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ABSTRACT

FLOW DIRECTION MEASUREMENT CRITERIA AND TECHNIQUES PLANNED FOR THE 40- BY 80-/ 80- BY 120-FOOT WIND TUNNEL INTEGRATED SYSTEMS TESTS

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A study was performed in order to develop the criteria for the selection of flow direction indicators for use in the Integrated Systems Tests (ISTs) of the 40- by 80-/80- by 120-Foot Wind Tunnel System. The problems, requirements and limitations of flow direction measurement in this wind tunnel were investigated. The locations and types of flow direction measurements planned in the facility were then discussed. A review of current methods of flow direction measurement was made and the most suitable technique for each location was chosen. A flow direction vane that employs a Hall Effect Transducer was then developed and evaluated for application during the ISTs.

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V - flow velocity

f_n - natural frequency (Hz)

W_n - natural frequency $\frac{rad}{sec}$

λ_n - natural wavelength

f_d - damped frequency

f - response frequency (Hz) ($1/t_s$)

λ_d - damped wavelength

ζ - damping ratio

t_s - settling time

β_o - initial offset angle

β_1 - first peak of response curve

D - delay distance

CHAPTER 1

Introduction

Background

In 1979, modifications were begun on the NASA 40- by 80-Foot Wind Tunnel located at Ames Research Center in California. The test section flow speed was increased from 200 to 300 knots with the installation of a new 100-MW fan drive system. A new 80- by 120-foot test section wind tunnel capable of flow speeds of 100 knots was also built in the form of a nonreturn leg that was grafted onto the 40- by 80-Foot Wind Tunnel at a 45-degree angle just ahead of the drive section (Figure 1).

In 1982 modifications were completed and the tunnels each began a set of check-out tests. During a test in the 80- by 120 mode of operation an accident occurred involving the failure and collapse of a turning vane cascade. The investigation of the accident and the resulting design reviews of all components of the facility have shown that flow direction is an important structural as well as aerodynamic design parameter.

Several components of the wind tunnel have been found to require flow alignment consideration. A well-aligned airstream in the test section is mandatory to assure data quality. Structural loading of turning vane cascades is sensitive to flow that is not entering and exiting at the proper angle (Reference 1). The performance of the large atmospheric inlet (Figure 2) and the structural loading of the tunnel walls depend on the direction of the wind (Reference 2). The fan drive efficiency depends on onset flow conditions and exit swirl (Reference 1).

Purpose of Study

A study was done to develop the criteria for selection of flow direction indicators for use in the 40- by 80-/80- by 120-Foot Wind Tunnel Integrated Systems Tests (ISTs). This task required an evaluation of the flow angularity that exists in this type of wind tunnel facility. Problems, requirements and limitations of flow direction measurement at the various locations in the wind tunnel were investigated. The current methods of flow direction measurement were then studied, and the final task was to determine which methods of flow direction measurement best suit each location in the wind tunnel.

Flow direction is seldom measured outside of the test section of a wind tunnel. Circuit flow angularity measurements done because of structural concerns is new. Flow misalignment outside of the test section has typically been ignored because the structure was designed with conservative load estimates. However, as a wind tunnel gets larger and materials get more expensive, the structure must be designed closer to load limits and flow direction becomes critical. Flow direction measurements around the entire flow path of the Langley 4- by 7-Meter Wind Tunnel were done during efforts to improve the aerodynamic performance of the facility (Reference 3).

Integrated Systems Test Description

Before the 40- by 80-/80- by 120-Foot Wind Tunnels can begin research testing, they must each be put through a set of start-up tests. These tests will assure that each component of the facility is structurally sound. Structural and aerodynamic loads must be close to predicted levels. Baseline information about the facility will be gathered in order to document tunnel performance and to assure research readiness. These start-up tests on the 40- by 80-/80- by 120-Foot Wind Tunnels are called the Integrated Systems Tests (ISTs). The ISTs are scheduled to occur during 1986 and 1987.

Flow direction will be measured at various locations in the wind tunnels during the ISTs. Flow misalignment is an important parameter that affects data quality in the test section, structural loading of the turning vane cascades and walls, and the performance of the fan drive and atmospheric inlet.

Problems, Limitations and Requirements of Flow Direction Measurement

Several factors must be considered when choosing or designing a flow direction indicator for use at a certain location in a large-scale, subsonic wind tunnel. Consideration must be given to the type of flow direction measurement that is required, the physical makeup of the indicator and support, the indicator accuracy and measurement range, and the indicator calibration. Thought must also be given to how data will be collected and transmitted.

Two types of flow direction measurements are made. Long time average measurements are done when the flow angle changes very little with time (essentially steady state). The second type is to measure how flow angle changes with time. For the second case, the frequency of the change in flow angle is an important parameter to consider when choosing an indicator.

The size of a flow direction indicator used to measure unsteady flow angle depends on the size of the eddies that cause the angle fluctuation. In large, open channels the eddies may be fifty feet in diameter while behind a turning vane cascade the eddies may be merely inches in diameter. To obtain approximately an instantaneous flow direction measurement, the vane size must be smaller than the eddy size and the response time must be as fast as the eddy passing frequency.

The size of the 40- by 80-/80- by 120-Foot Wind Tunnel leads to some special problems. Instrumentation must be mounted at great heights in order to sample centerline tunnel flow. This problem sometimes leads to the construction of tall, complex mounts or rigid booms to avoid deflections that will misalign the probe with respect to the tunnel centerline. Instrumentation must be installed outside the flow disturbances caused by these mounting structures. The method of traversing a probe across a wind tunnel has been used to evaluate the flow in smaller wind tunnels (Reference 3). This process becomes more difficult as the wind tunnel spans increase. Many fixed position probes can be used to get a flow direction profile across a tunnel. Care must be taken to assure that spacing is not so coarse that significant effects are missed, and that the probe mount is rigid.

Flow direction indicators must be rugged in order to survive the hazards in a large-scale, subsonic wind tunnel. Particle contamination of the flow from many sources can clog, jam or break wind tunnel instrumentation. Other possible hazards are vibrations and the process required to mount the indicators at great heights.

The measurement range of flow direction indicators varies greatly with tunnel location and flow conditions. In a test section the steady or unsteady flow angle may vary ±0.5 degrees away from the tunnel centerline and must be resolved to ±0.1 degrees. The average flow direction around a turning vane cascade may vary as much as ±5 degrees and must be measured with a resolution of ±1 degree. Exterior winds can be blowing from any direction at a given time and may only require to be resolved to ±5 degrees.

Flow direction indicators for use in a large-scale, subsonic wind tunnel should be accurate and able to operate at low flow speeds. For example, when the test section flow speed of the 40- by 80-Foot Wind Tunnel is 100 knots, as it will be at the start of the IST, the flow speeds in other portions of the wind tunnel will be as low as 10 knots. Valuable data can be lost if the flow direction indicator's velocity range does not extend low enough.

Calibration of flow direction indicators is generally done prior to installation. The indicators are then used and recalibrated periodically. Due to the large number of indicators required to cover large areas, the indicator mounting heights and the difficulty involved in aligning the indicators with a reference line, recalibration is not an easy task. A flow direction indicator that remains calibrated for long periods of time is desired.

Data will have to be transmitted great distances during the ISTs of the 40- by 80-/80- by 120-Foot Wind Tunnels. The form that this data is transmitted in must be considered. Long lengths of pressure tubing will damp any pressure fluctuations and average the data. If the tubing is shortened by placing a pressure transducer close to the measurement location, the problem of signal noise due to long lengths of wire occurs. Fiber optics has emerged as a solution to these problems. Voltage signals can be sent as digital light pulses across large distances with no signal noise problems. Another method that has been employed to reduce the distance problem is to use a microcomputer to collect the data near the measurement location.

Types of Flow Direction Measurements

Test Section Flow Angularity Measurement

The test section is the most important location to have steady aligned flow in a wind tunnel. Achieving good flow in the test section is the object of improving the aerodynamic performance of other portions of the wind tunnel. Flow misalignment in the test section will affect the quality of the data obtained from models. A steady flow angle away from the centerline will cause erroneous readings from balances. A fluctuating flow angle will have the same effect and may also cause dynamic structural loading problems.

A standard for acceptable flow angularity in the 40- by 80-/80- by 120-foot test sections has been established (Reference 4). Locations were chosen along the tunnel centerline, 1/4 of the test section span to the left and right of the centerline and just above the floor at the center of the turntable. These locations correspond to areas where most model testing is done. The longitudinal and lateral flow direction variation from centerline must be within ±0.5 degrees.

Low frequency, 1 Hz or less, changes in flow angle must also be measured. This type of flow angle variation has been called "meander." Meandering of the flow occurred during the initial check-out of the 80- by 120-foot test section.

Turning Vane Onset and Outflow Angularity Measurement

Flow angle ahead of a turning vane cascade must be known in order to calculate lift and drag loads on the entire cascade and the individual vanes. Steady flow entering at the wrong angle may increase the pressure loss of the turning vane cascade and reduce the speed of the flow in the test section (Reference 1). Unsteady flow angle may cause dynamic loads that threaten structural integrity.

Outflow direction from turning vane cascades will be measured at several locations during the ISTs. An average turning angle of the entire turning vane cascade is desired. Outflow direction coupled with onset flow direction affects the magnitude of the loads on the turning vane cascade. Aerodynamic testing of small-scale turning vanes and structural analysis has determined the maximum flow angle ranges to maintain loads at a safe level.

Fan Drive Onset and Outflow Angularity Measurement

Flow direction entering and exiting the fan drive system will be measured. Fan performance is affected by the entering flow. Misaligned and unsteady flows have the ability to stall and damage a fan drive system. Excessive swirling of the exiting flow from a fan drive affects the performance of the diffuser after the fan drive and may cause loads on the next turning vane cascade to be increased. A high swirl also is an indication that stator blades may be overloaded and need to be adjusted.

Exterior Wind Direction

Atmospheric wind conditions will be measured during the IST of each wind tunnel. Wind velocity and direction change with respect to time will be obtained. External wind can affect the quality of the flow in the test section of the 80- by 120-Foot Wind Tunnel. The performance of the inlet contraction and inlet flow treatment systems depends on the direction of the wind (Reference 2). Wind pressures on the North and South Walls (Figure 1) of the 40- by 80-Foot Wind Tunnel have emerged as a possible problem. These pressures may be adding to the internally generated pressures, thus causing a structural concern.

Current Methods of Flow Direction Measurement

Directional Pressure Probes

Directional pressure probes are the most common instruments used to measure flow direction in one or two directions. There are many different shapes and sizes of directional pressure probes with a variety of angle ranges that can be purchased commercially (Reference 5) or constructed. These simple, rugged indicators all operate on the principle that there is a distribution of pressure around a body immersed in a moving airstream. Flow angle is obtained by measuring the difference in pressure between two or more surface holes (orifices) located symmetrically on either side of the probe's streamwise axis. This difference in pressure is a function of flow angle.

The performance of a directional pressure probe depends on its overall size and orifice configuration. If a point measurement is desired, a small probe with orifices closely spaced is required. A small probe is also used if the indicator's disturbance of the flow is of concern. Probes with large orifice size and spacing can be used in large, steady, uniform flows where indicator disturbance of the flow has negligible effect. These indicators are sensitive to velocity and pressure gradients and should be sized to minimize this effect.

The pressure difference between two orifices of a directional pressure probe is dependent on the dynamic pressure of the flow. For this reason, a measurement of total pressure is generally made at the measurement location. Pressure difference is then divided by the local dynamic pressure to obtain a nondimensional quantity, $\Delta P/Q$, at each flow angle.

Calibration of a directional pressure probe must be done in a flowstream. The standard calibration procedure is to measure pressure differences through a range of angles. The probe is then inverted (turned 180 degrees) and rotated again through the same angle range. Comparison of the two curves yields a calibration curve (ΔP/Q versus flow angle) that is independent of any nonsymmetry of the probe. Calibrations of this type of indicator are generally infrequent.

The threshold velocity of directional pressure probes as given by Bryer and Pankhurst (Reference 6) can be as low as 1.5 m/s. The response and threshold velocity of a pressure instrument depends on factors such as the size and type of tubing used and the configuration of the indicator (Reference 7). For more detailed information on directional pressure probe performance, calibration, configurations and construction consult References 6, 8, and 9.

Free-Trailing Vanes

Flow direction vanes that rotate to follow the airstream have been used for some time in flight testing, wind tunnel testing and atmospheric wind applications. When the vane experiences a change in flow direction, a lift force is generated on the fin. This force causes a torque that overcomes any shaft bearing or angle transducer friction and aligns the fin with the airstream. Free-trailing flow direction vanes have been shown to be effective in measuring changes in flow angle of as low as 0.02 degrees over a complete 360 degree rotation in both steady and unsteady conditions (References 10, 11, and 12).

The flow angle measured using this type of indicator is not a function of flow speed. Determining the angle from a single, linear calibration curve is generally the only data reduction that is required. Flow direction vanes provide a single measurement (direct) means of obtaining flow angle. However, two vanes are required to make flow direction measurements in two directions.

Free-trailing flow direction vanes are commercially available (Reference 13) and easy to calibrate. Static calibrations can be done using a device that holds the fin at various angles. This type of indicator is mechanically simple but does have moving parts that have the potential for binding.

Fixed Force Vanes

Steady and unsteady flow angles have been measured using a fixed vane mounted on a strain gauged beam. When a fixed vane or "wedge probe" is inserted into an airstream that is angled with respect to the probe centerline, a lift force is generated. The force has been shown to be proportional to the flow angle and velocity head.

Crooks (Reference 14) has developed a fixed vane for measuring the airstream angle from an aircraft. This indicator has an output that is proportional to force and airstream angle over a ±7.5 degree range. It has the advantage of high response (about 200 Hz), ruggedness, no moving parts and simple data collection electronics. This type of indicator also has an angle resolution equal to its alignment uncertainty and can be continuously traversed. Negative characteristics of this method of flow direction measurement include a dependence on velocity head, the lack of commercial availability and problems with zero drift and damping.

Drag Force Anemometer

A drag force anemometer works on the same principle as a fixed vane on a strain gauged beam. Two small, rectangular plates with strain gauges bonded to their surfaces measure steady and unsteady flow angle as well as high frequency turbulence intensity. The moving fluid exerts a force on the small plates that is proportional to the output of the strain gauges. One small plate is aligned parallel to the airstream and has an output that is proportional to flow angle and velocity head. The other plate is aligned normal to the flow and has an output that is proportional to just velocity head. Division of the two outputs results in an instantaneous measurement of flow angle (Reference 15).

Krause and Fralick (Reference 15) have developed a drag force anemometer that will measure steady and unsteady turbofan inlet flow angles. This indicator can measure steady flow angles over a ±40 degree range, is rugged compared to hot wires and films, and requires simple data collection electronics. Negative features are that this probe is difficult to align and is not commercially available. The output has zero drift and ringing problems in certain applications and two channels of information are required to obtain a single flow angle measurement.

Laser Velocimeter

A laser velocimeter measures the average flow velocity of small particles in the flow at a point and has the capability of scanning very large areas. The laser velocimeter that is of interest for IST application has a 20-meter range and is capable of measuring two orthogonal components of velocity (Reference 16). These two orthogonal components of velocity can be reduced into flow direction and a flow direction map can be generated for the area of interest.

The laser velocimeter is a complex instrument requiring skilled operators. Long survey times are required and particle seeding of the flow is required if natural seeding is not adequate.

Tufts and Flow Visualization

If a qualitative flow direction trend is all that is required and visual contact with the area of interest is possible, tufts and other forms of flow visualization are an alternative. Tufts, smoke and oil flow visualization have been used extensively during small-scale aerodynamic tests of components of the 40- by 80-/80- by 120-Foot Wind Tunnel.

These inexpensive methods have been applied in several ways. Tufts attached to walls or wires that span a flow channel have been photographed with a strobe for lighting. The resulting multiple-exposure photograph consists of several overlapped images of the tuft. If the tuft images are all aligned, the flow angle is steady. Misaligned images indicate unsteady flow direction.

Smoke streams introduced into the flow give a good indication of the airstream direction. Full scale, three-dimensional effects can be captured on videotape for later viewing. If an area of interest can be coated with a viscous oil, the flow patterns give an indication of the flow direction. Oil flow patterns remain after the flow stops and can then be photographed (Reference 17).

Hot Wires and Film Anemometers

Hot wires and film are capable of measuring instantaneous flow velocities. This method works on the principle that when a heated wire or thin film is placed in an airstream it is cooled and its electrical resistance decreases. Two perpendicular wires or films can measure instantaneous flow direction (Reference 18).

The output of a hot wire or film is very close to a point measurement. This high response (0 to 30,000 Hz) flow direction indicator can be rapidly traversed and is nearly insensitive to velocity gradients. Some of the drawbacks of this method are complex calibrations, the requirement for a highly skilled operator, and the delicacy of the probes.

Results and Conclusions of Study

Several factors influenced the selection of flow direction indicators for the 40- by 80-/80- by 120-Foot

Wind Tunnel IST. Indicators that are commercially available or simple to construct were chosen because of time constraints. Probes that could be used at more than one location in the wind tunnel were chosen to simplify data collection equipment requirements. Large indicators that are rugged, easy to calibrate and easier to align with the tunnel centerline were selected. The flow direction indicators that were picked for use can measure angles smaller than the angle accuracy of alignment. They are also capable of measuring how flow angle changes with time up to the maximum frequency of interest. The cost of purchasing or constructing several of these indicators was also considered. See Table 1 for the expected conditions and flow direction indicators chosen for each measurement location.

Free-trailing flow direction vanes were chosen for use in both of the wind tunnel test sections, upstream and downstream of turning vane cascades and ahead of the fan drive system. These vanes could be constructed at moderate cost and are of particular interest because of their ability to measure flow direction independent of flow velocity and at very low flow velocities.

Large two-dimensional directional pressure probes were selected as an alternative at most of the free-trailing vane locations. These probes can be constructed and calibrated according to guidelines presented in Reference 6.

Due to the complexity of the exiting flow from a high drag (separated flow) turning vane cascade and the requirement for only an average outflow angle, a rake of two-dimensional directional pressure probes was chosen to make this measurement. Spacing of the probes should be optimized to a maximum value to keep the number of probes to a minimum.

The laser velocimeter could be placed in the 80- by 120-foot test section where no blockage effects exist. Oil flow visualization around the exit of the fan drive system should give a good indication of the exiting swirl angle. This technique was successfully used on small-scale tests of the fan drive system. Standard meteorological vanes to measure the direction of the exterior wind will be positioned on an existing weather tower located south of the inlet to the 80- by 120-Foot Wind Tunnel.

Purpose of Test

A set of flow direction indicators was chosen for performance testing. The purpose of the test was to calibrate and assess the dynamic response of a group of flow direction indicators that have possible application in the 40- by 80-/80- by 120-Foot Wind Tunnel Integrated Systems Test.

A directional pressure probe constructed by welding stainless steel tubing together and chamfering the ends was calibrated (Figure 3). This calibration was done in order to determine whether directional pressure probes can be cheaply constructed, efficiently calibrated and still fulfill performance requirements.

Flow direction vanes were tested in order to determine if static (no flow) calibrations are adequate or if calibrations in moving flow must be done. The dynamic response characteristics of the vanes were obtained to document unsteady flow performance. The threshold or minimum required flow speed for the vane to operate was also measured.

CHAPTER 2

Vane Response Theory

Several researchers have studied the dynamic performance of free-trailing flow direction vanes. Initially this work was done to design a more efficient meteorolcgical wind sensor. Later, the requirement to measure aircraft incidence angles in flight brought about a concern about vane response.

MacCready and Jex (Reference 11) define a flow direction vane as a second order system. The motion of a forced (f(t)) second order system with damping can be described by the mathematical relation:

$$m\ddot{y} + c\dot{y} + ky = f(t) \qquad \text{where,} \qquad (1)$$

m is the system mass

c is the system damping constant

k is the system spring constant

This relation can be shown to be:

$$\ddot{y} + 2\zeta w_n \dot{y} + w_n^2 y = f(t) \qquad \text{where,} \qquad (2)$$

W_n is the system natural frequency

ζ is the damping ratio

The damping ratio is defined as the actual damping constant of the system divided by the critical damping constant (for no overshoot).

The natural frequency and damping ratio derived from Equations (1) and (2) are:

$$w_n = \sqrt{\frac{k}{m}} \tag{3}$$

$$\zeta = \frac{c}{2\ m\, w_n} = \frac{c}{2\sqrt{k\,m}} \tag{4}$$

MacCready and Jex present an experimental method for determining the response parameters W_n and ζ for a vane. The vane is held a few degrees off the mean flow direction in a wind tunnel and is then released. This method generates a step input of flow angle to the vane. If the system is less than critically damped (ζ<1.0), the vane will overshoot the intended angle and a decaying oscillation will occur. Dynamic response parameters can be obtained by recording the transient output of the flow angle from the vane.

The transient response of a second order system for various damping ratios is shown in Figure 4. A damping ratio of 1.0 means that the system is critically damped and will not overshoot or oscillate. For damping ratios less than 1.0, the system is defined as underdamped and will oscillate. Flow direction vane systems are generally underdamped.

The damping ratio for a second order system can be derived from the logarithmic relation between two successive peaks of the response curve (Figure 4). This relation is:

$$\beta_1 = \beta_0\, e^{-\frac{\pi \zeta}{\sqrt{1-\zeta^2}}}$$

$$\zeta = \frac{\ln \beta_0/\beta_1}{\sqrt{\pi^2 + \ln^2 \beta_0/\beta_1}}$$ which yields,

This equation allows easy calculation of ζ from a transient response curve (Figure 4).

Natural frequency for a flow direction vane varies linearly with airspeed. For this reason, a natural wavelength ($\lambda_n = 2\pi v/W_n$) is used instead. The natural wavelength can be calculated two ways from the response curve. The natural wavelength is related to the damping ratio and the distance D (distance for the vane to reach 50% of β_0) by the following relationship:

$$\lambda_n = D(6.0 - 2.27\zeta) \qquad \text{(Reference 12)}$$

The second way to determine λ_n is to measure the damped wavelength (λ_d) from the response plot and calculate λ_n from:

$$\lambda_n = \lambda_d \sqrt{1 - \zeta^2}$$

The damped wavelength of a flow direction vane can be interpreted as the distance the air flows past the vane during the time it takes the vane to complete one cycle of oscillation about the desired angle (Figure 4, Reference 11).

The natural frequency and damping ratio are not clear ways of assessing vane dynamic performance. The settling time (t_s) is based on both of these response parameters and provides a clear measurement of vane performance. The settling time is defined as the time required for the vane to settle within 2% of the initial offset angle (Figure 4). For an underdamped, second order system the settling time is given by:

$$t_s = \frac{4}{\zeta W_n} \qquad (5)$$

It is clear that a short settling time is desired. The vane should respond swiftly and also reach the desired angle in the shortest possible time.

The settling time (or response time) and the threshold velocity are the two parameters used to describe vane response. The vane design factors that affect the performance parameters are: the system mass, friction and the vane fin area.

In order to decrease the settling time, the vane designer must obtain a high value of the denominator of Equation (5) ($\zeta \times W_n$). The natural frequency (Equation (3)) can be increased by decreasing the system mass. The damping ratio (Equation (4)) can be increased by decreasing the system mass or by adding friction (c) to the system. The addition of friction to the underdamped system will cause the vane to be closer to critically damped ($\zeta = 1.0$).

The threshold velocity of the vane is the lowest flow velocity required for the vane to rotate to the desired angle. The threshold velocity depends on the aerodynamic force required to rotate the vane. Decreasing the system mass will reduce the required force to rotate the vane. Increasing the fin area (without increasing the system mass) will increase the aerodynamic force and reduce the threshold velocity. Lowering system friction is also a way to decrease the flow direction vane's threshold velocity.

A lightweight vane system is desired for improved response characteristics. The vane must, however, be rigid and have adequate structural integrity. If measurements of flow angle are made in the horizontal plane only, the counterweight can be omitted to reduce weight.

Table 3 lists the vane response parameters and how they can be affected.

CHAPTER 3

Hall Effect Vane Development

After studying the flow direction measurements that were planned and the flow direction measurement methods that exist, it was decided to design a flow direction indicator that would satisfy a specific set of requirements. The requirements for a flow direction indicator for use in test sections ahead of vane sets and the fan drive are as follows:

1. The indicator must be able to measure flow angles of ±0.5 degrees with a resolution of ±0.1 degrees.

2. The indicator must have an angle range of ±10 degrees.

3. The indicator must be able to operate at flow speeds between 5 and 300 knots.

4. The indicator must have simple and rugged construction.

5. The indicator should have a small amount of support instrumentation and measure flow angle directly (no complicated data reduction).

6. The indicator should be inexpensive to construct and repair.

7. The indicator should be responsive enough to measure at least a 1 Hz flow angle fluctuation.

The free trailing flow direction vane concept was chosen as the measurement method to be used in the design. The development was divided into four parts: (1) design, (2) construction, (3) test (described in detail later), and (4) redesign (described in the conclusions).

Vane Design

The general configuration of the vane was the first consideration. Various experimenters (References 10, 11, 12, 19, and 20) have studied flow direction vane configurations. A single fin attached to a shaft has been used extensively for flight testing. The fin is usually counterbalanced by placing a mass on the other side of the shaft. This countermass balances the vane when it is required to measure flow directions not in the horizontal plane.

Choosing the size of the fin requires consideration of several factors. It is important to have a lightweight fin in order to have a low moment of inertia (system mass). A low moment of inertia reduces the response time and threshold velocity of the vane. The fin has to be structurally sound as well as lightweight. It must be rigid and able to withstand aerodynamic loads at the required flow velocity.

A very large fin will have a high threshold velocity and settling time due to a large system mass. A very small fin will have a short response time due to a low moment of inertia but a high threshold velocity due to the low aerodynamic loads generated on the fin surface. These small aerodynamic loads must overcome bearing and transducer friction.

Clearly a compromise must be made. Barna and Crossman (Reference 12) studied the effect of fin aspect ratio and size on vane response and damping. They found that a two-inch square (AR=1) fin provided the best optimization between high damping and short response time. Eddy sizes larger than the fin were assumed.

Lenschow (Reference 10), while studying vanes for sensing incidence angles of the air from an aircraft, found that drilling holes through the fin increased damping. A hole diameter of 0.2 centimeter with a hole spacing of about one centimeter was used.

The angle transducer selection was the next task. A transducer with the desired accuracy and range, minimum mechanical friction, simple support instrumentation, a linear output and low cost was desired. Hall Effect Transducers fulfilled all of the above requirements (Reference 21).

The Hall Effect Transducer has an output voltage that is proportional to the magnetic field strength. The motion of a magnet relative to the transducer causes a variation in the strength of the magnetic field and thus a voltage variation. The Hall Effect principle as applied to shaft rotation is illustrated in Figure 5. Several magnet/transducer configurations were considered. The dual magnet setup yielded a linear voltage versus flow angle relationship for ±10 degrees.

Vane Construction

Three "Hall Effect Flow Direction Vanes" were constructed for evaluation (Figure 6). The fins had an aspect ratio of 1.0 with an area of four square inches. The fins were constructed out of 0.1-inch-thick balsa wood and attached to a 0.18-inch-diameter shaft. Different size holes were drilled through the fins of two of the vanes to determine whether this affects damping.

To avoid affecting the magnetic field impinging on the Hall Effect Transducer, the wave support block and all attachments were constructed out of nonferrous materials. The vanes were constructed in-house at a low cost compared to the purchase of a commercially available vane system. A diagram of the vane is shown in Figure 7.

CHAPTER 4

Experimental System and Procedure

Test Apparatus

Wind Tunnel Description

The 1/10th Scale Component Tester Wind Tunnel was constructed to measure two-dimensional aerodynamic performance of turning vane cascade concepts for the 40 by 80-/80- by 120 Foot Wind Tunnel modification (Reference 1). Figure 8 shows the three-foot by three-foot straight through channel that is powered by a four-foot diameter ducted multi-blade fan/800 HP electric motor combination. The channel has a maximum flow speed of approximately 80 knots. The flow speed range and flow uniformity make the wind tunnel ideal for a flow direction indicator calibration and performance assessment.

Test Section Description

A cut-away view of the test area of the wind tunnel is shown in Figure 9.

A manually adjustable turntable was designed to mount through the top panel of the test tunnel. The turntable could be rotated 360 degrees and positioned at a desired angle using a disk dial and vernier that read in six-minute graduations (Figure 10). Flow direction indicators were mounted to the bottom surface of the turntable.

A ground plane with a rounded leading edge was installed in the test section. The flow direction indicators that were tested projected through an opening in the ground plane. The purpose of the ground plane was to assure that the indicators were in a uniform airstream isolated from any flow disturbance caused by the mounting system.

A Pitot probe was installed in the floor of the flow channel to measure freestream dynamic pressure.

A solenoid was modified to axially deflect a shaft when activated. This shaft movement was used to release a vane-type flow direction indicator from a pre-set offset angle in order to determine the dynamic performance of the vane. A simple on/off toggle switch was used to activate the solenoid.

Data Collection System Description

An HP 87 computer linked to an HP 3421A Data Acquisition/Control Unit was programmed to collect calibration and release test data. All of the data was stored on soft disk.

An oscilloscope was used to collect dynamic response transient outputs from the vane-type flow direction indicators that were offset and released. A trigger mode on the oscilloscope was used to capture the rapidly changing voltage output of the released vane's transducer. Photographs of the screen of the oscilloscope were taken to provide a permanent record of the data.

Indicator Alignment

All of the indicators tested were aligned with the test section centerline using a transit. This was done in part to determine whether the static (no flow) alignment method could be used with confidence during applications of the indicator. The transit also aligned the bases of the Hall Effect Vanes to assure that the magnet was correctly aligned with respect to the sensor (Figure 5).

Description of Flow Direction Indicators Tested

Directional Pressure "Cobra" Probe

A directional pressure probe was constructed out of 1/4-inch (outside diameter) stainless steel tubing using methods described in Reference 6. The tubes were welded together and one end of the tube cluster was chamfered as shown in Figure 3. The tubes were then bent into a cobra-like shape. This type of probe can measure total pressure and yaw angle. The chamfered tubes were attached to a one psid differential pressure transducer to measure yaw angle.

Hall Effect Vanes

The three Hall Effect Vanes described earlier were evaluated in the test tunnel. A photograph of the three vanes, one attached to the turntable mount, is shown in Figure 6.

Richardson Vane

A Richardson Vane (Reference 20) was tested to provide reference response data for comparison to the Hall Effect Vane response. The vane had a rectangular fin 60 mm wide and 120 mm long. An induction coil transducer was used to sense the angle of the fin. A photograph of the Richardson Vane attached to the turntable mount is shown in Figure 11. Note on the photograph the solenoid, vane release rod and solenoid actuator switch.

CHAPTER 5

Experimental Results and Discussion

The range of angle that produces a linear angle versus output plot was determined for each indicator tested. The directional pressure "cobra" probe had a linear output over a ±20 degree angle range (Figure 3). The Hall Effect Vanes with the magnet configuration shown in Figure 5 had a linear output for ±10 degrees (Figure 5). The Richardson Vane had a full ±180 degree linear range of output due to its linear induction coil transducer.

The natural frequencies of the flow direction vanes are plotted versus airspeed in Figure 12. A high natural frequency indicates that the settling time of the vane will be low. See Chapter 2 for a more detailed explanation of vane response theory. The natural frequency increased in a linear fashion with airspeed confirming the results of Reference 12. Hall Effect Vane #3 (with 0.5-cm diameter holes) had a natural frequency approximately 30% higher than the other two Hall Effect vanes (no holes and 0.2-cm diameter holes). The vane of similar configuration reported by Barna and Crossman (Reference 12) had a natural frequency approximately 30% higher than Vane #3. The Richardson vane tested had natural frequencies 10% lower than Reference 12 and 7% lower than a value measured by Richardson (Reference 20).

The natural wavelength of the vanes can be calculated when the natural frequency and flow velocity are known. The natural wavelength was plotted versus airspeed for the four vanes (Figure 13). The AR 1.0 vane from Reference 12 had a natural wavelength of 4.2 feet. The shortest natural wavelength of the vanes tested was 5.4 feet for Hall Effect Vane #3.

The damped wavelength can be calculated from the damped frequency of the vane. The damped wavelength is the length of the column of air required to rotate the vane through one cycle of oscillation about the desired angle. Hall Effect Vane #3 also had the shortest damped wavelength of the vanes tested (Figure 14).

Damping ratios for the four vanes that were evaluated ranged from 0.25 to 0.30 (Figure 15). The Barna and Crossman vane (AR = 1.0) had a damping ratio of approximately 0.4. The Richardson vane is reported to have damping ratios between 0.5 and 0.8.

Several factors could have caused the lower natural frequencies and damping ratios of the vanes evaluated. The test vanes used different angle transducers than the reference vanes. The Hall Effect Transducers had no mechanical friction, which means no rotational damping. The system mass of the Hall Effect vanes was most likely larger than the vanes tested by Barna and Crossman (Reference 12). Damping ratios reported by Richardson (Reference 20) for the Richardson Vane were for very small offset angles (1°).

The Richardson Vane that was evaluated was released from offset angles as high as 20 degrees.

The lowest measured velocity for the vanes tested was 10 ft/sec. Vanes released at this flow speed did return to an aligned position. This threshold velocity fulfills the requirement for IST application.

The settling time was determined from the natural frequency and damping ratio of each vane evaluated at an airspeed of 150 ft/sec. Vane #3 had the lowest settling time. The fin settled within 2% of the initial offset angle in 0.083 seconds (Table 3). This settling time can be inverted to obtain a vane response frequency of 12 Hz.

The dynamic performance of the flow direction vanes that were evaluated satisfies the requirement of 1 Hz for IST application by a wide margin. These experimental results are presented in order to document the maximum vane response parameters.

Questions about the test results that warrant further investigation include:

1. Does offset angle (or the operational angle range) of the flow direction vane affect the response parameters? A trend in the data of higher ζ and f_n for larger offset angles brought about this question.

2. How much would a significant reduction in system mass or an increase in system friction improve the dynamic performance?

3. Do holes in the fin surface improve the response by decreasing damping or by only decreasing system mass? Hall Effect Vane #3 with 0.5 cm diameter holes had better overall dynamic performance than the other Hall Effect Vanes (no holes and 0.2 cm holes). The natural frequency (which is independent of system damping) of Hall Effect Vane #3 was higher, indicating a lower system mass. A response test of two vanes of equal system mass where one vane has holes and the other has no holes would answer this question.

4. Though the transit alignment method worked at short range, how effective is this method at great distances?

Application of the Prototype Hall Effect Vane

Aerodynamic testing of a 1/15 scale model of the 80- by 120-Foot Wind Tunnel inlet (Figure 2) provided an opportunity to test a prototype Hall Effect Vane as a research tool. Horizontal traverses were being made across the test section portion of a 1/15 scale wind tunnel model to measure any possible flow angle variations due to inlet modification. A hot wire cross probe was being used to perform this measurement.

The hot wire began indicating approximately two degrees of flow angle change from one side of the test section to the other. It was decided to place one of the prototype Hall Effect Vanes on the traversing rig (Figure 16) to check the hot wire cross probe.

The vane and support were fitted with a streamlined shroud and mounted on the traversing rig. Accurate alignment of the vane with the tunnel centerline was not done because a change in flow angle was all that was required. A one-Hz low-pass filter was used on the output which was recorded on an X-Y plotter (flow angle versus location).

The Hall Effect Vane measured small scale flow angle variation (±0.5 degrees) but showed no overall flow angle variation from one side of the tunnel to the other (Figure 17). The data from the Hall Effect Vane could be confirmed by watching the position of the vane as it traversed the channel. The vane replaced the hot wire for several months in the application. It proved durable, simple to install and able to measure flow angle less than 0.5 degrees.

CHAPTER 6

Overall Conclusions

Flow direction measurement locations and indicators for possible use in the 40- by 80-/80- by 120-Foot Wind Tunnel Integrated Systems Tests (IST) were studied. Conditions at various locations in the facility were examined and then compared to the performance and specifications of various methods of flow direction measurement. The best-suited techniques were then chosen for each tunnel location (Table 1).

A free-trailing vane flow direction indicator was designed to fulfill requirements for flow direction measurement in the test section and ahead of the vane sets and fan drive of the 40- by 80-/80- by 120-Foot Wind Tunnels. The indicator utilized a lightweight balsa wood vane attached to a shaft. A Hall Effect Transducer was used to measure the vane shaft angle.

A flow direction indicator performance assessment test was conducted in a three-foot by three-foot wind tunnel. Three configurations of the Hall Effect Vane, a Richardson Vane and a "homemade" directional pressure probe were evaluated. The vanes were evaluated in order to measure ease of calibration and alignment, dynamic response and threshold velocity. The directional pressure probe was evaluated for ease of calibration and alignment. The unsteady flow angle measurement performance of this indicator was not studied. The response of a directional pressure probe depends on factors other than the probe configuration, such as the length and diameter of the tubing used.

The directional pressure "cobra" probe that was evaluated proved to be a simple, inexpensive way to measure steady flow angle. The probe had a linear output versus flow angle over a ±20 degree angle range (Figure 3). Cobra probes for use in the wind tunnel should be constructed with care. The chamfered end and orifices should be prepared by the methods discussed in Reference 6. The calibration of each indicator should also be done with the indicator inverted in order to cancel out any effects caused by asymmetry of the probe. An indicator alignment method should be designed into the probe support system.

The IST requirements for a flow direction vane design were listed at the beginning of Chapter 3. The Hall Effect Vane has fulfilled most of those requirements. The vane system has simple support instrumentation and linear voltage output versus flow angle for ±10 degrees. The vane was relatively inexpensive to construct and with careful consideration during a design iteration, it should be easy to repair, adjust and align.

The vane was found to have a settling time of 0.083 seconds. This represents a frequency of approximately 12 Hz, well above the required 1 Hz. The Hall Effect Vane was installed in a research test and proved that it could resolve 0.5 degrees of flow angle. The vane also measured flow angle fluctuations well above 1 Hz.

Before the Hall Effect Vane is used in a research application, another design iteration should be done. A list of recommendations and tasks for the iteration follows:

1. Add friction to the system to increase the damping ratio (ζ) and decrease the amount of overshoot.
2. Construct the vane out of lighter materials in order to improve the settling time (t_s) and the threshold velocity of the vane.
3. Design a fully adjustable magnet/Hall Effect Transducer holder for the indicator in order to simplify calibration.
4. Design a compact, modular system so a vane/transducer element can be positioned to measure horizontal or vertical flow angle and if defective, can be replaced by an identical element.
5. Design a fin and base alignment method into the system.

REFERENCES

1. Corsiglia, V. R.; Olson, L. E.; Falarski, M. D.: *Aerodynamic Characteristics of the 40- by 80-/80- by 120-Foot Wind Tunnel at NASA Ames Research Center.* NASA TM-85946, April 1984.

2. Eckert, W. T.; Mort, K. W.: Wind vs. Wind Tunnel: *The Aerodynamics of the Inlet for NASA's New, Very Large, Nonreturn-Flow Facility.* Journal of Wind Engineering and Industrial Aerodynamics, 9 (1982) 193-205.

3. Applin, Z. T.: *Flow Improvements in the Circuit of the Langley 4- by 7-Meter Tunnel.* NASA TM-85662, December 1983.

4. *Management Plan for the 40- by 80-/80- by 120-Foot Wind Tunnel Project.* NASA Ames Research Center, (last revision) November 1983.

5. United Sensor: *Probes.* General Catalog.

6. Bryer, D. W.; Pankhurst, R. C.: *Pressure Probe Methods for Determining Wind Speed and Flow Direction.* London: Her Majesty's Stationery Office, 1971.

7. Chapin, W. G.: *Dynamic Pressure Measurements Using an Electronically Scanned Pressure Module.* NASA TM-84650, July 1983.

8. Reed, T. D.; Pope, T. C.; Cooksey, J. M.: *Calibration of Transonic and Supersonic Wind Tunnels*, NASA CR-2920, November 1977.

9. Rae, W. H.; Pope, A.: *Low Speed Wind Tunnel Testing.* 2nd edition. New York: John Wiley & Sons, 1984.

10. Lenschow, D. H.: *Vanes for Sensing Incidence Angles of the Air from an Aircraft.* Journal of Applied Meteorology, December 1971.

11. MacCready, P. B.; Jex, H. R.: *Response Characteristics and Meteorological Utilization of Propeller and Vane Wind Sensors.* Journal of Applied Meterology, April 1964.

12. Barna, P. S.; Crossman, G. R.: *Fast Response Vanes for Sensing Flow Patterns in Helicopter Rotor Environment.* NASA CR-132545, June 1974.

13. Rosemount Inc.: *Model 92AN or 92AX Air Data Flight Test Boom*. General Catalog.

14. Crooks, W. M.: *A Fixed Vane Sensor for Measuring Turbulent Air Flows*. 10th National Aerospace Instrumentation Symposium, New York, NY: May 4 through May 6, 1964.

15. Krause, L. N.; Fralick, G. C.: *Miniature Drag Force Anemometer*. NASA TM X-3507, 1977.

16. Reinath, M. S.: *Laser Velocimeter for Large Wind Tunnels*. AIAA Paper 82-4303, December 1982.

17. Maltby, R. L.: *Flow Visualization in Wind Tunnels Using Indicators*. AGARDograph #70, April 1962.

18. Flow Corporation: *The Hot Wire Anemometer*. Flow Corp. Bulletin 53.

19. Wieringa, J.: *Evaluation and Design of Wind Vanes*. Journal of Applied Meteorology, December 1967.

20. Richardson, N. R.: *Dynamic and Static Wind Tunnel Tests of a Flow Direction Vane*. NASA TND-6193, April 1971.

21. Micro Switch: *Hall Effect Transducers, How to Apply them as Sensors*. Micro Switch Publication, 1982.

APPENDIX A

Figures

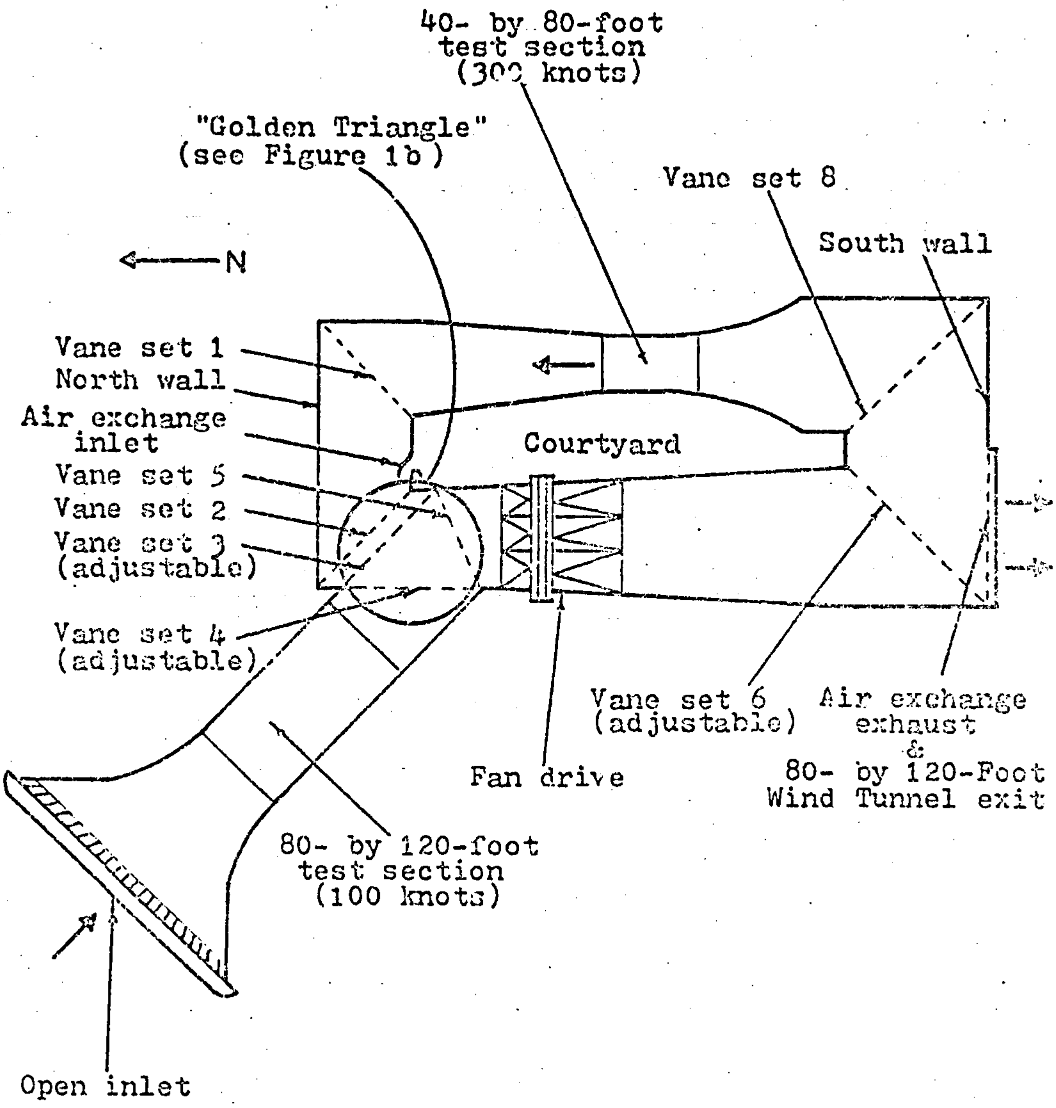

Figure 1a

Schematic of the 40- by 80-/80- by 120-Foot Wind Tunnel at NASA Ames Research Center

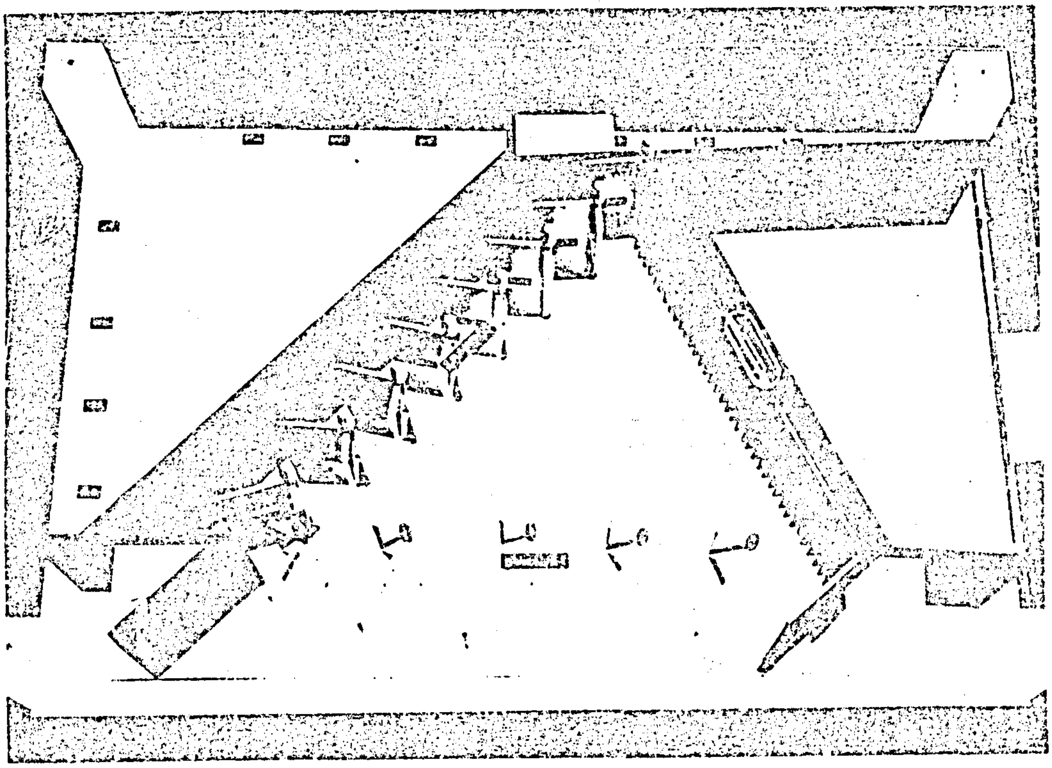

Figure 1b

Detail of "Golden Triangle" Area

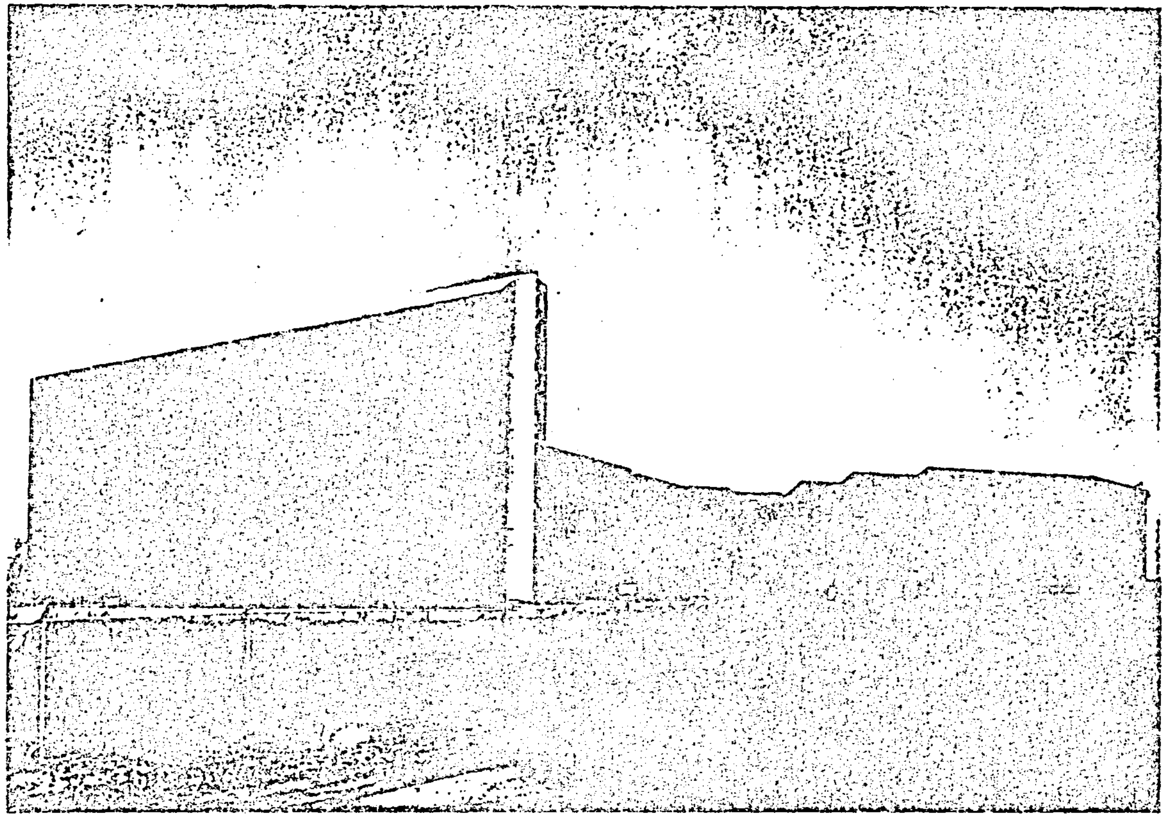

Figure 2

80- by 120-Foot Wind Tunnel
Atmospheric Inlet

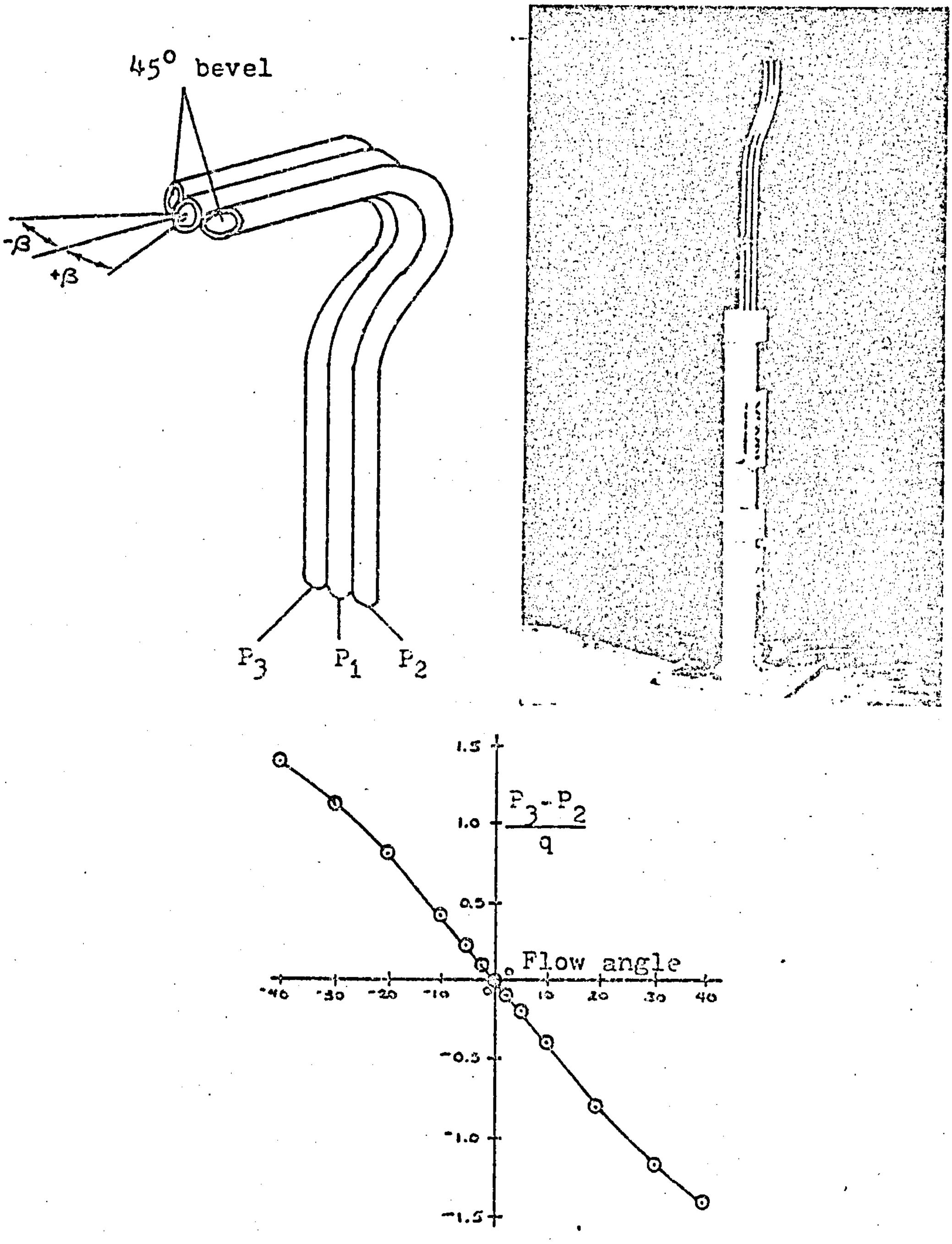

Figure 3

Directional Pressure "Cobra" Probe
Calibration Curve

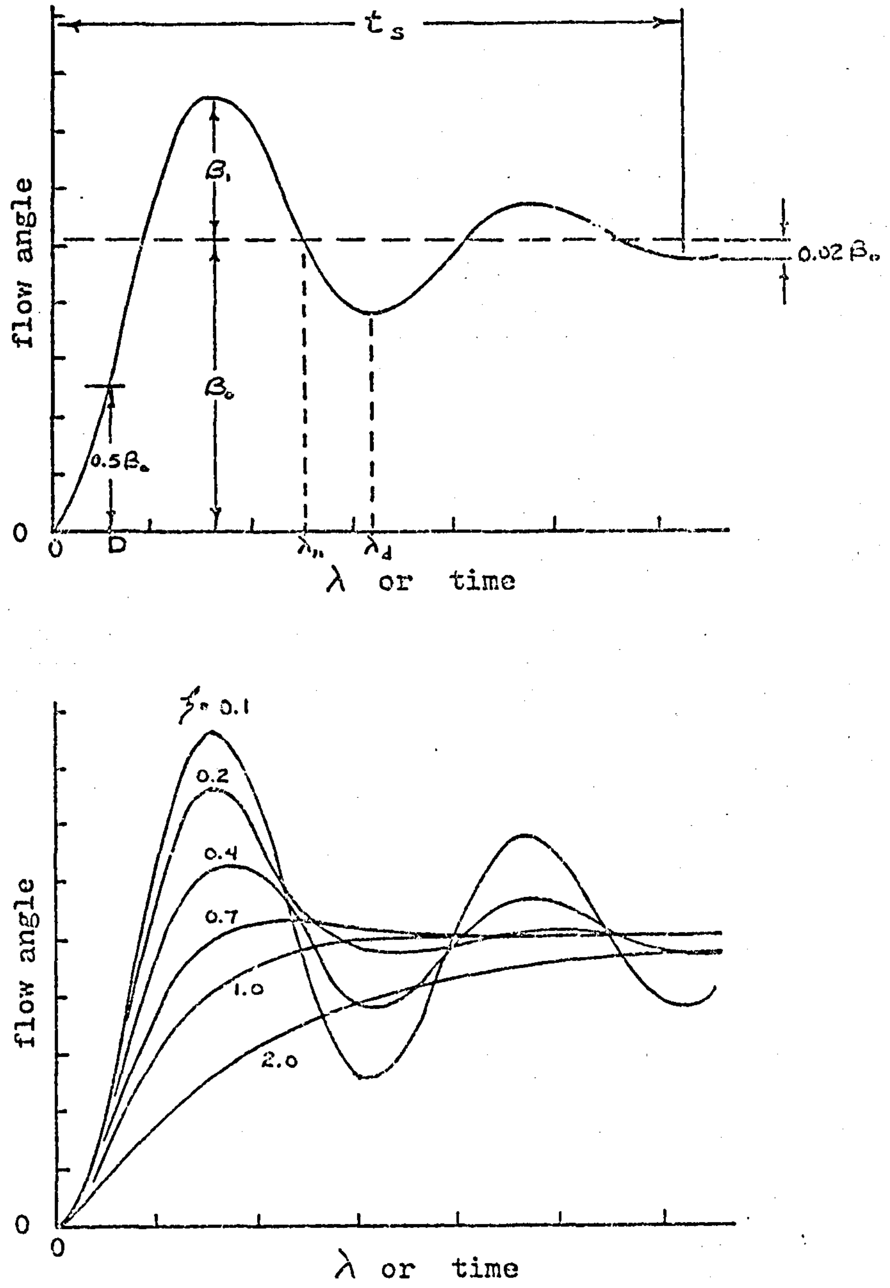

Figure 4

Transient Response of a Second Order System for a Step Input

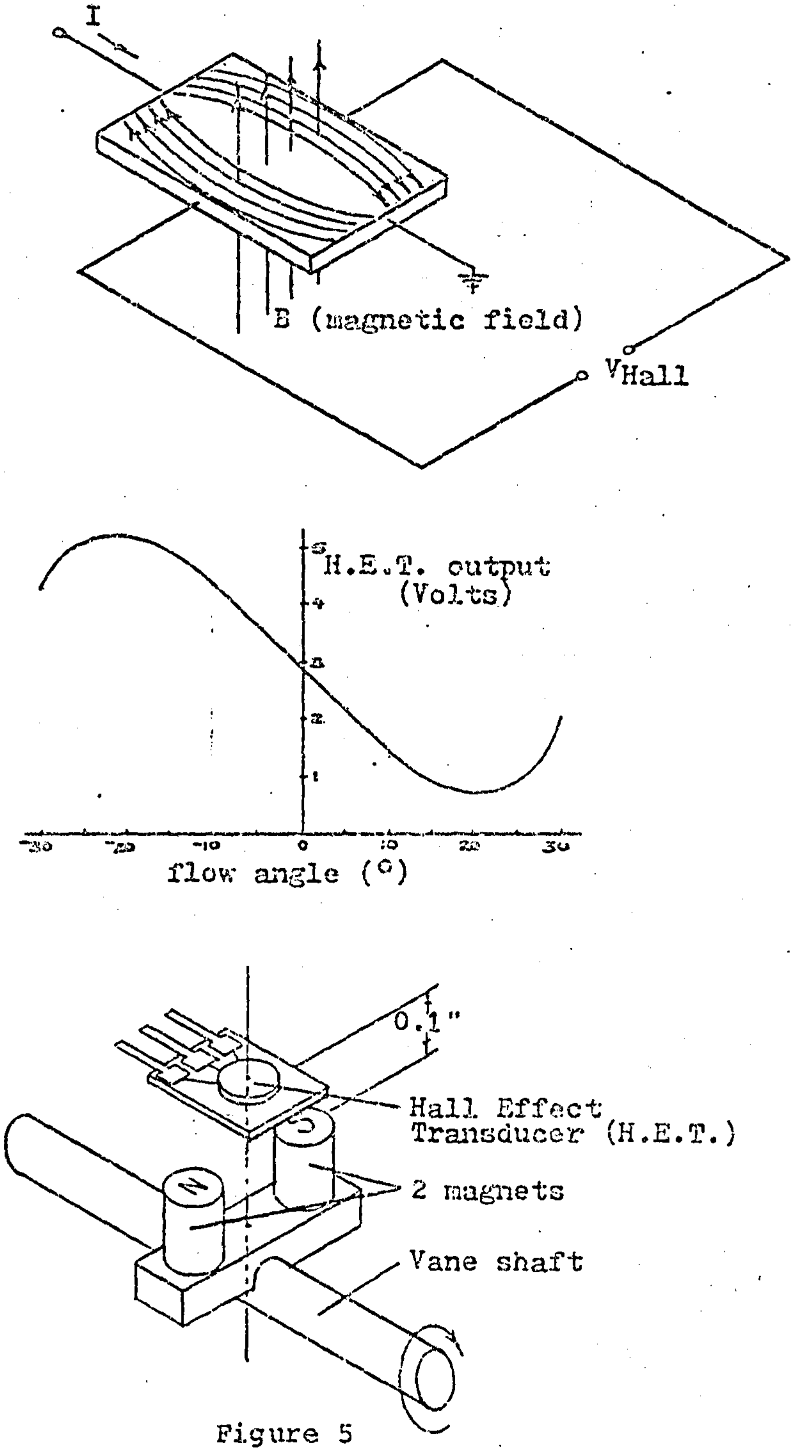

Figure 5

The Hall Effect Principle Applied to Shaft Rotation

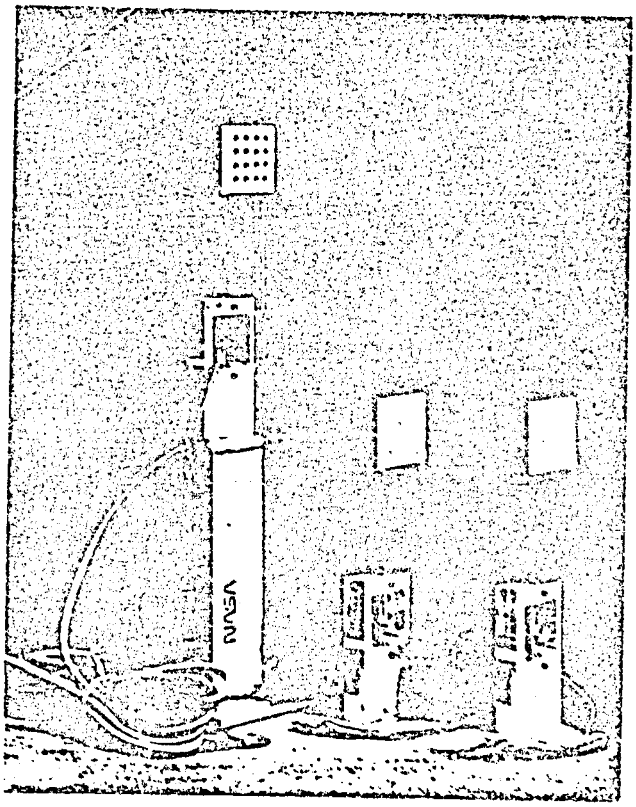

Figure 6

Hall Effect Flow Direction Vanes

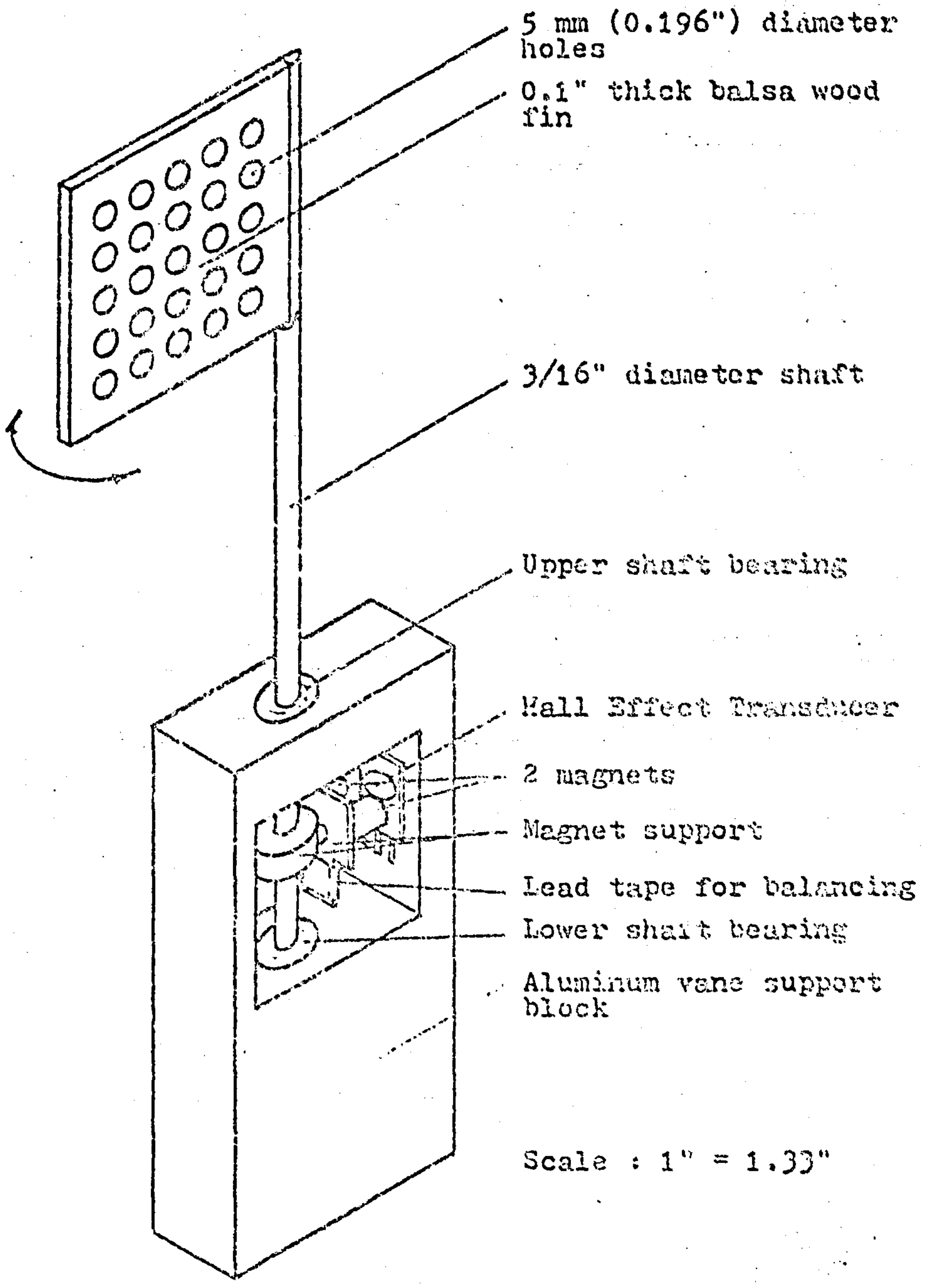

Figure 7

Diagram of Hall Effect Vane

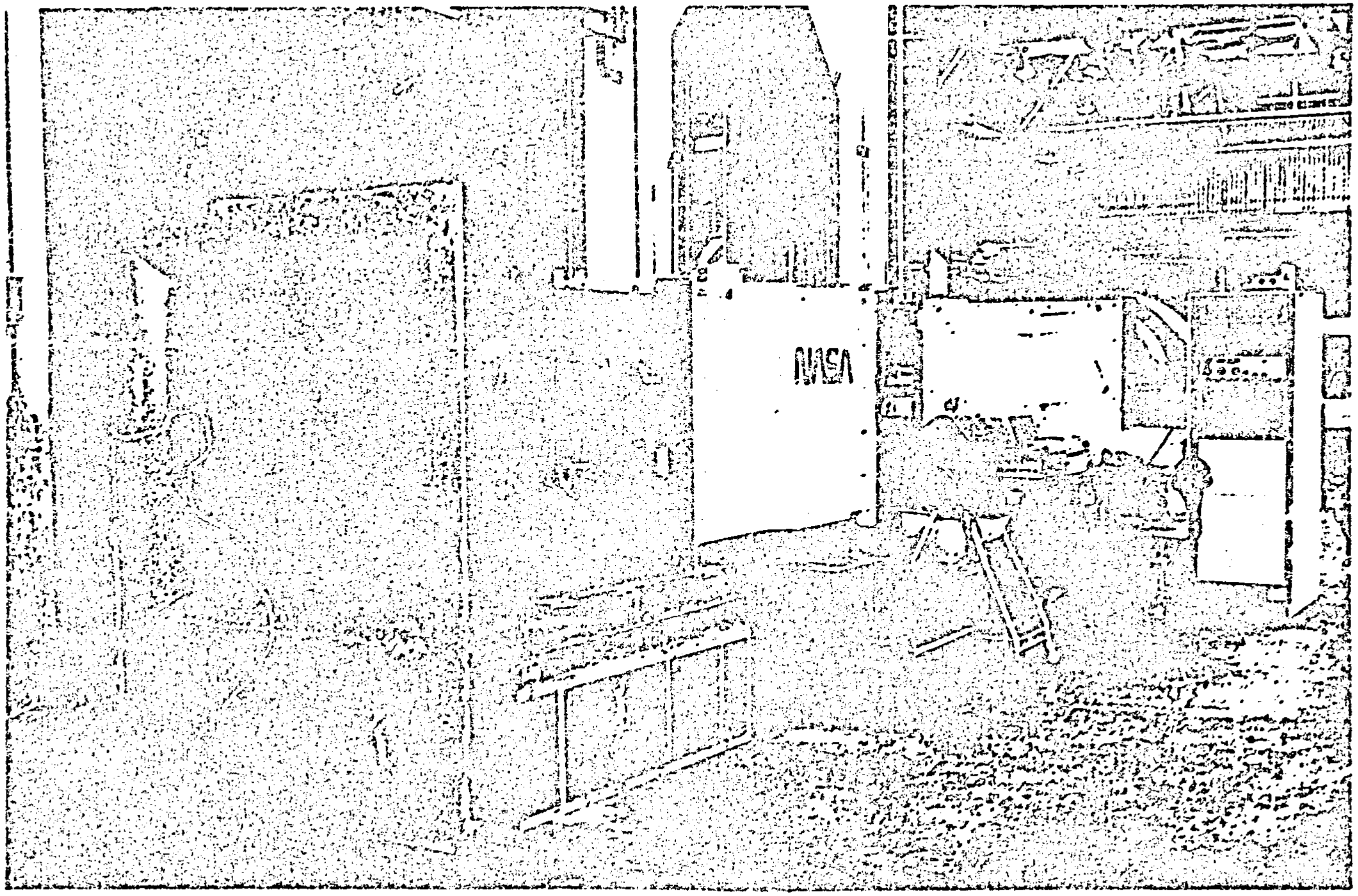

Figure 8

Three-Foot by Three-Foot 1/10 Scale Component
Tester Wind Tunner

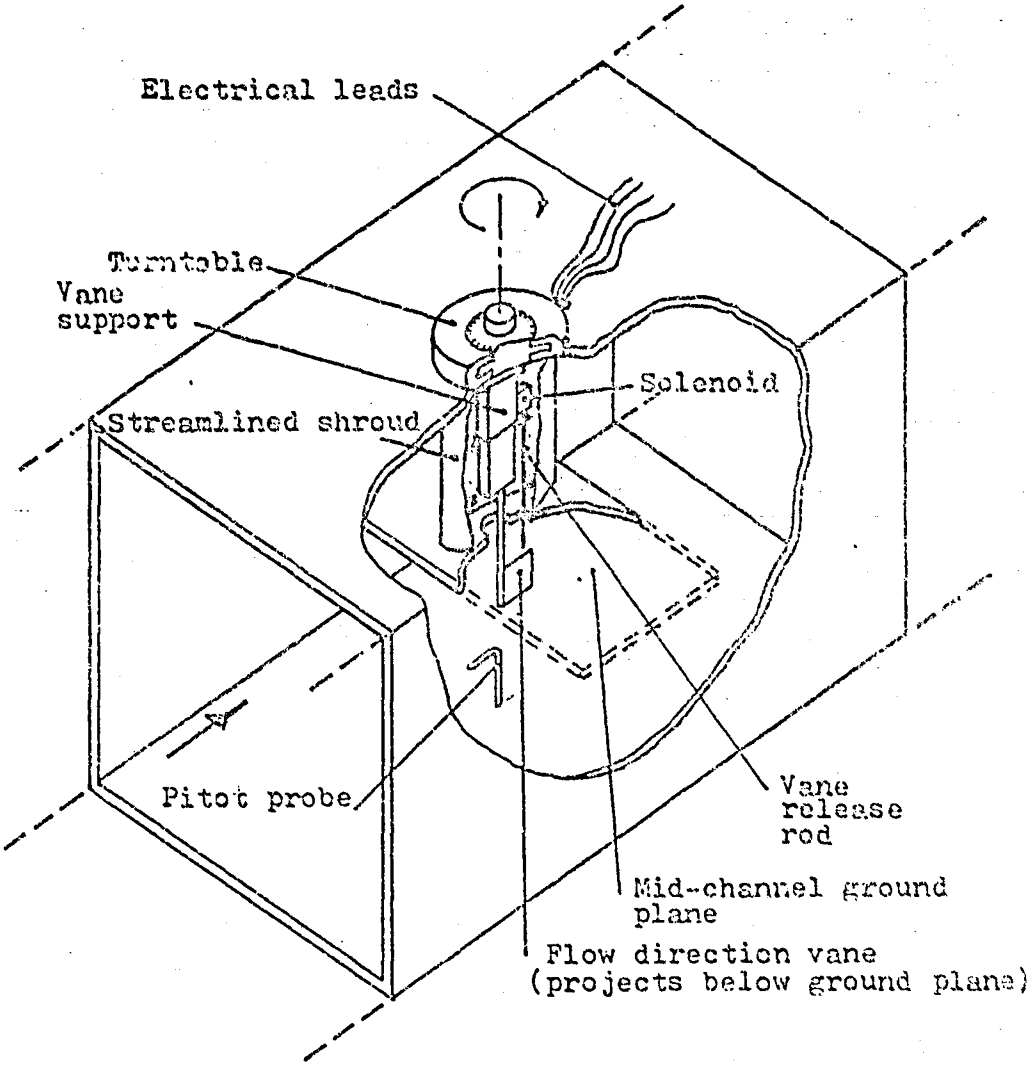

Figure 9

Cutaway View of the Test Area

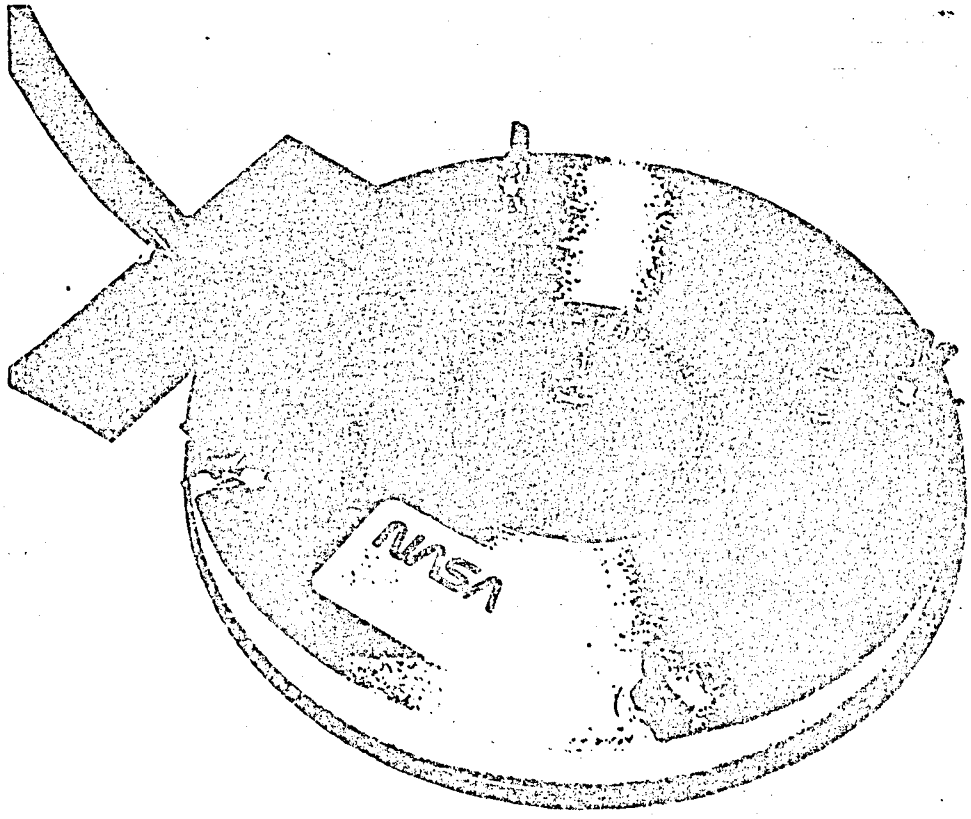

Figure 10

Manually Adjustable Turntable

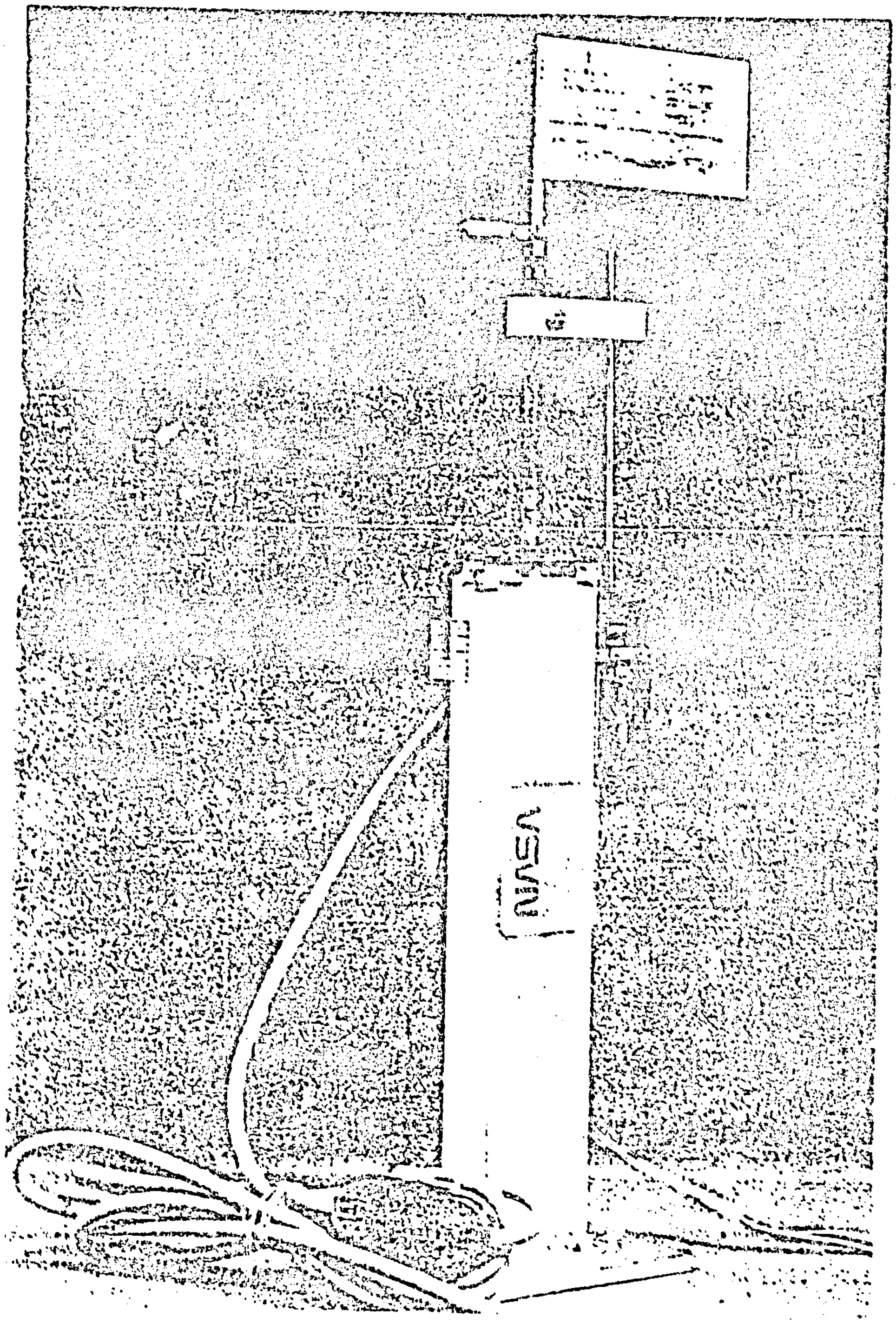

Figure 11

Richardson Vane on Test Mount

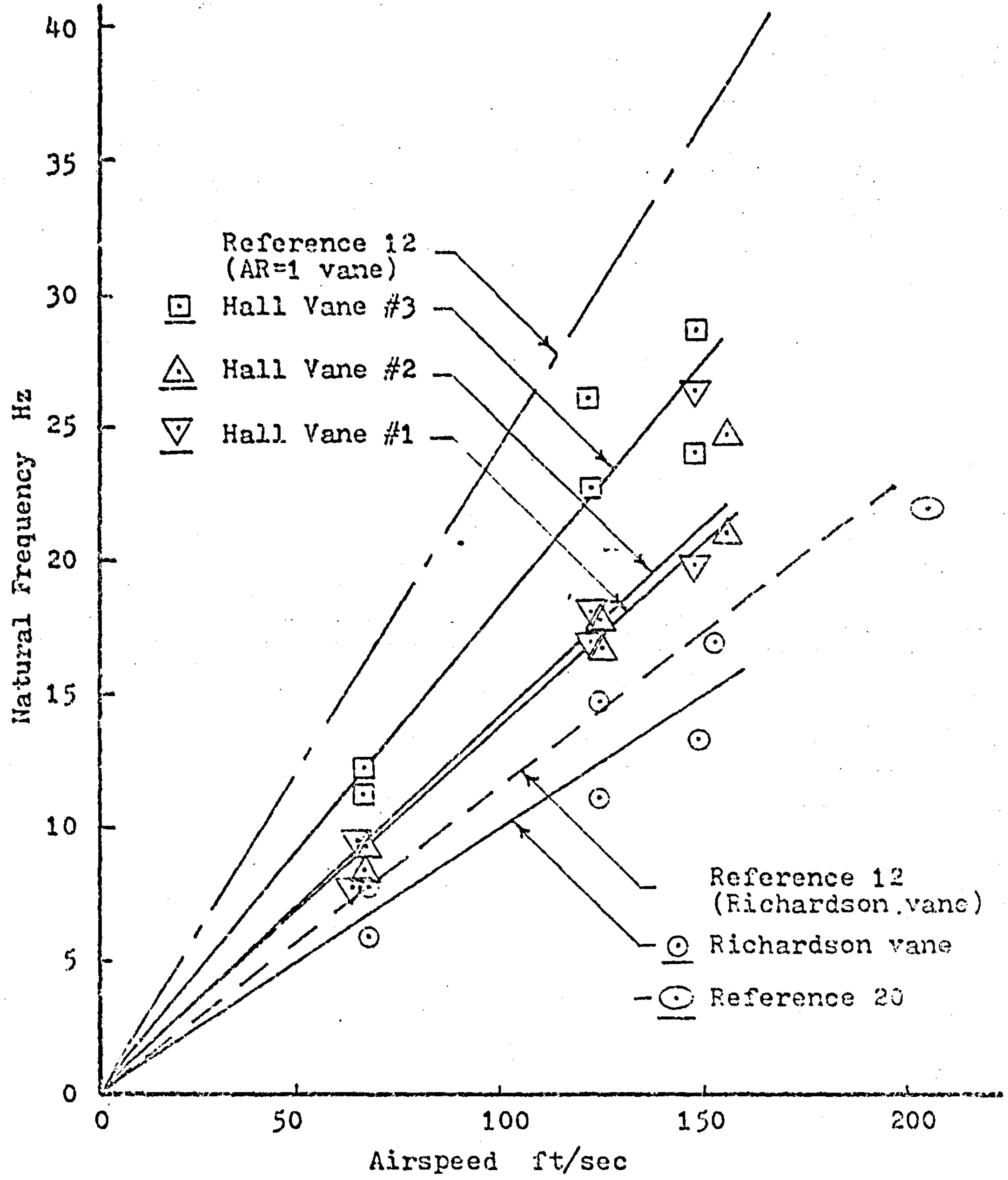

Figure 12

Flow Direction Vane Natural Frequencies

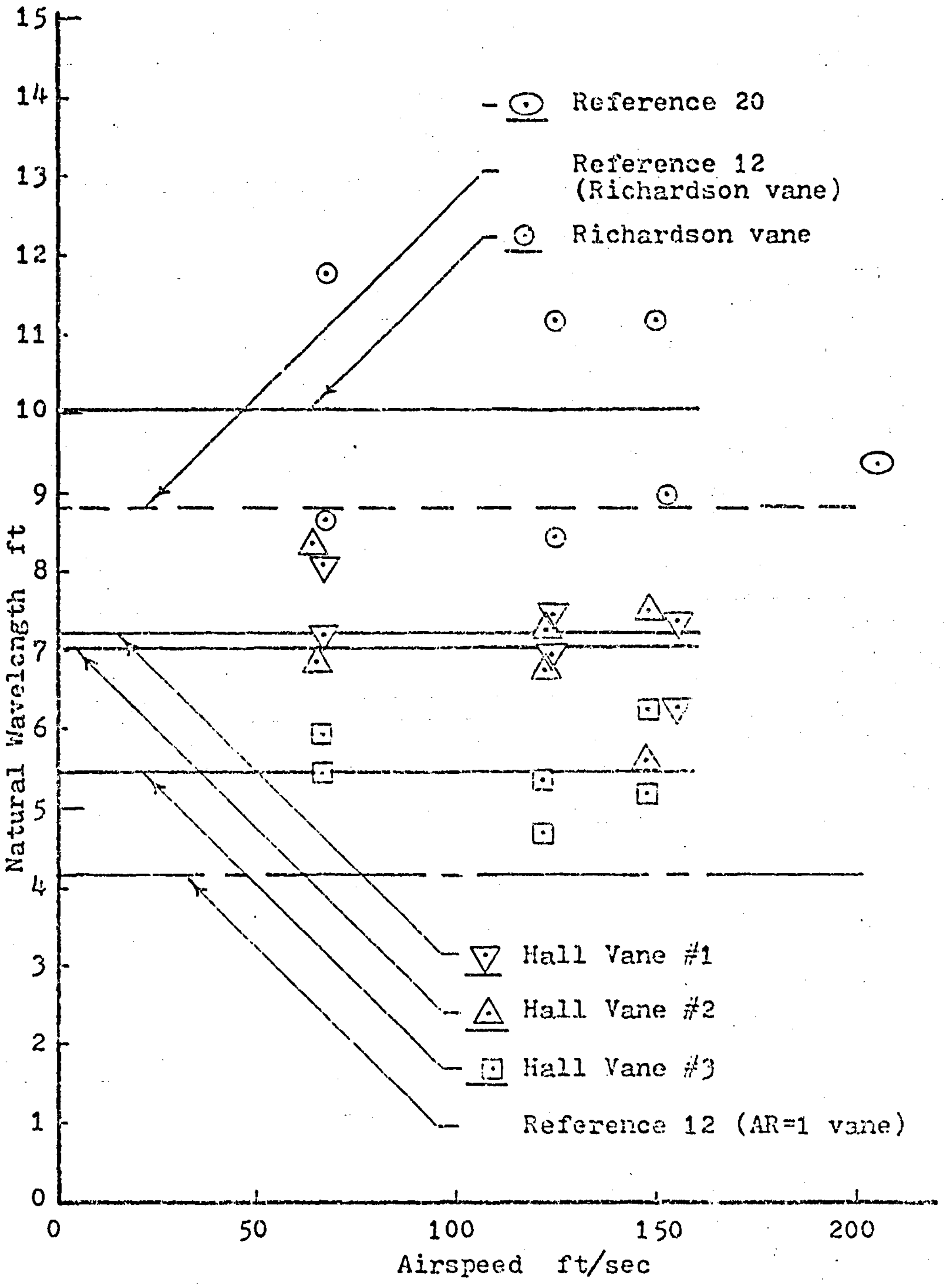

Figure 13

Flow Direction Vane Natural Wavelengths

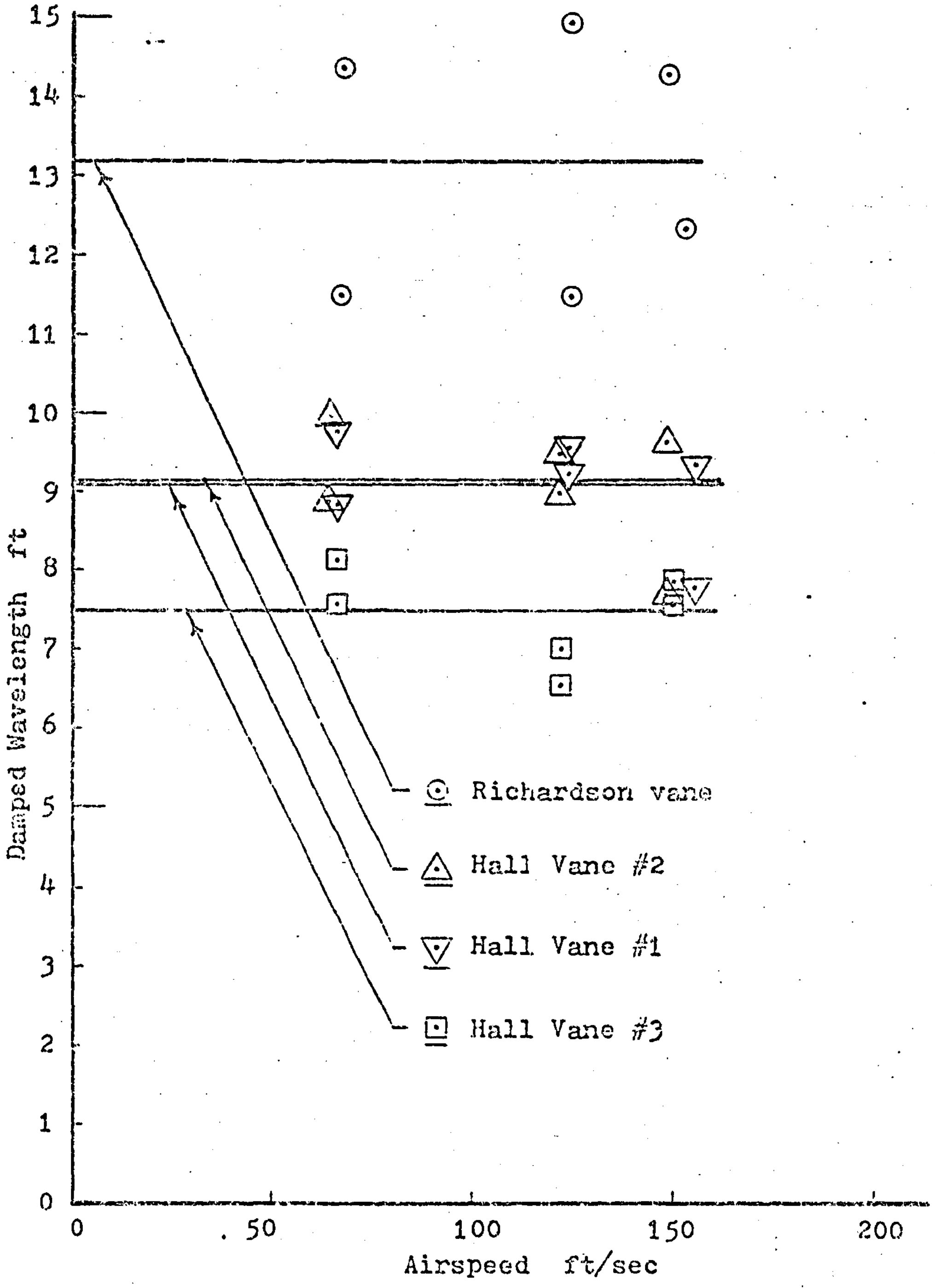

Figure 14

Flow Direction Vane Damped Wavelengths

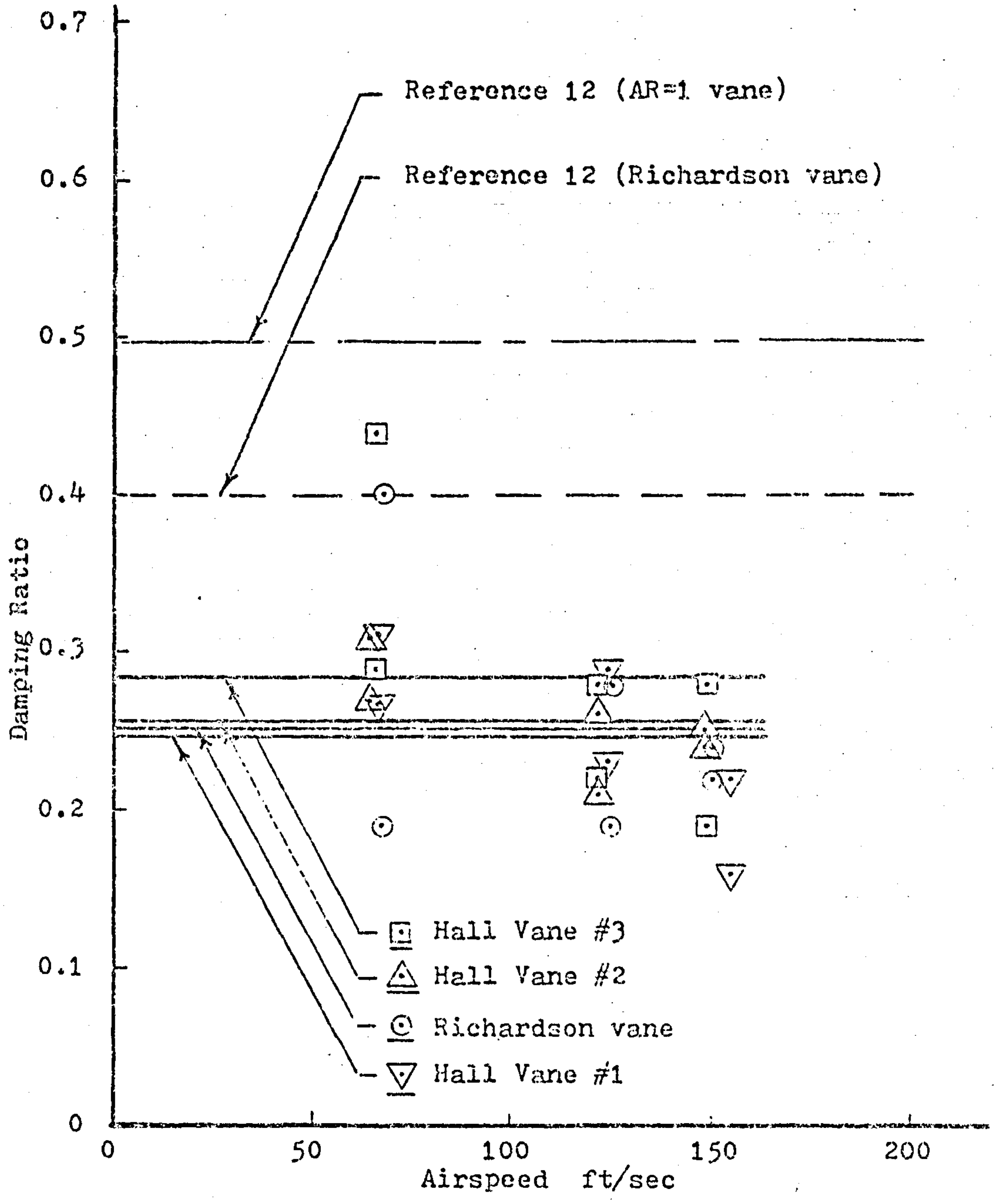

Figure 15

Flow Direction Vane Damping Ratios

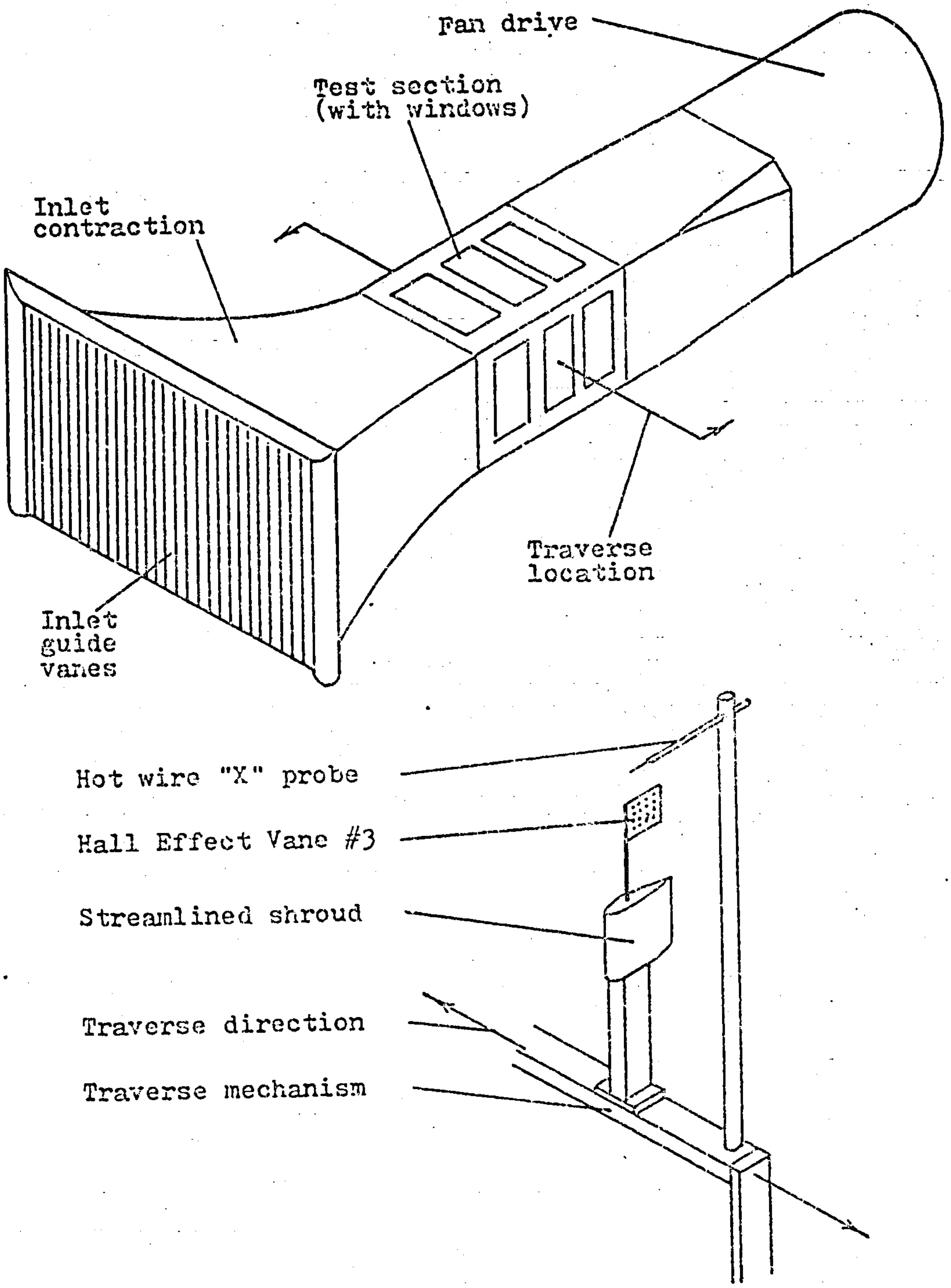

Figure 16

1/15 Scale Wind Tunnel Model Setup

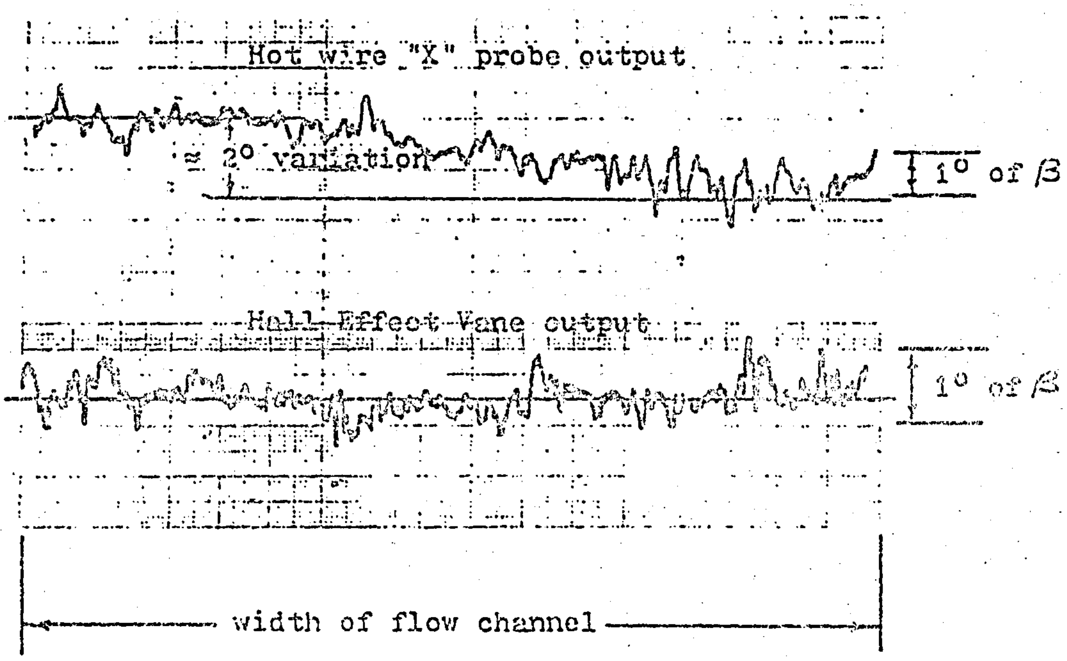

Figure 17

Hall Effect Vane Output- Sample Traverse
Across the 1/15 Scale Wind Tunnel Model
Test Section

APPENDIX B

Tables

Table 1

40- by 80-/80- by 120-Foot Wind Tunnel Flow Direction Measurement Information

MEASUREMENT LOCATION	EXPECTED CONDITIONS	FLOW DIRECTION INDICATOR
40- by 80-Foot Wind Tunnel Test Section	Maximum Angle Range - ± 3° Maximum Frequency of Dynamic Flow Angle - 1 Hz Speed Range - 0 to 300 kts Required Accuracy - ± 0.1° Large Area Measurement	A rotatable flow direction vane 2 large, two-dimensional directional pressure probes (oriented vertically and horizontally)
80- by 120-Foot Wind Tunnel Test Section	Maximum Angle Range - ± 5° Maximum Frequency of Dynamic Flow Angle - 1 Hz Speed Range - 0 to 100 kts Required Accuracy - ± 0.5° Large Area Measurement	A rotatable flow direction vane Laser velocimeter
Turning Vane Cascade Onset Flow Angle	Maximum Angle Range - ± 10° Maximum Frequency of Dynamic Flow Angle - 1 Hz Speed Range - 0 to 120 kts Accuracy Desired - ± 1° Large Area Measurement	A rotatable flow direction vane A large, two-dimensional directional pressure probe
Turning Vane Cascade Outflow Angle (low drag vane set)	Maximum Angle Range - ± 5° Average Angle Measurement Speed Range - 0 to 120 kts Accuracy Desired - ± 1° Large Area Measurement	A rotatable flow direction vane A large, two-dimensional directional pressure probe
Turning Vane Cascade Outflow Angle (high drag vane set with separated flow)	Maximum Angle Range - ± 10° Average Angle Measurement Speed Range - 0 to 120 kts Accuracy Desired - ± 1° Small Area Measurement	Small, two-dimensional directional pressure probes arranged on a flow direction indicator rake
Fan Drive Inlet	Maximum Angle Range - ± 20° Maximum Frequency of Dynamic Flow Angle - 1 Hz Speed Range - 0 to 50 kts Accuracy Desired - ± 1° Large Area Measurement	A rotatable flow direction vane A large, two-dimensional directional pressure probe
Fan Drive Exhaust	Maximum Angle Range - 0 to 10° Average Angle Measurement Speed Range - 0 to 100 kts Accuracy - ± 1° Large Area Measurement	Oil flow visualization
Exterior Wind Direction	Maximum Angle Range - 360° Maximum Frequency of Wind Gusts - 1/10 Hz Speed - 0 to 40 kts Accuracy - ± 5°	Large, weatherproof flow direction vanes

Table 2

Vane Response Parameters

VANE RESPONSE PARAMETERS - SUMMARY

1. Sett'ing Time (t_s) (or response time)

   Definition: the time required for the vane to settle within 2% of the initial offset angle

   Desire: a low value

   How to obtain a low value:

   a. Decrease the system mass to increase the natural frequency and damping ratio.

   b. Increase the system friction to increase the damping ratio closer to 1.0.

2. Threshold Velocity

   Definition: the lowest flow velocity required to rotate the vane to the desires angle

   Desire: a low value

   How to obtain a low value:

   a. Decrease the system mass to reduce the aerodynamic force required to rotate the vane.

   b. Increase the fin area (without increasing system mass) to decrease the aerodynamic force required to rotate the vane.

   c. Decrease system friction to decrease the aerodynamic force required to rotate the vane.

Table 3

Flow Direction Vane Settling Times and Response Frequencies

	t_s (sec)	f (Hz)
Richardson Vane	0.172	5.8
Hall Effect Vane #1	0.126	7.9
Hall Effect Vane #2	0.118	8.5
Hall Effect Vane #3	0.083	12.0

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