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INSTRUMENTATION FOR CALIBRATION AND CONTROL OF A CONTINUOUS-FLOW CRYOGENIC TUNNEL

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INSTRUMENTATION FOR CALIBRATION AND CONTROL OF A CONTINUOUS-FLOW CRYOGENIC TUNNEL*

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SUMMARY

This paper describes those aspects of selection and application of calibration and control instrumentation that are influenced by the extremes in the temperature environment to be found in cryogenic tunnels. A description is given of the instrumentation and data acquisition system used in the Langley 0.3-m transonic cryogenic tunnel along with typical calibration data obtained in a 20- by 60-cm two-dimensional test section.

SYMBOLS

c	chord of airfoil
M	Mach number
p	pressure
q	dynamic pressure
R	Reynolds number
T	temperature
$\bar{T}_t$	mean value of stagnation temperature
V	velocity

Subscripts

l	local value
ref	reference
t	stagnation value
∞	free-stream value

Abbreviations

GN_2	gaseous nitrogen	NTF	National Transonic Facility
LN_2	liquid nitrogen	PRT	platinum resistance thermometer
%	percent	TCT	0.3-m transonic cryogenic tunnel
2-D	two dimensional		

1. INTRODUCTION

The need for increased capability in terms of Reynolds number has been recognized since the earliest days of testing subscale models in wind tunnels. The need has been especially acute at transonic speeds where, because of the large power requirements of transonic tunnels, economic forces have dictated the use of relatively small tunnels.

In considering the various ways of increasing Reynolds number that have been tried or proposed for transonic tunnels, cooling the test gas to cryogenic temperatures (150 K or less) appears to be the best solution in terms of model, balance, and sting loads, as well as capital and operating cost.[1] In addition, having temperature as an independent test variable offers some new and unique aerodynamic testing capabilities which, in some instances, may be of equal importance with the ability to achieve full-scale Reynolds number.[2]

Personnel at the NASA Langley Research Center have been studying the application of the cryogenic wind-tunnel concept to various types of high Reynolds number transonic tunnels since the autumn of 1971 and, through extensive theoretical and experimental studies, have successfully demonstrated both the validity and practicality of the concept.[3-5]

There is, however, a price to be paid for the many advantages offered by a cryogenic wind tunnel. The price is added complexity in both the design and operation of the tunnel. Compared to an ambient temperature tunnel, the wide range of operating temperatures available in a cryogenic tunnel results in added complexity in such areas as model design and instrumentation, tunnel control, and the instrumentation used for tunnel calibration and control. This paper deals with the single area of instrumentation and associated equipment used in the calibration and control of cryogenic continuous-flow transonic pressure tunnels. Specifically, this paper addresses those aspects of instrumentation selection

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and application that are influenced by the extremes in the temperature environment to be found in cryogenic tunnels. The calibration and control instrumentation used in the Langley 0.3-m transonic cryogenic tunnel is described and examples of tunnel calibration data obtained in a 20- by 60-cm 2-D test section are given.

It should be noted that the use of trade names in this paper in no way implies endorsement or recommendation by the U.S. government.

2. INSTRUMENTATION SELECTION

In general, the process of selecting instrumentation for the calibration and control of a continuous-flow transonic pressure tunnel capable of being operated at cryogenic temperatures is no different from the process that would be followed for a similar tunnel that operates only at ambient temperatures. The steps to be taken are: (1) determine the accuracy requirements for the test parameters of Mach number M_∞, Reynolds number R, dynamic pressure q_∞, and velocity V_∞; (2) calculate the sensitivity of the test parameters to the uncertainties in the test conditions of total pressure p_t, static pressure p, and total temperature T_t; and finally, (3) select instrumentation which will meet the accuracy requirements.

2.1 Accuracy Requirements for M_∞, R, q_∞, and V_∞

The accuracy requirements of the test parameters will vary in a given tunnel depending upon the type of aerodynamic test to be performed. For most transonic applications, an accuracy in M_∞ of ±0.002 and accuracies in R and q_∞ of better than ±0.5% of reading are required. This accuracy requirement for Mach number can probably be relaxed for low-speed testing. However, larger variations in Mach number can cause significant changes in shock wave location at the higher transonic speeds. The accuracy requirements of R and q_∞ are independent of tunnel speed. In some applications, such as dynamic-stability testing, V_∞ is an important test parameter which must be determined. Here again, an accuracy of better than ±0.5% of reading is usually required.

2.2 Allowable Error in Pressure and Temperature Measurements

None of the test parameters - M_∞, R, q_∞, or V_∞ - can be measured directly with conventional instruments. However, all are functionally related to three quantities that can be measured directly, namely, stagnation pressure p_t, static pressure p, and stagnation temperature T_t. It then becomes necessary to determine the sensitivity of M_∞, R, q_∞, and V_∞ to the inaccuracies in the measured values of p_t, p, and T_t. Once this has been accomplished, the required accuracy for a given test parameter can be expressed in terms of the required accuracy for the pressure and temperature measuring instruments.

2.2.1 Allowable Error in Pressure Measurement

Calculations have been made to determine the allowable error in the measurement of stagnation pressure p_t for fixed errors in M_∞ and q_∞.[6] The results of these calculations are shown in Figure 1 as a function of M_∞. For an allowable error in M_∞ of ±0.002 and q_∞ of ±0.5% of reading, p_t must be measured to an accuracy of about ±0.25% of reading at the higher Mach numbers and to better than ±0.1% of reading at the lower Mach numbers. The sensitivity of M_∞ to errors in static pressure is the same as for stagnation pressure, but q_∞ is less sensitive, especially at the higher Mach numbers. It should be noted, however, that these are maximum errors for a single measurement. If the error analysis is based on most probable error or on standard deviation, the required instrumentation accuracy is not as great.

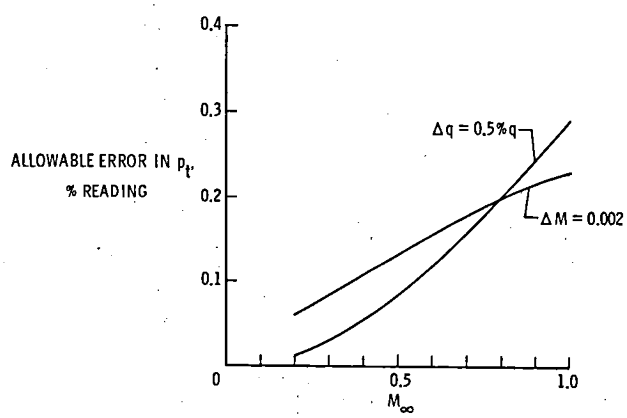


Fig. 1 Allowable error in p_t for fixed error in M_∞ and q_∞.

2.2.2 Allowable Error in Temperature Measurement

Calculations have also been made to determine the required accuracy of stagnation temperature T_t, necessary to have measurements of V_∞ and R accurate to ±0.5% reading.

Results of these calculations, in terms of allowable temperature error, are presented in Figure 2. Of the two parameters, R is the most sensitive to temperature, requiring an accuracy of ±1 K at ambient temperatures and about ±0.3 K at cryogenic temperatures. This is one area in which the accuracy requirements for instrumentation for a cryogenic tunnel are more severe than for an ambient temperature tunnel.

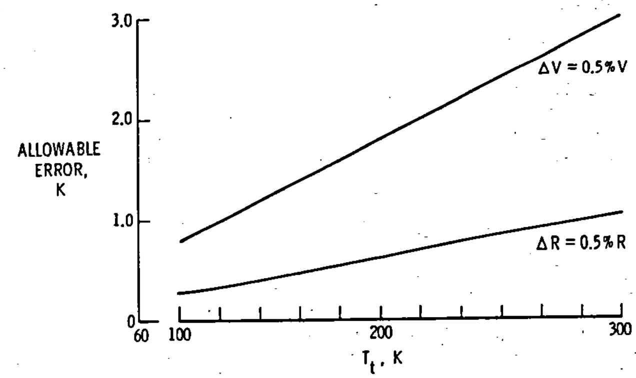


Fig. 2 Allowable error in T_t for 0.5% error in R and V_∞.

2.3 Other Considerations

The final step in the selection process is one of choosing from the available instrumentation that which will meet the accuracy requirements. However, other factors, such as the range of the test variable, response time, compatibility with the test environment, and cost and budget constraints, must also be considered.

2.3.1 Accuracy of Available Instrumentation

2.3.1.1 Pressure instrumentation.- The accuracy of three types of commercially available pressure transducers as a function of percent load are shown in Figure 3. Typical "high accuracy" strain-gage devices have an accuracy of about 0.25% of full scale. When converted to percent of reading, this increases to about 1% at 25% of full-scale load. Variable capacitance transducers have a quoted accuracy of 0.25% of reading throughout the load range but their cost is at least an order of magnitude greater than a strain-gage device. The quartz bourdon tube transducer is by far the most accurate, although it costs about 50% more than the variable capacitance transducers.

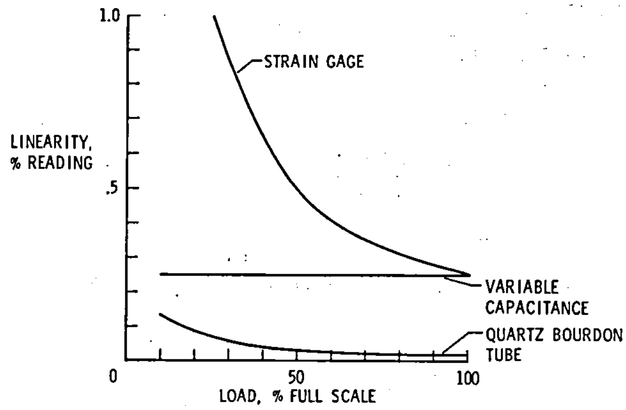


Fig. 3 Accuracy of pressure instrumentation.

Because pressure instrumentation accuracy on the order of 0.1% is required to give the desired accuracy in Mach number and dynamic pressure, the quartz bourdon tube instrument has been selected for the primary tunnel pressure instrumentation for both the 0.3-m TCT and the National Transonic Facility (NTF), the large transonic cryogenic tunnel now under construction at Langley. The quartz bourdon tube instrument is also used as the primary pressure instrumentation in other pressure tunnels at Langley. Unfortunately, the quartz bourdon tube pressure instrument has a response time that is generally much too slow for use with automatic tunnel control systems. Thus, as will be described in more detail later, less accurate but more responsive pressure instrumentation is used to provide the inputs to these systems.

2.3.1.2 Temperature instrumentation.- Two general types of temperature measurement devices are available for use at cryogenic temperature. These are resistance devices, such as the platinum resistance thermometer (PRT), and thermocouples, both of which are being used in the 0.3-m TCT. As shown on Figure 4, the PRT has an accuracy of ±0.25K which meets the accuracy requirement for measuring T_t. However, it also has a very slow response time, varying from 10 to 100 seconds, depending upon its design and size. Again, as was the case for the pressure instrumentation, the high accuracy devices do not have adequate response time for use in automated tunnel control systems. Thermocouples, which have accuracies from ±0.5 K to ±2 K, depending upon the temperature range, have response times which vary from about 0.1 to 20 seconds. This

- RESISTANCE DEVICES
  - PLATINUM RESISTANCE THERMOMETER (PRT)
  - ACCURACY ± 0.25 K
  - RESPONSE TIME 10 - 100 SECONDS
- THERMOCOUPLES
  - ACCURACY ± 0.5 K TO ± 2 K
  - RESPONSE TIME 0.1 - 20 SECONDS

Fig. 4 Temperature transducers suitable for cryogenic tunnels.

response time is a function of both the wire diameter and the type of thermocouple (bare wire, shielded, etc.), and for unshielded thermocouples in the smaller wire diameters, the response times are compatible with automatic tunnel temperature control systems.

One disadvantage of thermocouples is their very low voltage output, being on the order of a few millivolts. Another disadvantage with thermocouples is due to the fact that the net voltage output is a function not only of the base metals of the two wires but also of any material inhomogeneities which produce a parasitic voltage if located in a temperature gradient. Inhomogeneities in the wire can be produced by either a variation in the chemical composition along its length or by mechanical strain such as a kink.

The presence of defects such as these can be detected by testing lengths of thermocouple wire in a temperature gradient by using a device, such as shown in Figure 5, which runs the wire through a liquid nitrogen bath and records the voltage output resulting from the temperature gradient. However, the effects of inhomogeneities cannot be readily corrected. Typical results obtained at Langley by Germain on three types of thermocouple wire in the test apparatus shown in Figure 5 are presented in Figure 6. The voltage spikes for the type E (Chromel vs. Constantan) and K (Chromel vs. Alumel) thermocouples are typical of those recorded throughout the length of wire tested whereas the spike for the type T (Copper vs. Constantan) thermocouple was the only one found in that sample of material.

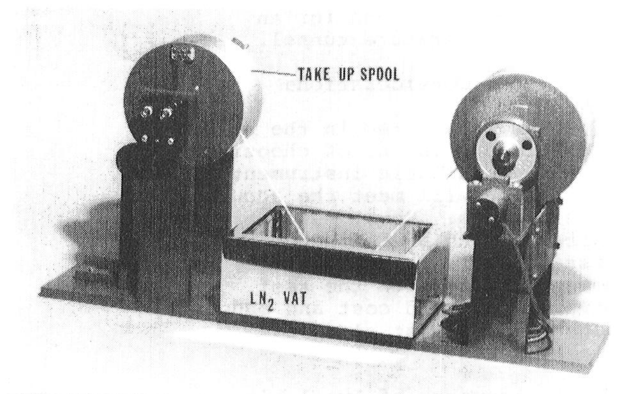


Fig. 5 Homogeneity test rig.

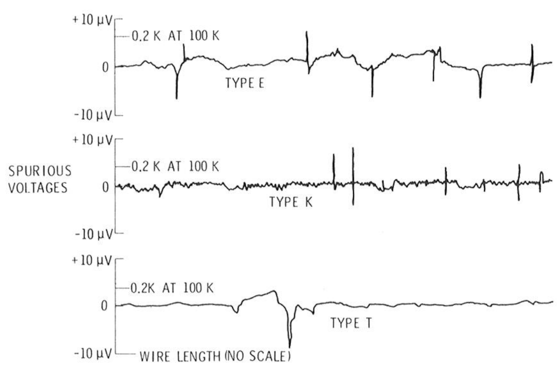


Fig. 6 Typical homogeneity test results.

Based on these results and on company literature, it appears that having one wire of pure copper makes it easier to control the overall chemical composition of type T thermocouples than either types E or K which have both wires of alloyed metal. For these reasons, type T thermocouples are being used in the 0.3-m TCT and have been selected for use in the NTF. An additional practical advantage of the type T thermocouple is that it is available in a "premium quality" wire which has a good (±1%) match to published voltage standards at cryogenic temperatures. None of the other types are so available. Our experience over the years has been that only the type T "premium" thermocouple remains within the ±1% band at cryogenic temperatures.

The standard limits of error for commercial premium grade type T thermocouple wire are presented in Figure 7 as a function of temperature. These results, from a calibration of four selected thermocouples, show their error to be only about one-half of the limit of error specification, with the largest error occurring in the cryogenic temperature region. Using calibration data such as these can increase the accuracy of a thermocouple reading, but it must be remembered that the effect of inhomogeneity cannot be accounted for.

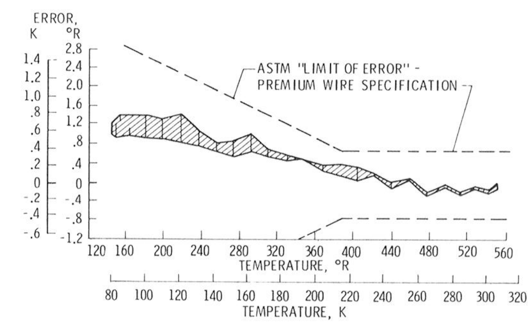


Fig. 7 Calibration of type T thermocouples.

2.3.2 Range of Test Variables

In the selection of instrumentation to meet the required accuracy, the range of the variable to be measured can be a major factor. For example, a liquid column manometer is a very accurate device for pressure measurement. However, if the pressure level exceeds two atmospheres or so, the height of the liquid column makes it impractical to use a manometer. The range of test conditions for both the 0.3-m TCT and the NTF are shown in Figure 8 to illustrate the ranges to be encountered in these tunnels as well as to indicate the ranges likely to be encountered in other transonic cryogenic tunnels. The largest difference to be noted between these two tunnels is in stagnation pressure where the maximum pressure in the NTF is about 50 percent greater than in the 0.3-m TCT. The differences in Mach number do not affect the selection of instrumentation to any great extent.

	0.3-m TCT	NTF
MACH NUMBER, M_∞	0.1 - 0.9	0.2 - 1.2
STAGNATION TEMPERATURE, T_t, K	78 - 340	78 - 339
STAGNATION PRESSURE, p_t, atm	1.0 - 6.12	1.0 - 8.85
STATIC PRESSURE, p, atm	0.5 - 6.12	0.5 - 8.85

Fig. 8 Range of test conditions.

2.3.3 Response Time

Because of the relatively high cost of operation of high Reynolds number tunnels, fast response times are desirable for all instrumentations. Response time is especially important when an instrument is used to provide an input signal to an automatic closed-loop tunnel control system. For example, the tunnel control system inputs for the 0.3-m TCT come from instruments with as short a response time as practical, at the sacrifice of some accuracy. Separate dedicated instrumentation, which is less responsive but more accurate than that used with the tunnel controls, is used to give highly reliable readings of the test variables p_t, p, and T_t. Details of this particular instrumentation as well as further discussion of response times are given in subsequent portions of this paper.

3. INSTRUMENTATION USED IN THE 0.3-m TCT

In the 0.3-m TCT, the practice of isolating instrumentation from the cryogenic environment has been adopted when possible. With the obvious exception of temperature transducers, most instrumentation is located exterior to the tunnel pressure shell, thus completely avoiding problems related to temperature variation. If a device must be located in the cryogenic environment, it is enclosed in an insulated container which is maintained automatically at approximately 300 K by using a thermostatically controlled electric heater. Devices such as slidewire potentiometers, digital shaft encoders, and pressure scanning valves have been successfully operated within the tunnel pressure shell in this manner. However, with each of these systems there are heaters, thermostats, wires, electrical connections, electrical feedthroughs, and power supplies which add to the complexity of the system and, inevitably, reduce its reliability. On many occasions, run time in the 0.3-m TCT has been lost due to the failure of one of these simple support devices rather than due to any failure in the instrument itself. Based on our experience with the 0.3-m TCT, we must conclude that it is best to locate electronic equipment exterior to the tunnel in an ambient temperature and pressure environment if at all practical.

Some details of the instrumentation presently being used in the 0.3-m TCT are now described.

3.1 Pressure Instrumentation

For two-dimensional airfoil tests, the 0.3-m TCT is equipped to obtain static-pressure measurements on the airfoil surface, total head measurements in the airfoil wake, and static pressures on the test section sidewalls, floor, and ceiling. Static-pressure taps are also located throughout the tunnel circuit to obtain information on the performance of the contraction and diffuser sections, fan pressure rise, and pressure losses across various elements of the tunnel circuit. To measure the pressures for such a large number of points, a scanning valve system capable of operating ten 48-port scanning valves is used. Because of the large changes in dynamic pressure of the tunnel over its operational range (a factor of about 75), conventional strain-gage pressure transducers are not used. Instead, we use commercially available high-precision capacitive potentiometer-type pressure transducers.[7]

The pressure transducers are mounted in instrument racks adjacent to the test section in order to reduce response time. To provide increased accuracy, the transducers are mounted on thermostatically controlled heater bases to maintain a constant temperature and on "shock" mounts to reduce possible vibration effects. The electrical outputs from the transducers are connected to individual signal conditioners located in the tunnel control room. The signal conditioners are autoranging and have seven ranges available. As a result of the autoranging capability, the analog electrical output to the data acquisition system is kept at a high level even though the pressure transducer may be operating at the low end of its range.

Pressure transducers with a maximum range of 6.8 atm are available for model and tunnel wall pressure. More sensitive transducers, having a maximum range of 1.36 atm, are available for pressure measurements in the airfoil wake. The transducers have an accuracy of ±0.25% of reading from -25% to 100% of full scale. At present about 35 pressure transducers are available. However, the system is being expanded and 125 pressure channels will be available in early 1981.

To determine M_∞ to an accuracy of ±0.001, it is necessary to use instrumentation that is much more accurate than the capacitive potentiometer type pressure transducer. As a result, the commercially available quartz bourdon tube type of pressure gage previously described is used for the measurement of p_t, p, and the reference pressure used on other differential pressure transducers. This system has an accuracy of about 0.01% of full scale at low pressures to about 0.02% of full scale at the high end of its range.

3.2 Temperature Instrumentation

The characteristics of both thermocouples and platinum resistance thermometer (PRT) temperature sensors have been previously described. Based on response time, accuracy, and to some extent cost, it has been necessary to use both thermocouples and PRT's in the 0.3-m TCT.

Type T thermocouples are used for a fixed temperature survey rig located in the settling chamber of the tunnel. In this application, we are trying to determine the distribution of temperature and the absolute level is relatively unimportant. The various thermocouples on the rig are made from the same roll of wire and care was taken to avoid kinking the wire or introducing other possible sources of error into the system.

In addition, type T thermocouples are used in the test-section—plenum area to monitor temperature differences during and immediately after tunnel cooldown in order to avoid taking aerodynamic data with the relatively thick test section walls distorted due to thermal gradients. Although the amount of thermally induced distortion is small, even small changes in test section area have a major effect on the longitudinal distribution of M_∞ at the higher values of M_∞.

As previously mentioned, because of the need for rapid response time, the type T thermocouple is also used as the temperature sensor for the closed-loop automatic temperature control system. In this application, the rapid response requirement has been achieved at the expense of accuracy.

The reference temperature for the thermocouples is provided by a commercially available "ice point" junction which automatically maintains the reference junction at 273.2 K ± 0.025 K.

The values of T_t which are used to calculate the tunnel parameters are obtained from PRT's located just downstream of the screen section. As previously described, the higher accuracy requirements for T_t have been achieved at some sacrifice in response time by using PRT's. Although the long response times of the PRT's would introduce problems if they were used in the automatic temperature control system, the nature of the testing in the 0.3-m TCT is such that sufficient time is available for the PRT's to come to equilibrium with the stream before temperature readings are required for the accurate determination of T_t.

3.3 Mass-Flow Measurement and Control Instrumentation

One special instrumentation requirement for the 0.3-m TCT is associated with the 2-D test section sidewall boundary-layer removal system. The requirements for this system are to remove from 1% to 4% of the test section mass flow through porous plates in the test section sidewalls and to measure and control the removal rate to within 1% of the desired set point. With the large operational range of the 0.3-m TCT, the ratio of maximum to minimum removal rate is about 140 to 1. This range of mass-flow control and its measurement to the required accuracy is well beyond the capability of conventional mass-flow control and measurement devices.

Two commercially available (Process Systems Incorporated) microprocessor controlled 11 bit digital valves have been selected to meet these requirements since they have the ability to handle both the control and measurement functions. These digital valves are similar to those presently being used at the 0.3-m TCT for the control of LN_2 injection into the tunnel and the control of GN_2 exhaust from the tunnel. Although the 11 bit valve does not give the desired 1% of reading accuracy over the entire mass-flow range, it gives the desired accuracy over the most important portion of the operating envelope. The two digital valves and their associated control microprocessor are currently under construction and should be operational at the tunnel in late 1980.

3.4 Traversing Wake-Survey Probe

A vertical traversing probe system is located on the left sidewall of the 2-D test section downstream of the turntable. The mechanism has a traversing range of 25.4 cm. The distance between the airfoil and the centerline of the probe support can be varied with the probe capable of being located either at tunnel station 26.0 cm or at tunnel station 31.1 cm. The probe is driven by an electric stepper motor and can operate at speeds from about 0.25 cm/sec to about 15 cm/sec. The stroke and speed can be remotely controlled from the operator's panel in the control room. Although the primary purpose of this system is to survey the total pressures in airfoil wakes by using a pitot tube survey rake, the probe can be equipped with other types of instruments such as thermo-

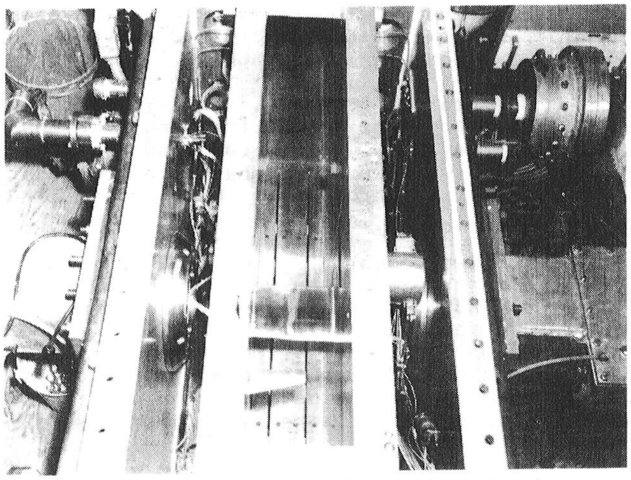


Fig. 9 View of 2-D test section showing airfoil and survey rake.

couples or hot wires. Figure 9 is a general view of the 2-D test section which shows an airfoil in place and the present pitot-tube survey rake located in its most forward position in the test section. For this configuration, the pitot tubes are located 0.88 chord downstream of the airfoil trailing edge.

Details of the multitube pitot probe are shown in Figure 10. Three disc type static probes as well as six pitot probes are mounted on the assembly. Tunnel sidewall static pressure taps are also provided in the plane of the pitot probes for use in the determination of the airfoil drag coefficient. Individual transducers are used for each tube on the probe assembly in order to keep pressure response time low. The vertical position of the probe is recorded on the data acquisition system using the output from a digital shaft encoder geared to the probe drive mechanism.

3.5 Flow-Quality Instrumentation

During the calibration of a wind tunnel it is highly desirable to obtain information on the flow quality as well as on the Mach number distribution. The flow quality is generally determined by measurements of sound pressure level and velocity fluctuations in the different planes.

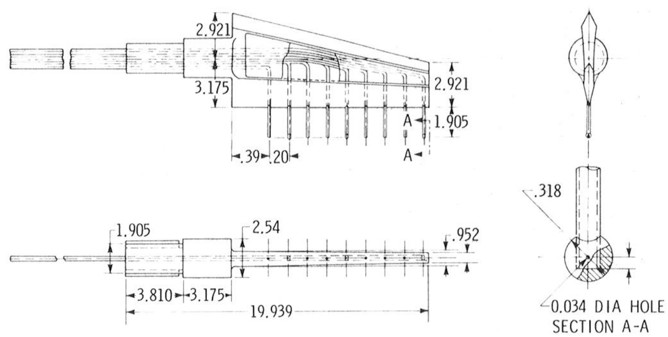


Fig. 10 Details of wake-survey probe.

The sound pressure level can be measured by the use of piezoelectric transducers. One such device has been used in the test section of the 0.3-m TCT at Mach numbers up to 0.9 for stagnation pressures to 5 atm.[5] During these tests, T_t was varied from ambient to near liquid nitrogen temperatures. Because this particular transducer has a sensitivity to temperature of about 0.05% per 1 K, it must be calibrated dynamically throughout its operational temperature range if accurate measurements are required. This type of calibration is difficult to obtain and little has been done to date.

Velocity and temperature fluctuations can be measured by using hot-wire probes. To date, hot wires of 5 micron diameter and a length-to-diameter ratio of about 250 have been successfully used in the 0.3-m TCT only to Mach numbers of about 0.1 for stagnation pressures up to 5 atm under cryogenic temperature conditions. Further tests are planned in the near future using 3.8 micron diameter wire at higher Mach numbers. The limit to which hot-wire probes may be used has not yet been determined.

Laser doppler velocimeter (LDV) systems can also be used to determine fluctuating velocities in a tunnel of this type. A simple LDV setup is currently being prepared to make preliminary tunnel empty measurements. The requirements for seeding particles and, hopefully, resolution to any problems that might arise as a result of cryogenic operation of the tunnel are expected to be obtained during these preliminary tests.

4. 0.3-m TCT DATA ACQUISITION SYSTEM

Data from the 0.3-m transonic cryogenic tunnel are recorded on magnetic tape at the Langley central data recording system. This system, which was installed in the late 1950's, serves several wind tunnels and other test facilities on a time-share basis. A total of 99 analog channels of recording capability are available at the tunnel with a maximum range of 100 mV and a resolution of 1 part in 10,000. In a continuous mode, all data channels can be scanned at a sample rate of 20 per second while in a single scan mode the maximum rate is about 4 scans per second. All analog data are filtered with a 4 Hz low pass filter.

A small computer is used to sequence the data acquisition system, provide timing input signals for the scanning-valve drive system, provide real-time visual displays and plots, and control the angle-of-attack and wake-survey-probe drive systems. The computer is programmed to allow the recording of from one to nine single frames of data for each port on the scanning valves. The time between each frame of data and the dwell time on the port before the first frame of data is taken are both variable inputs.

All inputs to the computer are made through a teletype keyboard. An X-Y plotter is used to produce real-time plots of pressure distribution over the airfoil and total head loss through the airfoil wake. Other real-time displays include digital readouts of Mach number and Reynolds number. Angle-of-attack and wake-survey-probe drive commands are also entered through the teletype and are transmitted through the computer to the respective drive system.

The wake-survey drive can operate in either of two modes. In the first or manual mode, the initial and final location of the probe in the tunnel as well as the number of steps between are the input parameters. In the second or automatic mode, the computer determines the upper and lower boundaries of the airfoil wake automatically by first making a continuous sweep of the survey probe through the tunnel before the data recording sequence begins. The wake-survey probe is synchronized with the scanning valves so that the probe is moved to a different vertical location each time the scanning valves are advanced to a new port. If more survey probe points are desired than scanning valve ports, the probe will continue on its traverse after the scanning valves have reached their last port.

5. TYPICAL CALIBRATION RESULTS FROM THE 0.3-m TCT

A sketch of the Langley 0.3-m TCT is presented in Figure 11. In this view the flow is clockwise. An array of thermocouples is located at the upstream end of the screen section to measure vertical and lateral temperature distributions. The primary pressure and temperature sensors are located in the contraction section, just downstream of the screen section. Details of the plenum and 2-D test section of the 0.3-m TCT are shown in Figure 12. Pressure taps are located in longitudinal rows along the centerline of both top and bottom slotted walls and along the centerline of one solid sidewall. Both left and right turntables are also instrumented with pressure taps for tunnel empty calibration purposes. The reference static pressure is measured on a manifold which connects four orifices, two on each sidewall located as far upstream of the turntable as practical.

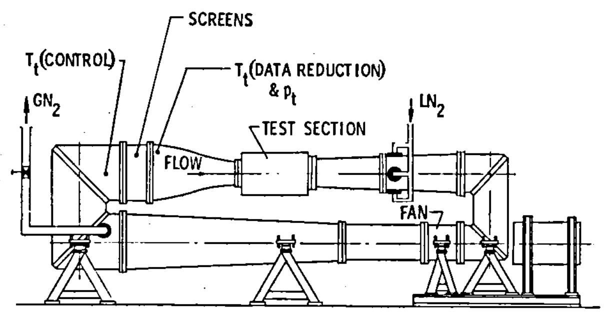


Fig. 11 Sketch of Langley 0.3-m TCT.

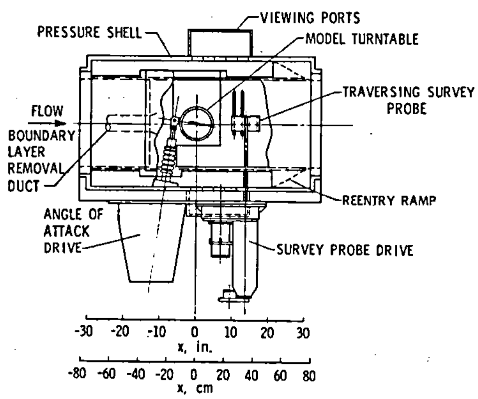


Fig. 12 Sketch of 2-D test section.

5.1 Mach Number Distribution

Typical results of the longitudinal distribution of local Mach number along the centerline of the top slotted wall are presented in Figure 13. This distribution is for a stagnation pressure of 3.1 atm and a stagnation

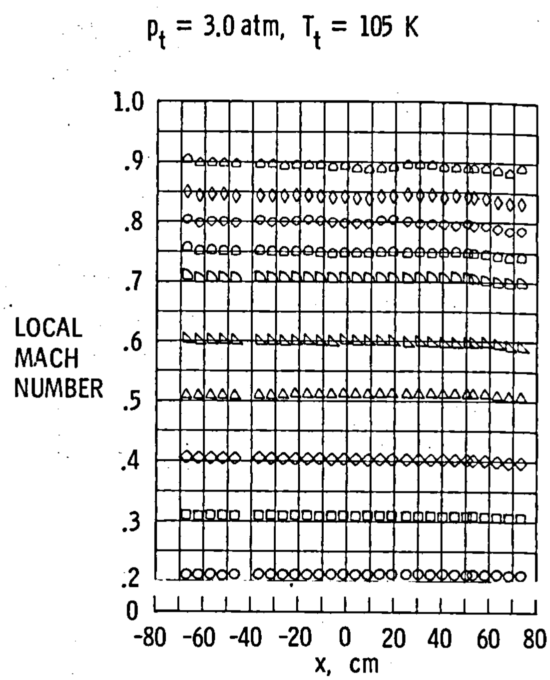


Fig. 13 Typical local Mach number distribution along top slotted wall.

temperature of 105 K. The top and bottom slotted walls were diverged about 0.5° from the centerline whereas the two solid sidewalls were parallel to the centerline. The data show that for Mach numbers below about 0.75, the distribution is relatively uniform to about 50 cm downstream of the center of the turntable where the speed begins to drop off. This location roughly corresponds to the location in the test section where the slots begin to open rapidly. At higher Mach numbers, a negative gradient is observed, indicating the walls were diverged slightly more than necessary.

Figure 14 shows the local Mach number distribution on one of the model turntables for the same conditions of 3.1 atm and 105 K. As shown on the sketch, there are 5 rows of pressure taps on the turntable, two horizontal, two diagonal, and one vertical, numbered 1 through 5. This figure again shows the longitudinal gradient in rows 1 through 4, but the data from row 5 indicate essentially no vertical gradient.

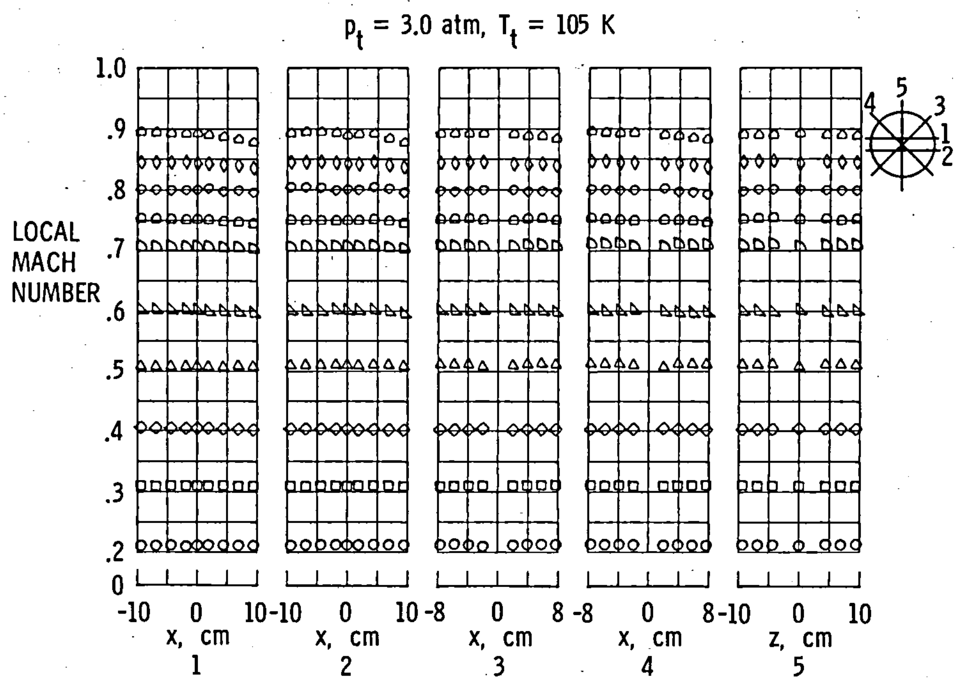


Fig. 14 Typical local Mach number distribution on model turntable.

The test section Mach number M_∞ has been defined based on the average of the 36 pressure taps located on the turntable. The calibration factor ΔM is defined as the difference between the calculated reference Mach number M_{ref} and the test section Mach number M_∞. A plot of the calibration factor is presented in Figure 15 as a function of M_{ref}. Data are presented for four stagnation pressures and at three stagnation temperatures at each pressure. These values of temperature and pressure include combinations which are close to the operational extremes of the tunnel. Although a large increase in the calibration factor occurs at Mach numbers above approximately 0.75, due to the previously discussed longitudinal gradient, it should be noted that there is little effect of temperature and pressure on the calibration factor. The scatter of the data is generally within an error band of about 0.001 which, it should be noted, is within the accuracy of the test instrumentation.

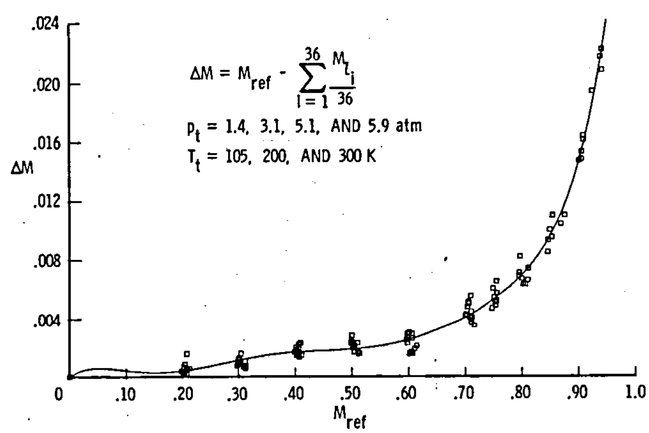
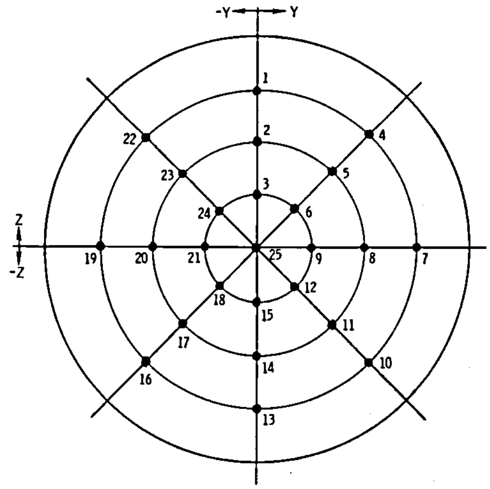


Fig. 15 Mach number calibration for 2-D test section of 0.3-m TCT.

5.2 Temperature Distribution

A typical lateral temperature distribution in the screen section of the tunnel is presented in Figure 16 for a Mach number of 0.70 and a stagnation pressure of 5.9 atmospheres. As shown on the figure, there are eight radial rows of instrumentation with three thermocouples on each row, spaced equidistant between the centerline and the wall. There is also a single thermocouple located on the centerline. Each temperature shown on the figure is the average of 185 readings of the thermocouple during a time span of 72 seconds. During this time, the tunnel was at a steady state condition and pressure data were being obtained using scanning valves. For this case, which is near the maximum Reynolds number capability of the tunnel, the average of the 25 thermocouples is 105.9 K and the standard deviation, σ, is 0.20 K. As mentioned previously, the absolute value of this temperature may be slightly in error due to the accuracy of the thermocouple wire, but the differential temperatures should be reliable.



T_1 106.0 K	T_6 106.2 K	T_{11} 106.0 K	T_{16} 105.4 K	T_{21} 105.8 K
T_2 106.0	T_7 106.0	T_{12} 105.9	T_{17} 106.0	T_{22} 105.8
T_3 106.2	T_8 106.0	T_{13} 105.7	T_{18} 105.6	T_{23} 105.6
T_4 106.1	T_9 106.2	T_{14} 105.7	T_{19} 105.7	T_{24} 106.0
T_5 106.0	T_{10} 105.8	T_{15} 105.8	T_{20} 105.7	T_{25} 105.9

Fig. 16 Typical lateral temperature distribution.

Data such as presented in Figure 16 have been obtained throughout the operational range of the tunnel during the tunnel empty calibration process. Results, in the form of standard deviation, are presented in Figure 17 for selected Mach numbers at three different stagnation temperatures and for near minimum and maximum stagnation pressures. The results show that the variations in standard deviation of stagnation temperature in the screen section of the tunnel are less than about 0.5 K and that the results do not vary in any systematic way with either Mach number or stagnation temperature. The value of the deviation does, however, tend to be lower at the higher stagnation pressure.

	T_t, K					
	105		200		300	
	P_t, atm					
M_∞	1.4	5.9	1.4	5.9	1.4	5.9
0.20	0.51 K	0.16 K	0.49 K	0.23 K	0.12 K	0.05 K
.30	.43	.16	.50	.15	.13	.09
.40	.38	.14	.41	.12	.11	.12
.50	.31	.19	.50	.13	.24	.24
.60	.27	.21	.41	.16	.19	.31
.70	.21	.20	.35	.21	.50	.30
.80	.18	.18	.27	.19	---	---
.90	.17	---	.37	---	---	---

Fig. 17 Standard deviation of stagnation temperature survey.

6. CONCLUSIONS

Some of the aspects of selecting and using instrumentation for the calibration and control of continuous-flow cryogenic wind tunnels have been discussed and examples of instrumentation used in the Langley 0.3-m TCT have been given in this paper. In addition, typical calibration results from the 0.3-m TCT have been described. The main conclusions to be drawn from our experience at Langley are:

(1) Adequate pressure and temperature instrumentation is commercially available to meet the requirements for calibration and control of continuous-flow cryogenic wind tunnels.

(2) The response time of high accuracy instrumentation is usually much too slow for use with automatic tunnel control systems. Thus, it may be necessary to use one set of less accurate but highly responsive instrumentation for control purposes and a separate set of highly accurate but less responsive instrumentation for the determination of the test conditions.

(3) Thermal isolation of the instrumentation from the cryogenic environment is the best way of avoiding problems related to temperature variation. However, the ancillary equipment needed for thermal isolation inevitably results in reduced reliability.

(4) Conventional flow-quality instrumentation, such as hot-wire probes, has yet to be used successfully except at extremely low speeds in the 0.3-m TCT.

(5) The use of a piezoelectric transducer to measure sound pressure levels has been demonstrated. However, because these transducers are sensitive to changes in temperature and are exposed to the cryogenic environment, they must be dynamically calibrated over the entire operational temperature range of the tunnel if high accuracy measurements are desired.

(6) For applications such as sidewall boundary-layer removal systems, measuring and controlling mass flow can be realized to any desired degree of accuracy by using commercially available "digital" valves.

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15. Supplementary Notes

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16. Abstract

This paper describes those aspects of selection and application of calibration and control instrumentation that are influenced by the extremes in the temperature environment to be found in cryogenic tunnels. A description is given of the instrumentation and data acquisition system used in the Langley 0.3-m transonic cryogenic tunnel along with typical calibration data obtained in a 20- by 60-cm two-dimensional test section.

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