Initial Flow Calibration Results from the Florida Technological University four-inch supersonic wind tunnel

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INITIAL FLOW CALIBRATION RESULTS FROM THE FLORIDA TECHNOLOGICAL UNIVERSITY FOUR-INCH SUPERSONIC WIND TUNNEL

BY

JAMES K. BECK
B.S.A.E., Purdue University, 1953

THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering in the Graduate Studies Program of Florida Technological University

Orlando, Florida
1973
ACKNOWLEDGMENTS

The author wishes to express his appreciation to those members of the faculty whose comments and suggestions contributed to the successful completion of this investigation. Special thanks to Dr. R. D. Evans and Dr. R. C. Rapson for their direct aid in the experimental portion of the study and to Drs. D. B. Wall and B. G. Nimmo for their helpful suggestions on the manuscript.

Also, a note of appreciation to Mr. Joseph Haibach who did an excellent piece of work in fabricating the calibration probe.

Finally, the author takes this opportunity to express deepest appreciation to his wife, Peggy, for her encouragement and understanding.
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NOMENCLATURE

M  Mach number, dimensionless.

$P_{t_1}$  Tunnel stagnation pressure, psi.

$P_{t_2}$  Stagnation pressure downstream of normal shock, psi.

Pset  Preset stagnation pressure, psi.

$P_{c_{up}}$  Cone static pressure on upper surface, psi.

$P_{c_{lo}}$  Cone static pressure on lower surface, psi.

$\Delta P_c$  Differential pressure across cone (upper minus lower), psi.

R  Throat counter reading, dimensionless.

$\epsilon$  Flow inclination angle, deg.

$\delta$  Aerodynamic error of conical probe, deg.

Y  Distance above or below tunnel centerline, in.

h  Throat half-height, in.

Re  Reynolds number, dimensionless

$\ell$  Characteristic length of test specimen, inches
INITIAL FLOW CALIBRATION RESULTS FROM THE FLORIDA TECHNOLOGICAL UNIVERSITY FOUR-INCH SUPersonic WIND TUNNEL

by

JAMES K. BECK

ABSTRACT

The Florida Technological University supersonic wind tunnel is a conventional blowdown-type having a four-inch square test section. The flexible plate nozzle and maximum stagnation pressure capability of 250 pounds per square inch permit generation of a range of supersonic Mach numbers of from 1.5 to about 5.0.

This thesis establishes a familiarity with the facility and obtains initial calibration data on the flow quality so that estimates to the extent of its usefulness in a particular application may be ascertained.

The measurements recorded for determining local Mach number and flow angularity were obtained from electro-mechanical transducers which sensed pressures at the apex and on the upper and lower surface elements of a 25 degree half-angle cone. The conical probe was positioned at various angular settings, in both upright and inverted attitudes, for determining flow inclination parameters. Additional data were obtained in the vertical plane at several elevations. Flow field measurements
were made at nominal Mach numbers of 2, 2.5, 3, 3.5, and 4 and at the operating pressures recommended by the facility contractor. These pressure levels are essentially the minimum operational values for models of moderate dimensions and bluntness, i.e., those having low tunnel blockage effects.

As is typical for a facility of this type, the results indicate that the desire for flexibility that the nozzle design permits does compromise the flow uniformity to some extent. In general, the local Mach number varied about $\pm 0.02$ over the vertical plane of measurement. The most significant deviation occurred at the Mach 2 nozzle setting for which the Mach number showed a significant increase below the centerline (to $+0.07$ maximum). The flow angularity is, in general, equal to about $\pm 1$ degree depending on the tunnel conditions. The maximum centerline measured flow angularity occurred at Mach 3 as an upflow of about 1.8 degrees.

Dr. Donald B. Wall, Chairman
CHAPTER I

INTRODUCTION

A four-inch by four-inch supersonic blowdown wind tunnel has been installed in the Engineering Building on the campus of Florida Technological University located at Orlando, Florida. The facility was installed for use as an educational supplement to the classroom and as a research tool for those applications where a supersonic airstream is required. The information in this thesis has been gathered for the purpose of providing a description of the facility and providing the experimenter with some knowledge of the general flow properties which can be anticipated in planning a future investigation.

At the time of installation, the only information regarding the test section flow conditions generated by the flexible plate nozzle was a theoretical relationship between the three-digit reading of the throat adjustment counter and the throat height. The throat height (and width) is related through the throat-to-test-section area ratio and consequently Mach number. The resulting Mach number is only a nominal value and it becomes necessary to perform a flow field measurement to determine more precisely the actual Mach number distribution in such an airstream. Because of the strong influence of the nozzle shape, it is possible to have induced local velocity perturbations in both magnitude and
direction, i.e. flow angularity may be introduced. Therefore, it is desirable to make the measurements necessary to define the flow field as precisely as possible, so that these effects may be accounted for in any future experimental program.

A complete test section calibration for the range of capabilities available from the facility was not deemed feasible for this initial investigation. Rather, a restricted study was planned and executed to develop the experimental techniques involved as well as make some measurements that could be used as indicators of flow quality.

A 25 degree half-angle cone was used as the flow sensing probe. Pressure taps were located in the cone apex to sense stagnation pressure and on the upper and lower cone elements to sense primarily a differential pressure. These pressure measurements were then related to the tunnel stilling chamber (stagnation) pressure for determining the quantities of interest.

Approximately 100 tunnel operations were made to gather the data during the period of March and April, 1973. All measurements were made at the test-section window centerline in the vertical plane of the airstream.
CHAPTER II

DESCRIPTION OF FACILITY

General

The four-inch supersonic wind tunnel is a conventional blowdown, single-pass design capable of generating flow Mach numbers in the range of 1.5 to 5.0. The tunnel facility, consisting of the pressurization system, flow circuit, associated instrumentation, and model hardware was designed and fabricated by Kenney Engineering Corporation of Pasadena, California. The facility is designed for semi-automatic operation requiring only the opening of the manual gate valve, adjusting the operating pressure and flow-on timer, and depressing the start button. Further convenience has been incorporated into the design through the addition of a remote tunnel controller which the operator may utilize as far as 25 feet from the main console. Two views of the tunnel installation are shown in Figures 1a. and 1b. The major components such as the supply pipe from the air storage tank, the main control valve, the conical subsonic diffuser and settling chamber, and the nozzle, test section, supersonic diffuser, and flow silencer are readily discernible. Additional information on the installation is supplied in the following paragraphs and in Reference [1].
Fig. 1a.—Photograph of the supersonic wind tunnel installation; overview of the facility
Fig. 1b.--Photograph of the supersonic wind tunnel installation, side view
Pressurization System

The 329 cubic foot air storage tank is supplied by a 50 horsepower two-stage compressor regulated to a maximum pressure of 250 pounds per square inch. Following compression, the air flows through an aftercooler and separator for removal of the condensed water. It is then processed through an oil-vapor filter and finally through a silica gel dryer to remove the excess water vapor. The stored air has a design dew point in the range of -20 to -40 degrees Fahrenheit, conservative by the standards of Reference [2]. The dryer has the capacity for an eight-hour pumping period, after which the silica gel must be regenerated by the internally mounted electric strip heaters. The tunnel stagnation pressure is automatically controlled by a feedback system between the stilling chamber and the main four-inch double-ported control valve.

Tunnel Circuit

The circuit is made up of components typical to this type of single-pass blowdown wind tunnel. A conical subsonic diffuser reducer the air velocity to the screened stilling chamber. The air then passes to the nozzle and test section assembly which is unique to the Kenney-engineered facility. Since the flow Mach number is predicated on the test section to throat area ratio, the throat height is varied through a smoothly operating mechanism and the flexible upper and lower walls assume a gradually decreasing curvature as shown in Figure 2. This design approach yields a flexibility in designing an experiment for an unlimited selection of intermediate test section Mach numbers. The flexible nozzle can
Fig. 2.—The flexible plate nozzle
be removed and replaced with precisely contoured nozzle blocks, if desired. The test section windows, of 1-1/4 inch plate glass (selected for good optical quality) give a 26 square inch viewing area.

A remotely-driven model support strut, as shown in Figure 3, allows additional flexibility in tunnel operation. A linkage has been incorporated into the design which permits the model to be driven either in an angular mode or translation mode in the vertical plane. Effectively, this permits the model angle of attack to be varied through ± 20 degrees, maximum, at the most aft center of rotation to any intermediate plus and minus (including 0) range at a more forward center of rotation (≈ for pure translation). The strut has a total movement of ± 3 inches; therefore, extreme care must be exercised when changing the model's center of rotation. Limit switches have been installed to prevent driving the model into the top or bottom of the test section; these switch positions must be checked when making this change.

The second throat is a simple four inch square duct having no wall adjustments. It is followed by a 40 inch long transition section to an 8-1/2 inch round section which enters an extension fitted to the large muffler. The diffuser section is caster-mounted to allow access to the model and strut.

Instrumentation

The supplied instrumentation is contained in the tunnel console. The information displayed includes:

1. Storage tank pressure: 0 - 300 psig.
Fig. 3.--The open test section and support strut mechanism
2. Tunnel stagnation pressure: 0 - 300 psig.
3. Tunnel stagnation temperature: -75 to +225°F.
4. Six data channels from test section: -30 in. Hg to +30 psig.
5. One data channel from test section: -30 in. Hg to +100 psig.
6. Tunnel preset pressure.
7. Strut position and angle of attack.
8. Strain gage readout for normal forces, axial force, and rolling moment.

The test-section/model pressures above may be read out from eight-inch Bourdon-type gages which may be sealed off during tunnel operating to facilitate data recording after the run is completed. Tunnel stagnation temperature is required to define the Reynolds number, which can vary as a result of expansion from the storage tank pressure to the running pressure.

The half-inch diameter four-component strain gage balance has been designed to the following maximum load conditions:

- Front normal force \( \pm 25 \) lb.
- Rear normal force \( \pm 25 \) lb.
- Axial force \( \pm 20 \) lb.
- Rolling moment \( \pm 20 \) lb.-in.

The loads are read-out by meter indicators or, for better reading accuracy, by a null-balance digital system. The front and rear-mounted gages allow computation of pitching moment about a pre-selected reference point using the standard data reduction procedures outlined in Reference [1]. The balance and assorted model hardware are pictured in Figure 4.
Fig. 4.--The strain-gage balance and assorted model hardware
A schlieren optical system is available for flow visualization. It is a standard single-pass system utilizing six-inch parabolic mirrors of 48-inch focal length and a 1000 watt BH6 mercury vapor light source. A viewing screen is available; no camera facilities for permanent recording are installed as of this writing, but arrangements can be made to satisfy this requirement. Two examples of schlieren photos obtained from the viewing screen are shown in Figures 5a. and 5b. for Mach numbers 2 and 3, respectively. Note the intersection of the conical bow shock with the window surface at Mach 2.
Fig. 5a.—Typical schlieren photographs; Mach number 2
Fig. 5b.--Typical schlieren photographs; Mach number 3
Determination of Mach Number

For the range of Mach numbers over which the calibration was accomplished, there was not much choice of method for accurate Mach number determination. The possibilities examined included:

1. The measurement of wall static pressure and/or freestream static pressure and comparing either to the stilling chamber pressure through the Rayleigh-pitot equation.

2. Measurement of cone surface pressure or shock wave angle and comparing these data with cone theory.

3. Measurement of the stagnation pressure downstream of the shock formed ahead of the measuring device and comparing to the stilling chamber pressure.

The first possibility is probably best for Mach numbers up to about 1.5 - 1.6, the second introduces too many possible errors (wall effects, boundary layer interactions, probe geometry, etc.). As a result, the last approach was chosen as the most suitable for the task. The only assumptions necessary are that the upstream shock is locally normal to the stagnation streamline and that the flow is brought to rest isentropically aft of the shock. References [3] and [4] provide a complete listing of compressible flow Mach number functions useful for these type experiments.
Determination of Flow Angularity

Of the different types of yawmeters that may be used for determining flow angularity, the wedge or cone is generally used for supersonic wind tunnel calibration [2]. The cone is less sensitive to angle changes due to its three-dimensional relieving effect; however, it is easier to fabricate and for this reason was chosen in preference to the wedge. In addition, the cone was readily adaptable to allowing measurement of both Mach number and angularity with a single probe by putting a pressure tap in the cone apex. The pressure taps on the upper and lower surface of the cone yielded a differential pressure which could be related to the flow angle measurement.

Probe Description

The probe geometry was a compromise result of consideration for sensitivity, size, and degree of bluntness, keeping in mind the effect of the latter items on starting pressure ratio. Figure 6, which has been reproduced from Reference [2], shows the effect of varying the cone angle on sensitivity for Mach numbers in the range of interest. These data may also be generated from the cone theory of Reference [3]. Note that the graph on the lower half of the figure is merely a cross-plot of the upper one. At the higher Mach numbers the sensitivity appears to level off in the region of 40 - 60 degrees included cone angle. The cone angle chosen was a median 50 degrees. The base diameter of the cone was restricted to one inch to limit the adverse blockage effects on starting pressure ratio. The cone was attached to a half-inch sting support for
Fig. 6.—Sensitivity of the conical probe to inclined flow.
mounting in the strut mechanism. The upper and lower surface taps were located 180 degrees apart and 0.25 inch longitudinally from the base. This distance is not critical and was set near the base to ease the fabrication effort. A sketch of the probe geometry is shown in Figure 7.

Supplementary Instrumentation

Because of a desire to increase the accuracy of the pressure measurements and to provide for a permanent data record, four electro-mechanical transducers were utilized as sensing devices. The transducer types and ranges were as follows:

1. Stilling chamber: Statham UC3 universal transducer equipped with inter-changeable pressure diaphragms.
2. Cone apex: Statham P69-10D-120 having a range of +10 psig differential.

In addition, a mercury manometer was put in parallel with the cone-surface transducers as a verification for the upper and lower surface pressure differences. All transducers were calibrated for linearity and repeatability prior to installation and check loadings were applied prior to each daily operation to verify the transducer/recorder system. The low pressure calibrations were accomplished using a mercury manometer as the standard; the stilling chamber transducer was calibrated against the Heise (0 - 300 psi) gage mounted in the tunnel console. The cone apex transducer was found
Fig. 7.—Probe geometry
to be linear to about 13.5 pounds per square inch which was satisfactory for the conditions encountered during these experiments.

Each transducer had its own DC power simply because of the different excitation voltages required and to preclude electrical interactions discovered during calibration. The outputs were amplified through a Honeywell Accudata 117 DC multi-channel amplifier. The resulting signal was then fed to a Honeywell Model 1508-A Visicorder for permanent recording. The instrumentation schematic and a typical data record are shown in Figures 8 and 9, respectively. (The traces on Figure 9 have been retraced on graph paper for reproduction purposes.) The run times for taking data lasted about 8 - 10 seconds on the average. Note the changes in transducer sensitivity for differing test conditions. The relatively slow rate of change in cone surface pressure was caused by a time lag induced by the pressure taps that were slightly small for the test conditions. Though the agreement was generally very good, it was decided that the manometer measurement of $\Delta P_c$ was the more accurate since the manometer could be read to about $\pm 1\text{mm}$ of mercury ($\pm 0.04$ psi) compared to about $\pm 0.2$ psi for the transducers.

The console meters depicting angle of attack and strut position were deemed not sensitive enough for this investigation. Therefore, calibrations were made of the potentiometers (0.5% linearity) sensing these parameters using a vernier scale for translation measurements, and a three-inch protractor-level for angular measurements. Potentiometer voltage drops were recorded on a digital voltmeter. The results of these calibrations are indicated in Figure 10. It is rather obvious that the linearities are very good and, if the strut attitude is always approached from the same direction (as it was in these experiments)
Fig. 8.--Schematic of the instrumentation
Fig. 9a.—Typical data record from the visicorder, Mach number 2
Fig. 9b.—Mach number 3
Fig. 9c.—Mach number 4
Fig. 10a.—Translation potentiometer

Fig. 10b.—Angular potentiometer

Fig. 10.—Strut Position Calibrations
repeatibility of model setting is readily accomplished. The angle of attack potentiometer was actually calibrated over a greater range (+14 degrees) than that shown to amplify non-linearities.
CHAPTER IV

DISCUSSION OF RESULTS

An initial test-section flow survey has been conducted at five Mach numbers in the vertical plane at the window centerline of the four-inch supersonic wind tunnel. This section of the thesis discusses the data obtained from this survey.

It should be noted that, as indicated previously, the information contained herein is only intended as an overview of what can be expected from this tunnel by future experimenters. In general, it is common practice to have a complete calibration of such a facility available, but this "ideal" requires an effort which was deemed beyond the scope of this initial presentation. It is anticipated that the calibration will be a continuing effort over a lengthy time period. For example, the tunnel stagnation pressure is variable to a value considerably above that investigated for each Mach number in this experiment. Since the flow Reynolds number would vary in direct proportion to pressure, there is no doubt that a significant effect on flow properties would be noted.

The pressures that have been investigated were those recommended as nominal values by Kenney Engineering. Because of a pressure-controller operational anomaly, the preset pressure must be adjusted to a value approximately 40 - 50 pounds per square inch above the desired running pressure. Figure 11 summarizes this effect. The measured values were
Fig. 11.—Tunnel operating pressure requirements
satisfactory for the 50 degree cone used in these experiments, but may not work successfully for larger or more blunt models because of the usual starting problems that may be encountered. Note, for example, that at Mach 4 the stagnation pressure had to be increased about 10 pounds per square inch above the recommended value to achieve a satisfactory tunnel start. Even at this pressure, Figure 9c indicates a reluctance to start - note the cone apex pressure trace.

Freestream Mach number was determined for five throat counter readings (a digital readout geared to the adjusting mechanism) and five points in the vertical plane of the test section at the window centerline. These data are presented in Figure 12. With the exception of the distribution found at Mach 2, the experimental points indicate a variation of about ± 0.02 across the vertical survey plane. Note that, at Mach 3, the data were rerun in order to establish a confidence level in data repeatability which indicates a variation of about ± 0.01. To an investigator familiar with similar measurements from a facility utilizing computer designed, finely contoured, fixed nozzle blocks, such values would seem to be high. Two thoughts must be interjected at this point to place these results in perspective:

1. The facility was purchased primarily as an educational tool so that flexibility was considered to be a more desirable characteristic.

2. Fixed nozzle blocks may be purchased to replace the semi-flexible nozzle as requirements (and budget) dictate.
Fig. 12.—Mach number distribution in the vertical plane

R is the throat counter reading
The upper and lower flexible plates are restrained by the adjustment mechanism at several points (see Figure 2) but otherwise seek a contour dependent on the local stress distribution. Therefore, some flow asymmetry and property gradients in the test section are to be anticipated. Figure 13 is included to indicate the slight deviation between the measured Mach number and the theoretical equation, developed by the contractor, relating throat counter reading and test section Mach number (through area ratio and a constant boundary layer allowance) [1].

The above comments are amply reinforced by the results of the investigation of local flow angularity within the test section presented graphically in Figures 14 and 15. Figure 14 has been introduced as an aid to interpreting the procedure used in determining angularity at those positions for which only cone-upright data were available. The data from Figure 15 indicate the following variation in flow angularity at the window centerline with nominal Mach number: (the aerodynamic error arises from a fabrication bias)

<table>
<thead>
<tr>
<th>Mach number</th>
<th>Angularity, ε</th>
<th>Cone Aerodynamic Error, δ</th>
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<tr>
<td>2</td>
<td>- 1.1 deg</td>
<td>0.4 deg</td>
</tr>
<tr>
<td>2.5</td>
<td>- 0.2 deg</td>
<td>0.5 deg</td>
</tr>
<tr>
<td>3</td>
<td>+ 1.6 deg</td>
<td>0.6 deg</td>
</tr>
<tr>
<td>3.5</td>
<td>+ 0.4 deg</td>
<td>0.6 deg</td>
</tr>
<tr>
<td>4</td>
<td>+ 0.2 deg</td>
<td>0.5 deg</td>
</tr>
</tbody>
</table>

These data were obtained by simply putting the theoretical slope of Figure 6 through the test data without regard for the probability that the cone error is actually a constant value. With the exception of
Fig. 13.—Calibration of throat counter reading

\[ h = \frac{1}{2} \left( \frac{R-748}{63} \right) - \left( \frac{R-748}{63} \right)^2 (0.003) \] [1]
In general:
\[
\varepsilon = -\alpha_1 = - \left[ \frac{\Delta P_c \text{ UPR}(\alpha=0)}{d(\Delta P_c)} \right] - \delta
\]
where
\[
\delta = \alpha_2 - \alpha_1
\]

\(\varepsilon\) = flow angularity

(-) Downflow

(+) Upflow

Fig. 14.—Interpretation of flow angularity data
Fig. 15a.—Flow angularity data at centerline of window, Mach 2
Fig. 15b. -- Mach 2.5
Cone angle of attack - degree

Fig. 15c.--Mach 3
Fig. 15d.--Mach 3.5

Differential pressure across cone $- \frac{\Delta P}{\Delta t}$

Cone angle of attack - degree

Fig. 15e.--Mach 4

Differential pressure across cone $- \frac{\Delta P}{\Delta t}$

Cone angle of attack - degree
only a few data points, the correlation with theory is considered very good. The most difficult measurement to make with a high degree of accuracy was the probe angle of attack. The centerline (Y=0) flow angularity data above do indicate a reasonably smooth trend with Mach number rather than a random scattering, which would indicate also that the plate curvature is influenced by the mechanism restraints and the gradually changing internal stresses with throat height adjustments.

As the probe was traversed in the vertical plane, cone surface pressures were measured at each position point and the mercury manometer reading for differential cone pressure was recorded. This pressure difference (model upright) was then utilized as indicated in Figure 14 to calculate the flow angularity off centerline. To further substantiate the method, a series of check runs was made at Mach 3.5 with the cone at zero angle of attack both upright and inverted (off centerline). The theoretical sensitivity slopes were drawn through each of the data points as shown in Figure 16, and the angularity agreed within 0.2 degree to that calculated using the upright-only data.

A data summary is contained in Figure 17 for maximum Mach number deviation and maximum upflow and downflow recorded during this investigation. The upper graph is a plot of the maximum measured values of Mach number deviation from the actual centerline value which is plotted on the abscissa. For example, at Mach 3.45 (the measured centerline value) the maximum measured value at other points in the vertical plane was 3.47 and the minimum value was 3.46, so that the maximum deviation was no more than ± 0.02. Likewise, only the maximum values of recorded upflow or downflow are shown. Therefore, the flow uniformity is
Fig. 16.--Correlation of flow angularity data at Mach 3.5

Cone angle of attack - $\alpha$

Cone angle of attack - $\alpha$
Fig. 17.--Summary of maximum Mach number deviation and maximum flow angularity measurements
always as good or better than that indicated in Figure 17 for the survey plane investigated.

Because of the relative brevity of data measurements (which required about 100 tunnel starts) no formal data-accuracy analysis was performed. However, as noted previously, a number of repeat points were obtained to indicate a confidence level of the several quantities recorded. Based on these data, and observations made during transducer calibrations, strut position calibrations and readings from the Visicorder charts, the data are believed to represent the actual flow quality to a reasonable level of accuracy, i.e., Mach number to $\pm 0.01$ and flow angularity to about $\pm 0.25$ degree.

It should be reiterated that these investigations were conducted at the approximate stagnation pressures recommended by the manufacturer. The storage pressure available will permit a considerably greater variation in flow Reynolds number, as indicated in Figure 18. It must be kept in mind, however, that the nominal maximum and minimum values may be difficult to achieve under certain practical constraints. Such things as instrumentation range, model size, mass flow rates (run time), noise level, and operational safety must be considered when operating any facility of this type to its limits.
Fig. 18.--Reynolds number capability
CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

An experimental investigation has been conducted to establish an initial indication of the quality of flow generated in the Florida Technological University four-inch supersonic wind tunnel. The results of this investigation indicate that:

1. The tunnel circuit and its components operate satisfactorily.
2. In general, the Mach number distribution is uniform within $\pm 0.02$ at the window centerline for all Mach numbers except 2.1 (R=877). At this setting, measurements made below the longitudinal centerline indicated a definite increase in Mach number to 2.17 at $Y = -1.0$ inch, which represents the maximum Mach number deviation of $\pm 0.07$.
3. The magnitude of the flow angularity data is generally about one degree (up or down) depending on the nozzle setting and location. It was shown, however, that at Mach 3 and 3.5 values as high as $1.8 - 2.0$ degrees upflow may be encountered.
4. The measured results have been estimated to be within $\pm 0.01$ in Mach number from repeat data results and within $\pm 0.25$ degrees in flow angularity from repeat data and physical observation.
Based on the planning and execution of this study, it is recommended that future investigations of this type include:

1. A minimum of four additional vertical plane surveys at two-inch increments, both upstream and downstream of the window centerline, to better define the flow field.

2. Examination of Reynolds number effects on flow uniformity.

3. The incorporation of a differential pressure transducer for direct recording of the cone pressure difference as opposed to manual recordings from the manometer.

4. The addition of strut-position readout on the chart recorder to simplify the operational procedure in conducting the experiments.
LIST OF REFERENCES


