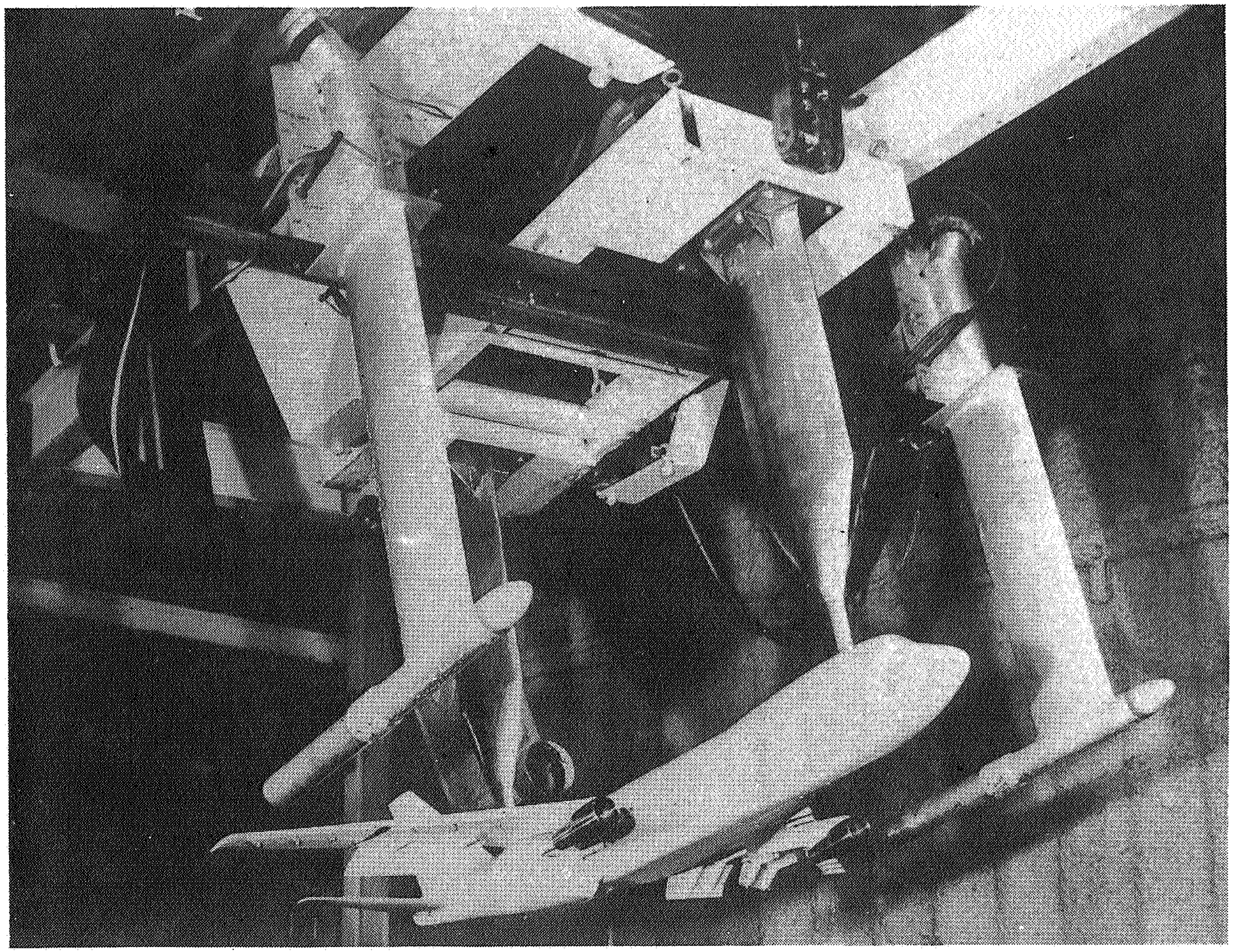


Figure 3.--Thrust simulation apparatus used in Hydronautics Ship Model Basin.

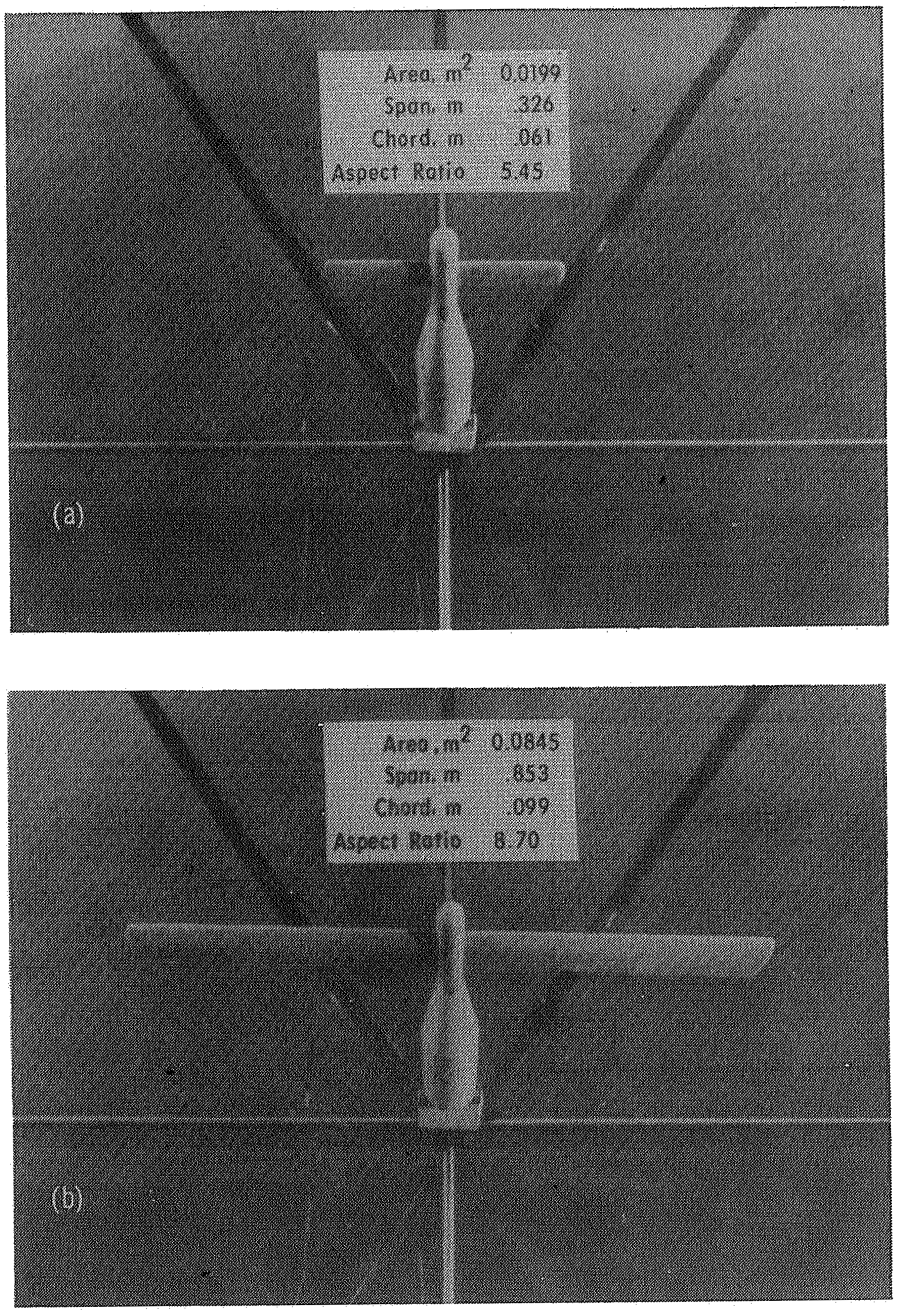


Figure 4.––Photograph of trailing models. (a) Small. (b) Large.

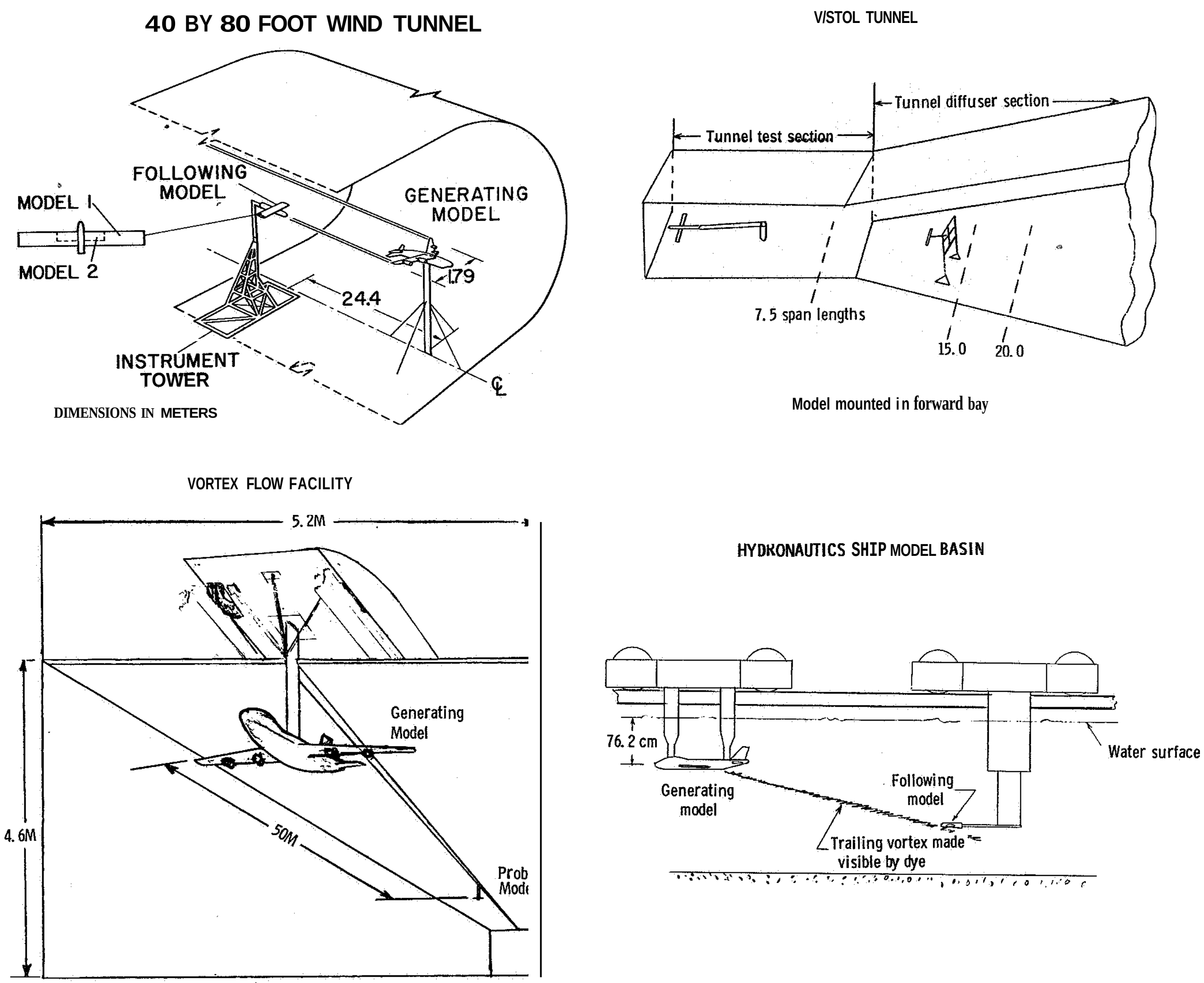


Figure 5.--Test arrangement in evaluation facilities.

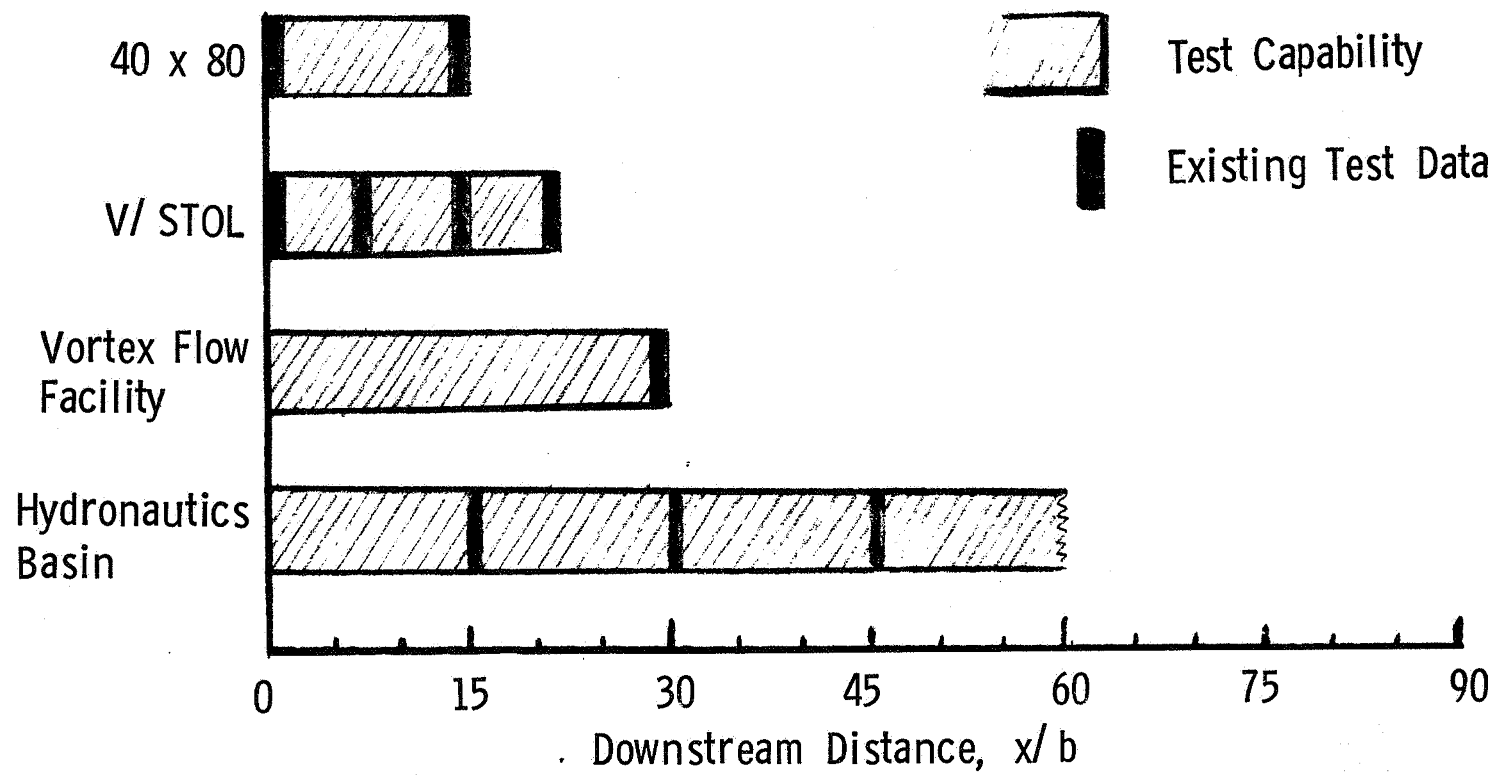


Figure 6 --Range of downstream test capabilities in evaluation facilities.

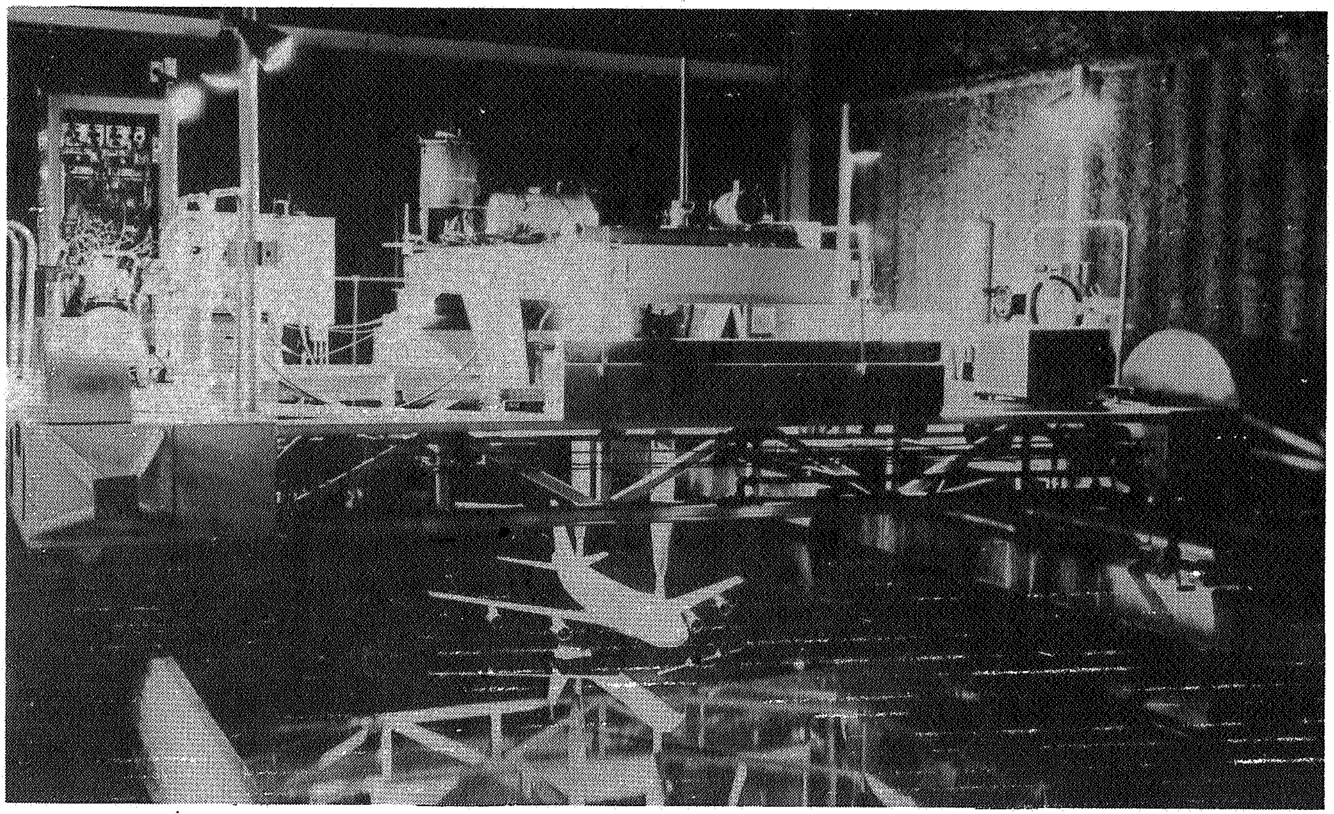


Figure 7.--Generating model carriage system--Hydronautics facility.

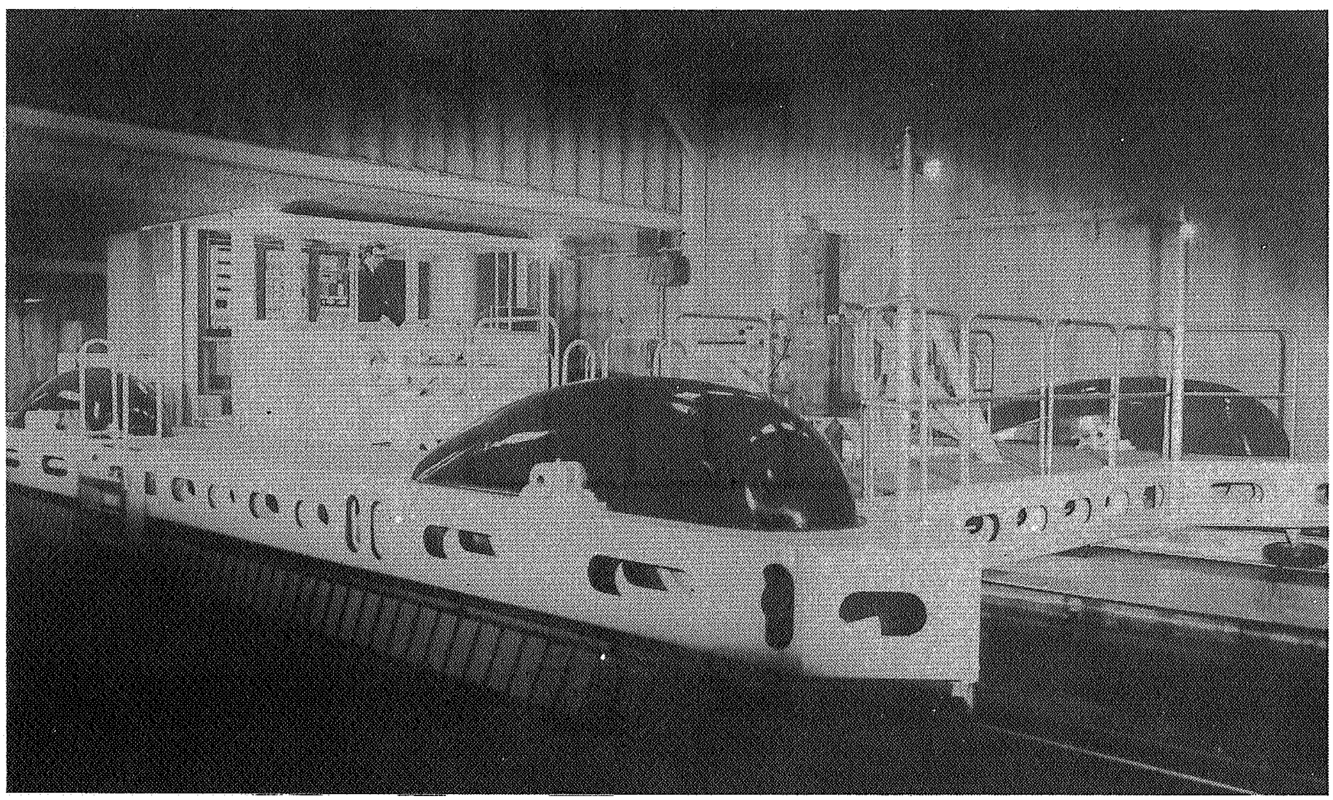


Figure 8.--Probe model carriage system--Hydronautics facility.

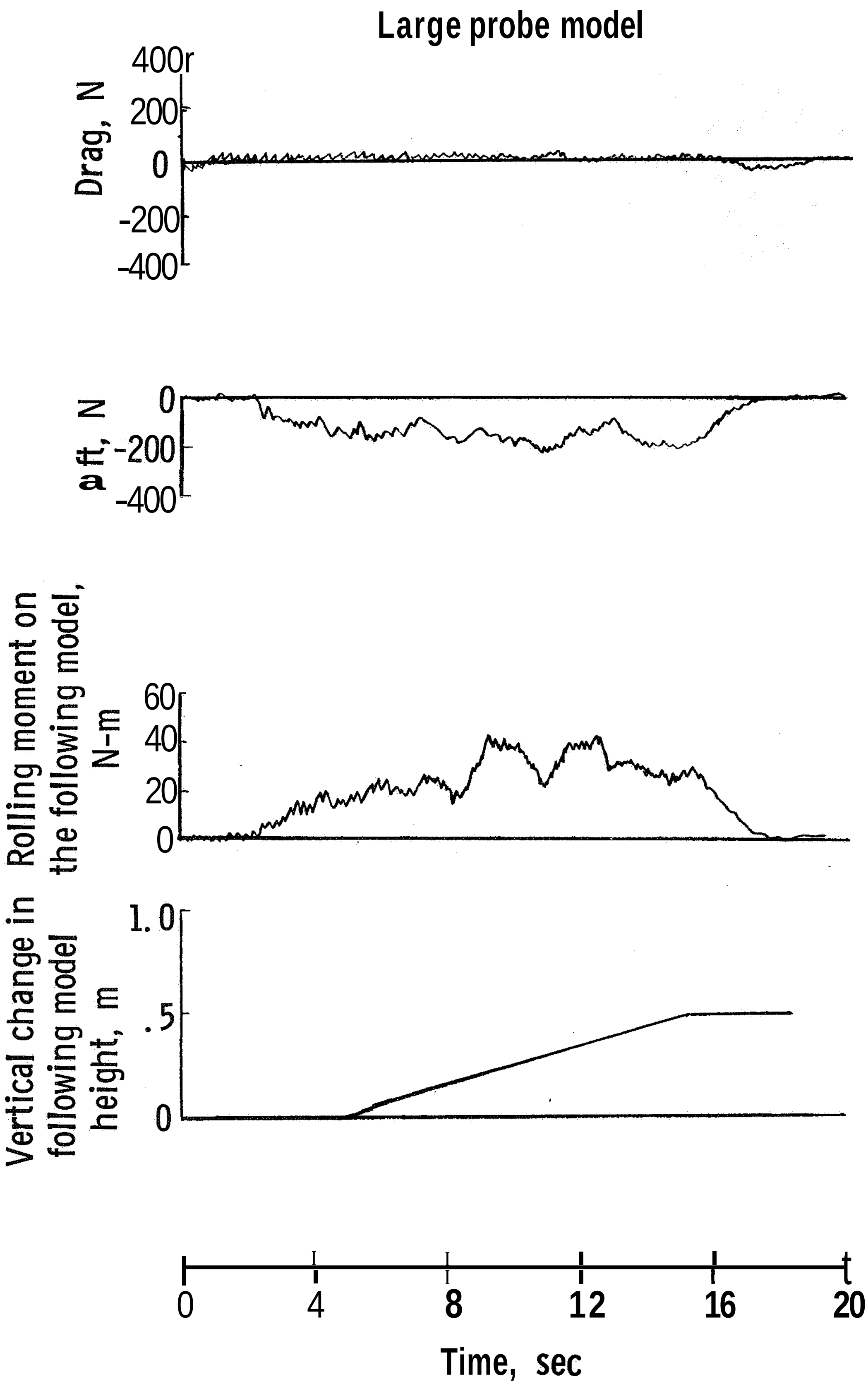


Figure 9.--Sample time history of vortex penetration--Hydronautics facility.

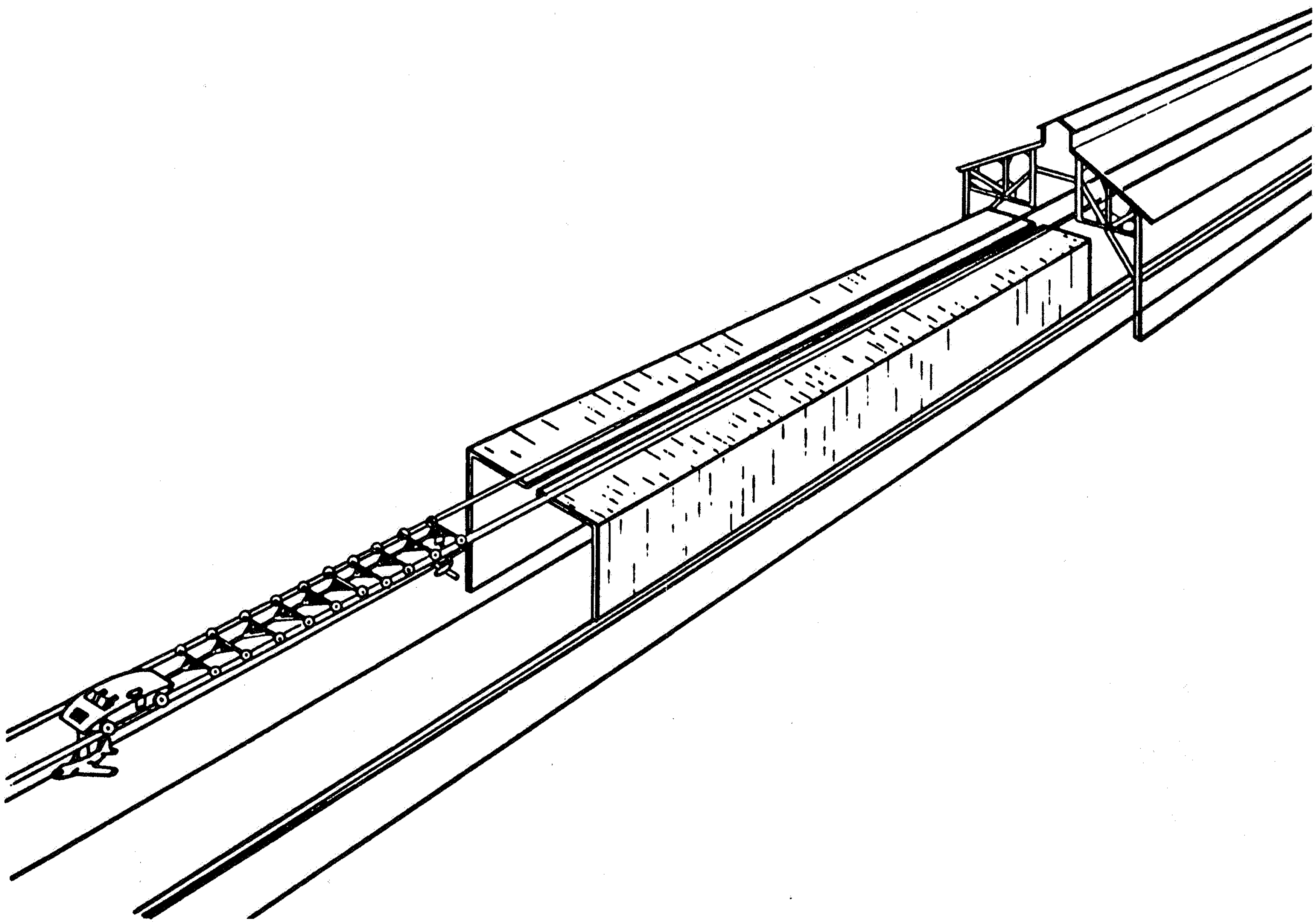


Figure 10.--Sketch showing the Langley Vortex Research Facility.

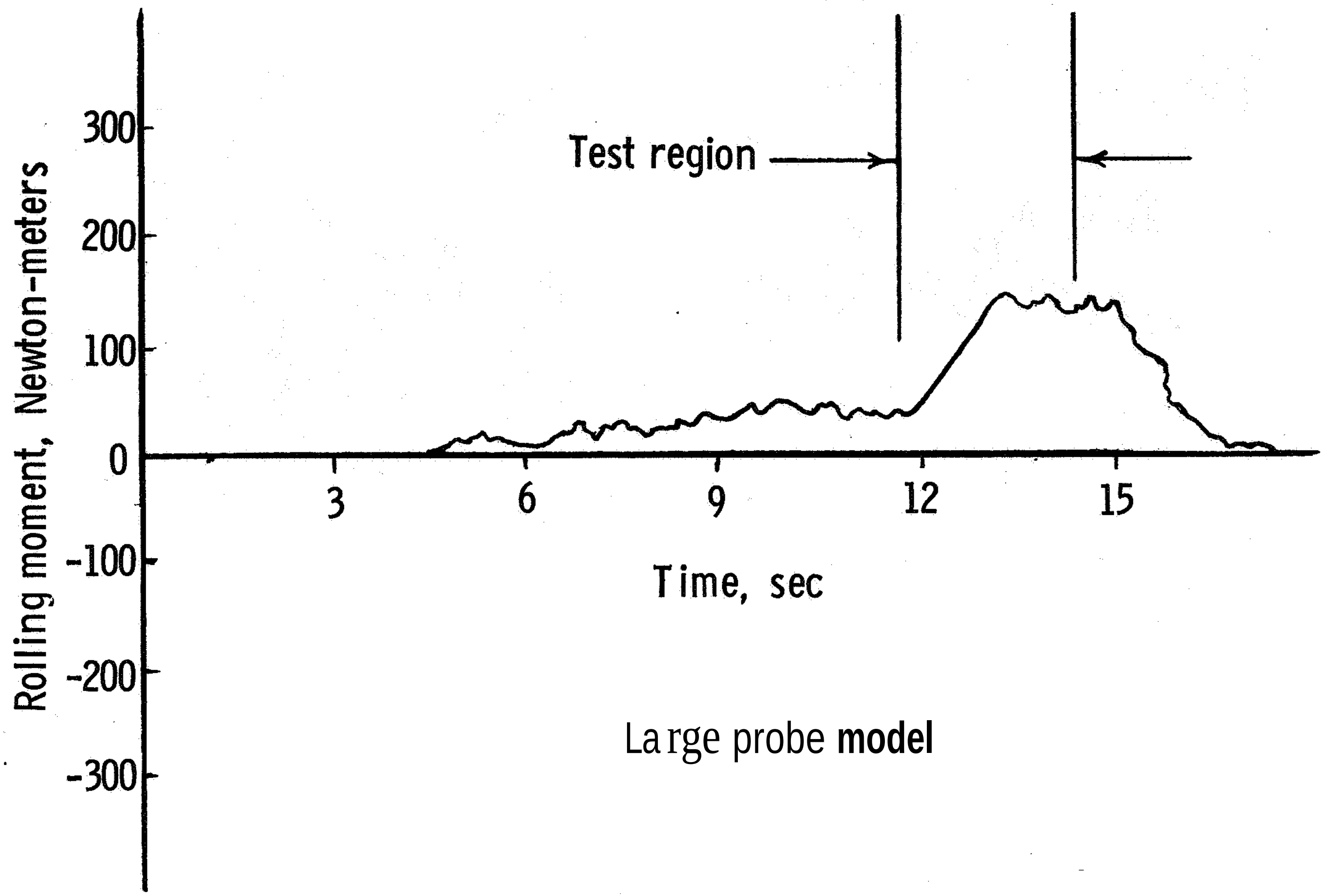


Figure 11.--Sample time history of vortex penetration--Vortex Research Facility.

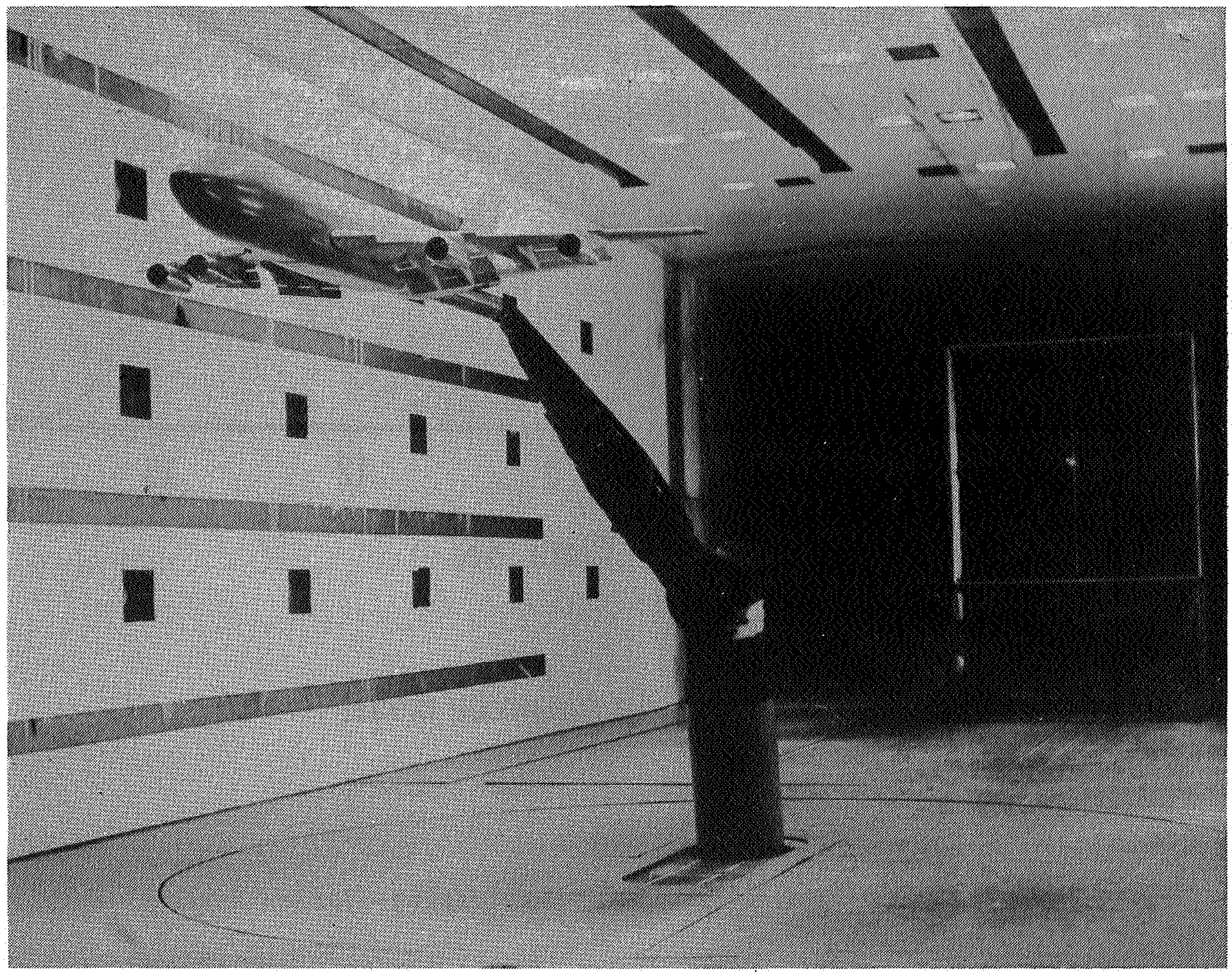


Figure 12.--Photograph of test apparatus in V/STOL tunnel.

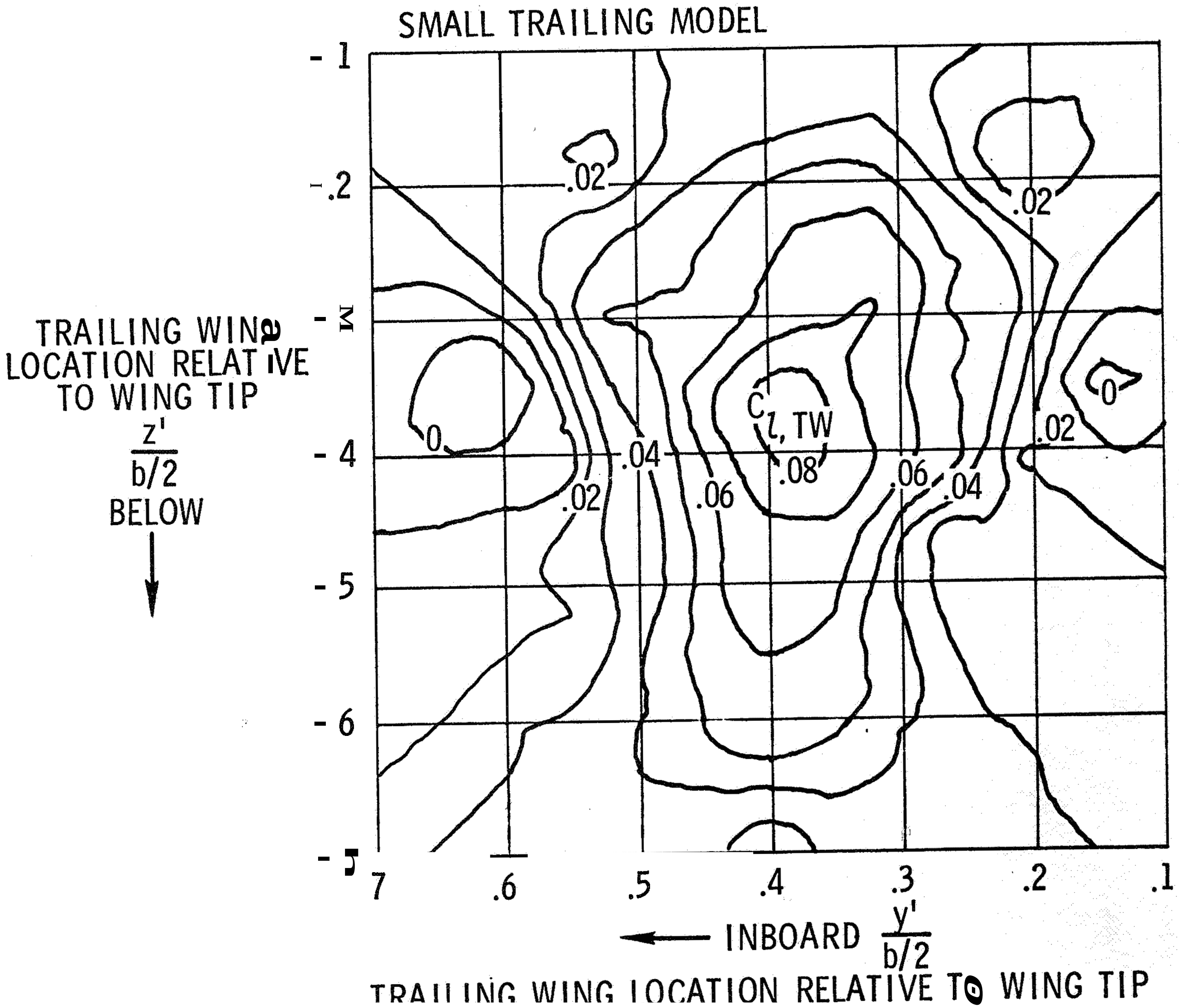


Figure 13.--Data sample showing rolling-moment contours--V/STOL tunnel.

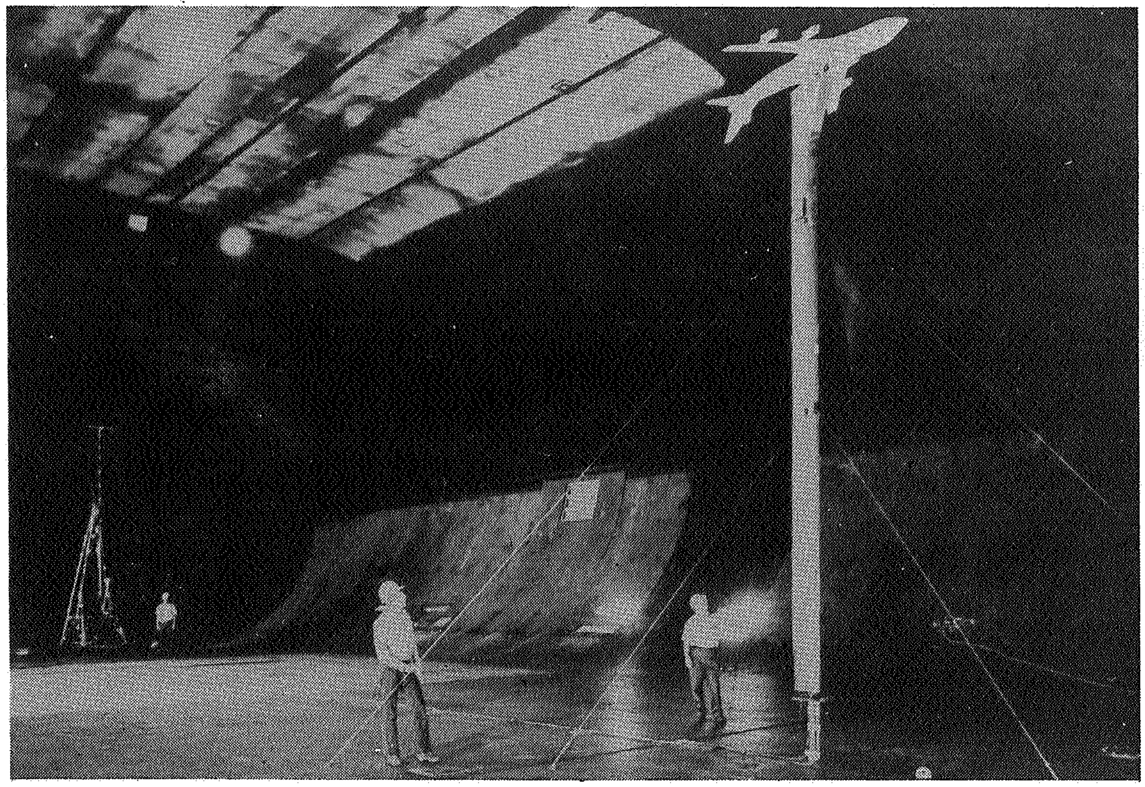


Figure 14.--Photograph of test setup in the 40- by 80-ft wind tunnel.

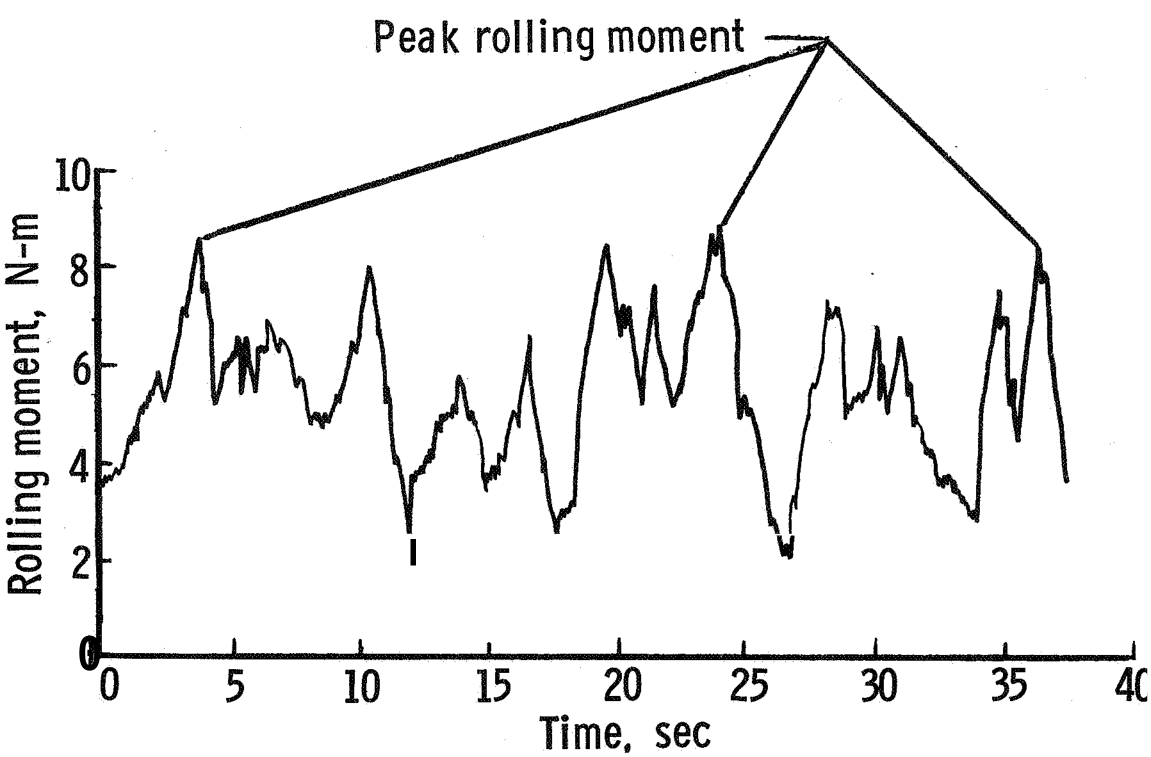


Figure 15.--Sample of rolling moment variation with time in the 40- by 80-ft tunnel.

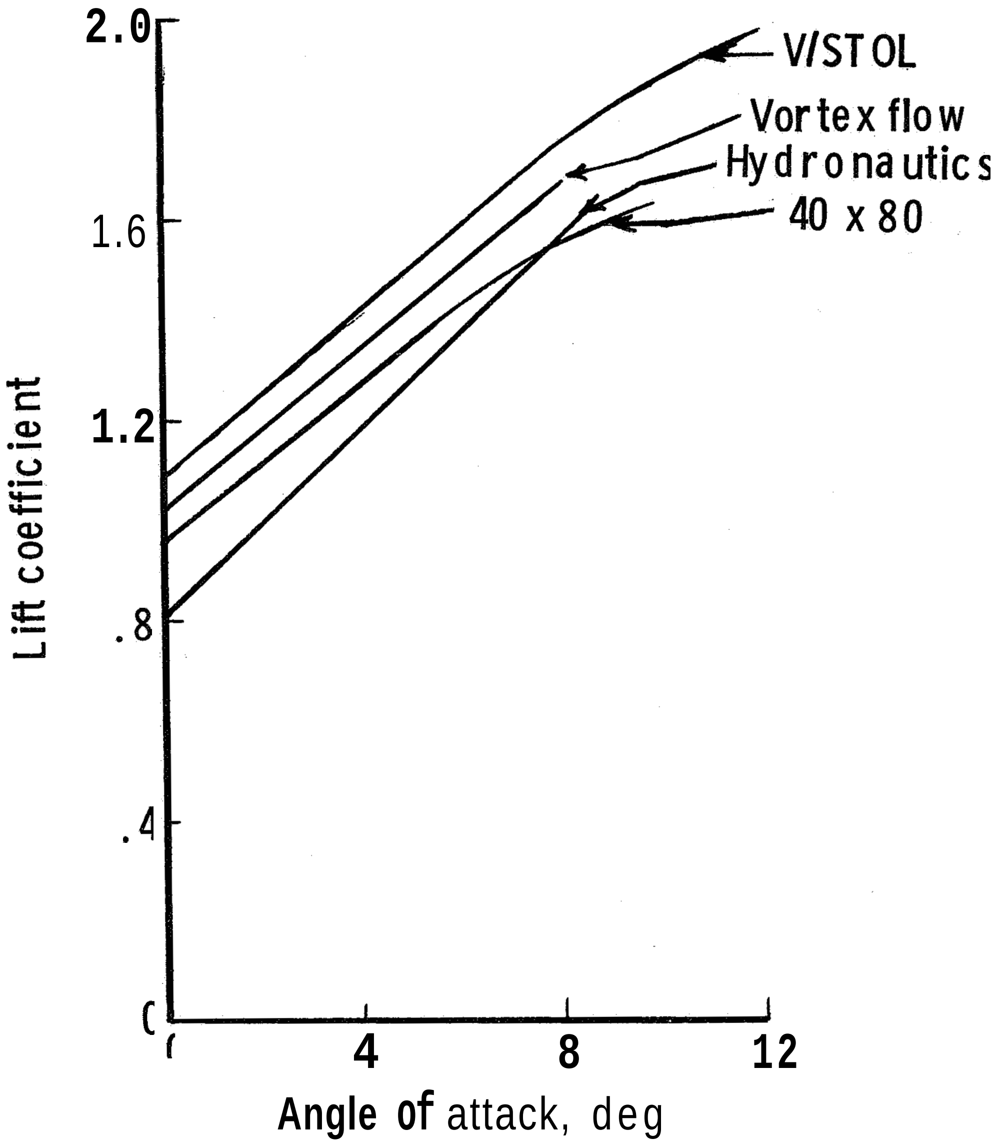


Figure 16.--Comparison of generating-model lift coefficient data from the evaluation facilities.

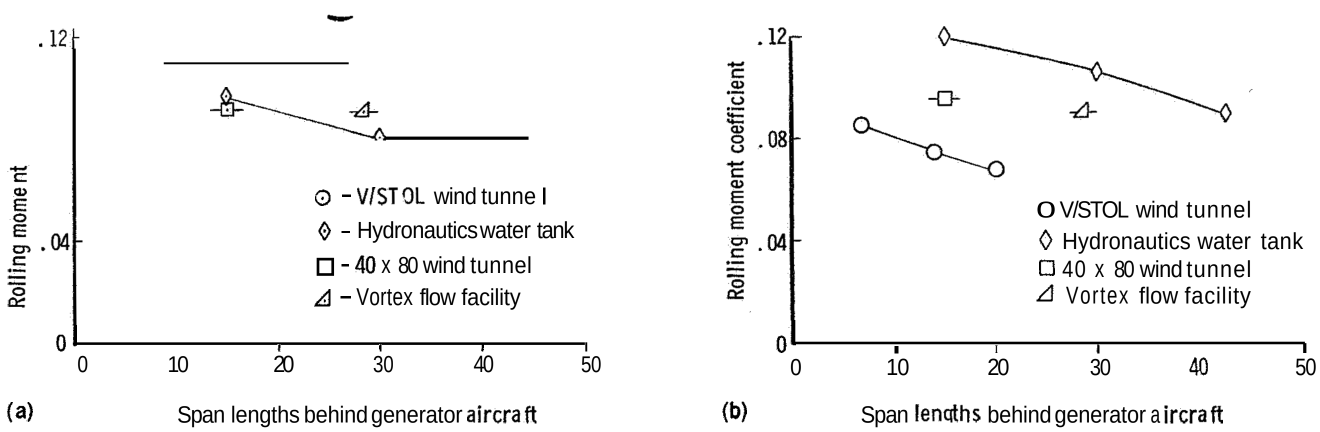


Figure 17.--Comparison of induced rolling-moment coefficients from the evaluation facilities. (a) Large probe model. (b) Small probe model.