Chapter 4. Experimental Apparatus

All experiments were performed inside a rectangular test section of normally low turbulence, in a low speed open circuit type wind tunnel. The generated isotropic turbulence was realized by way of a stationary grid fixture positioned upstream of the test section. The ultrasonic travel time technique was used to diagnose the turbulent flow parameters utilized in our investigation. The experiment was designed to ensure that the region of non-linearity in the acoustic travel time variance with respect to the travel distance and occurrence of the caustics would be realized. The latter sections of this chapter describe the essential elements of the experimental apparatus including: the wind tunnel, grid fixture and geometry, ultrasonic measurement systems, temperature monitoring controls, and the data acquisition and analysis system.

4.1 Wind Tunnel

The AEROLAB low speed, low turbulence wind tunnel used to provide and maintain the turbulent flow conditions is an Eiffel or Open Circuit type, with a rectangular test section measuring 45.25” in length, 11.75” wide and 11.62” high. Airspeeds of 0 to 80 mph were produced by an infinitely variable control system, enabling smooth transitional increases over the entire range. Aerodynamic losses and mean flow instability were minimal due to the tunnel’s high energy ratio, achieved in part through a contraction ratio of 16:1, a small angle diffuser and an efficient fan system.
The AEROLAB wind tunnel consists of three main sections: the fan unit, the test section, and the diffuser as shown in Fig. 4.1.

A passive noise reduction system, in the form of an acoustic damping blanket, line the inside cavities of the fan section to reduce unwanted vibrations and noise. The tunnel’s test section was entirely rebuilt and retro fitted with Lexan plates designed specifically to operate in concert with other experimental systems. GE Lexan was chosen over traditional fiberglass (which the previous test section was constructed from) due to its ease in machining. High density polyvinyl rubber foam was applied to the perimeter of the access panel sealing surfaces to increase the integrity of the seal and minimize pressure losses. The interior panels were also sealed, using quick dry putty that was worked into the smaller areas of the test section. Lastly the diffuser was equipped with an aluminum honeycomb, four turbulence management screens, and orifice rings both in the contraction and upstream used to
compute the airspeed from the differential pressure drop across both ends using an external digital manometer with integrated pressure transducer. The digital readout enabled monitoring of the differential pressure in inches of water with a high level of accuracy. Thus, flow speed was determined by inputting these pressures in inches of water into a modified Bernoulli’s equation as defined by Eq. (4.1.1) - (4.1.3):

\[ P_T = P_s + \frac{1}{2} \rho V^2 \]  
\[ \Delta P = \frac{1}{2} \rho V^2 \]  
\[ \sqrt{\frac{2\Delta P}{\rho}} = V \]

where \( P_T \) and \( P_s \) are the total and static pressures respectively, \( \rho \) the air density and \( V \) the flow speed.

Air flowing into a test section forms a boundary layer on the walls of the tunnel. It is determined that for this flow the boundary layer displacement thickness is given by:

\[ \delta^* \sim 0.0033x^{\frac{1}{3}} \]  

where \( x \) is a distance downstream of the grid-fixture in the tunnel (Andreeva, 2003). Thus, it can be estimated that the maximum displacement thickness \( \delta^* \sim 0.0027m \) corresponding to the measurements taken at \( x = 0.68m \) downstream of the grid. Thus, boundary layer interacts were avoided during experiments by maintaining a minimum of approximately \( 1 \frac{1}{4} \) inch clearance from the walls of the test section.
4.2 Grid-Fixture & Resulting Turbulence

The generated turbulent flow was the result of a stainless steel welded wire mesh grid fixture situated upstream of the flow at the entrance of the test section. The fixture consisted of two square frames that when clamped together served as a mounting platform for the two different square welded wire meshes screens that were used in the experiment. The upper and lower sections of the framing were machined down to a minimum thickness in order to minimize the perturbation to the near wall flow (i.e. production of turbulent eddies after the grid threshold) by the introduction of a step in the flow stream. A consistent origin of turbulent flow generation was maintained by positioning the fixture behind two set-screws in the wind tunnel.

Grid-turbulence is made by disrupting laminar flow with a grid to generate a set of jets. These jets will interact with the air at rest behind the bars, become instable and make the transition to turbulence. The mesh size, or distance between centers of the stainless steel mesh rods, is one of the critical parameters that are used to determine the resulting turbulent flow. In our investigation two different mesh sizes of 0.25” and 0.50” were used. The two different grid mesh sizes were chosen based on there relationship to the plot of the acoustic travel time variance, with the x-axis proportional to the ratio of the characteristic length to the grid mesh size as shown in Fig. 1.2. Graphically, varying these grid mesh sizes along with the flow velocity allowed use to populate the upper regions of Fig. 1.2 that correspond to larger length scales.
4.3 **Ultrasonic Measurement System**

The ultrasonic measurement system consisted of two subassemblies supporting the ultrasonic transducers to form the flow diagnostics apparatus. The transducers produced and sensed ultrasonic waves. Transducers, by definition, are any mechanism or device that converts input energy of one form into output energy of another. The transducers in this study were a low frequency narrow band disc type of 100 kHz working frequency, operated with a high degree of precision based on the underlying material characteristics of asymmetrical crystals and the piezoelectric effect.

![Image](https://via.placeholder.com/150)

**Figure 4-2 - Pierre Curie (center), and Marie Curie (left) in their laboratory, awarded half of the Nobel Prize for Physics in 1903.**

Historical references to the piezoelectric effect date back to 1880 and the Curie’s who established that crystals which lack a centre of symmetry when compressed along a certain axes develop positive and negative charges of magnitude proportional to the applied pressure (Richardson, 1962). Conversely, they also observed changes in the
crystals dimensions when a potential difference was applied. From these observations it was determined that an oscillating potential when applied could deform the crystals at a high rate of change to produce mechanical vibrations. As such, piezoelectric transducers are designed to be used as both transmitters and receivers.

The monolithic piezoelectric plate transducer is an assembly of piezo-crystals and dynamic mechanical components with interspersed electrical circuitry. The main components can be characterized by the active element, backing, and wear plate. The active element is usually constructed from piezoelectric or ferroelectric material; although a combination of other materials as of late are becoming more common. It converts an oscillating electric potential, such as an excitation signal from a function generator, into ultrasonic sound waves. The backing is usually a damping material of high density, used to control the vibration of the transducer by absorbing the overflow of energy that radiates from the back face of the active element. The wear plate is a protective structure used to shield the transducer elements from their environment.

The Curie constant describes the relationship between crystalline deformation and excitation energy by the ratio of mechanical movement to the applied voltage. Various piezoelectric crystals can be used as oscillators such as tourmaline, Rochelle salt, and ammonium dihydrogen phosphate (ADP) in multiple configurations.

The nominal detection range of an ultrasonic distance is determined by the operating frequency in two ways. First, the attenuation coefficient \( \alpha \) of ultrasound, which increases with the operating frequency, establishes a firm limit as to the maximum distance at which even good reflecting objects can be detected (Lynnworth, Mágori, 1999). Second, the decay time of the ultrasonic signal at the transducer after a
transmission is inversely proportional to the operating frequency, which in turn dictates a minimum distance at which objects can be observed. These factors are all both critical to the arrangement of the ultrasonic transducers within our experimental apparatus, and integral in exploiting their operational capabilities.

The remainder of the section describes the structural components of the ultrasonic apparatus and their functionally with respect to the larger system.

![Image of 6105-T5 Aluminum Extrusion Cross Section]

Figure 4-3 – 6105-T5 Aluminum Extrusion Cross Section

The primary transducer support structures were fabricated from 6105-T5 Aluminum EX-11 ¼” slotted extrusions and represent the skeleton of the ultrasonic flow meter. The slotted rectangular beams were fastened together using flanged button head cap screws and T-nuts in a rectangular frame configuration, bisected by a single rail. This interior railing represents the active site of the fixture on which a single mount linear bearing was placed to control the movement of the active member. The active member in our apparatus denotes the ultrasonic transducers responsible for transmitting and
receiving ultrasonic waves after they traverse the mean flow. Both transducers were partially submerged in the flow, and their movement controlled externally. In this configuration, the ultrasonic path lengths were varied by sliding the transducers, placed atop of the linear bearing mounts, along the center railing for angular orientations. For perpendicular orientations, the ultrasonic path lengths were varied by sliding the entire main structure up or down along the six stationary support beams affixed to the tunnel. Additionally, a set screw was placed on the side of the bearing mount to allow the linear bearings to operate from a stationary position on the railing during wind tunnel operation.

Figure 4-4 - Schematic of Linear Slide Rail Operation

To minimize flow interactions with the ultrasonic transducers that are present in the mean flow path, they were placed inside protective streamlined coverings made from sailboat spreaders. Sailboat spreaders are designed and used to decrease the overall drag on the rigging used to support masts of high performance sailboats. As such, we are using these structures for a similar purpose.
Figure 4-5 - Path length variation in perpendicular orientation

Figure 4-6 - Spreader cross-section

The spreaders reduce the overall wake produced by the ultrasonic transducers and related wiring, thus preserving our desired flow characteristics and minimizing vortex shedding from the transducer supports. The length of the two spreader
components (approximately 7.25” each) was dictated by the minimum ultrasonic propagation distance chosen for this investigation of approximately 1.97 inches.

Figure 4-5 - Transducer Spreader Sub-Assembly

This minimum propagation distance was achieved by maintaining tight tolerances set for machining the spreaders in addition to fine adjustments made to the levels of the support structures affixed to the wind tunnel. All subsequent ultrasonic path lengths were increased as described previously. However, angular experimental orientations demanded that the spreaders be angled to preserve the line of sight between transmitter and receiver as they were moved further apart along the center railing. Transducer line of sight was verified using the Hewlett Packard 54645A/D Oscilloscope to visually observe the maximum amplitude of the received signal with respect to the spreaders angular
orientation. Angular mobility was achieved through custom T-brackets and pivot joints affixed to the top of the linear bearings.

![Diagram of Complete Spreader Assembly]

**Figure 4-8 - Complete Spreader Assembly**

The resulting fabricated apparatus as described represents the bulk of the mechanical fixtures present in our ultrasonic flow diagnostics apparatus. The remaining portions represent electrical components integral in the generation, processing, and overall computation of acoustic travel times as outlined in the subsequent explanation of our data acquisition systems.
4.4 Temperature Monitoring Controls

The temperature inside the wind tunnel test section was monitored effectively using an Omega DP41-TC high performance temperature indicator and fast thermocouple. The temperature indicator was configured for use with fast thermocouples and featured a cold junction board which applied the sustaining reference voltage from which to measure temperature changes. The digital temperature indicator and thermocouple combination was capable of monitoring temperature fluctuations in the mean flow of 0.2 degrees Celsius and 0.3 degrees Fahrenheit. The J type thermocouples used were rated to operate in temperatures from -210 to 760 C and -346 to 1400 °F. The J thermocouple was passed through a small hole in the top of the wind tunnel test section and placed in stream of the mean flow far downstream of the grid fixture. Monitoring the flow temperature during data acquisition allowed for rough estimates of the acoustic travel time to be made based on sound speed. Moreover, experiments were only conducted during periods of constant temperature within +/- 0.2 °F.

4.5 Data Acquisition System

The major components of the data acquisition system are shown in Figure 4-12. These primary components included the function generator, amplifier, oscilloscope, National Instruments data acquisition card, CompuScope data acquisition card, and the controlling PC.


4.5.1 Acquisition System Hardware

A Hewlett Packard 3314A programmable function generator was used to produce the excitation signal that controlled the composition of the transmitted waves. This function generator was triggered externally by the PC to initiate the ultrasonic pulses, thus enabling the data acquisition software to record the exact instance of each transmission. The generator was set to transmit bursts of four square waves at 100 kHz frequency with amplitudes of 50 mV. To boost the signal, it was passed through an Amplifier Research 50A15 power amplifier before it was sent to the transducers.

A Hewlett Packard 54645A/D Oscilloscope was connected directly to the function generator and receiving transducer to observe the transmitted and received signals and check for abnormalities. The oscilloscope featured 16 digital and 2 analog channels with a range of 1mV/div – 5V/div and maximum input of 400V. Ultimately this device served as a secondary confirmation of the excitation and received signals that were monitored primarily by the LabView National Instruments data acquisition software. The instrument was also used to measure the alignment (i.e. line of sight) of the ultrasonic transducers while conducting tests in the angular configuration. The orientation of the transducers was varied until the received signal was observed to have achieved maximum amplitude.

For acoustic time of flight measurements, the two most important pieces of information pertaining to each ultrasonic wave is the exact instance that the wave was initiated and then received after it traverses the mean flow. These two times were used to compute the acoustic travel time of the wave using a correlation function. A comparison
of the difference in transit time between the no-flow and turbulent flow situations allowed for an accurate determination of the mean flow’s dynamic contribution to the traveling wave propagation. The departure times corresponding to the instant of transmission of the ultrasonic wave bursts are detected by the NI-DAQ with a high degree of accuracy. On each rise of the square wave pulse, the system is triggered and thus the departure time of the wave is recorded.

![Figure 4-9 - Transmitted Square Wave Burst Signal](image)

The two signals, sent and received, were correlated using LabView to determine the acoustic travel time. The program’s correlation function was written as:

\[ K_{12}(t) = \overline{e_1(t + \tau)e_2(t)} \]  

(4.5.1)

The correlation function was written into a signal correlation program in IMSL Fortran programming language, as described in detail in Appendix B.
Each correlated sent and received signal yields a corresponding travel time. For example, Fig. 4.10 illustrates a typical sent and received signal acquired by the CompuScope 82G system.

![Figure 4-10 – Sent and received wave signals e₂ and e₁ respectively](image)

These two signals are input into the IMSL Fortran signal correlation program, and its output, as illustrated in Fig. 4.11, is the correlated signal. Thus, the maximum amplitude of the correlated signal corresponds to the acoustic travel time of the transmitted wave.

Over a period of 45 seconds with the NI-DAQ transmitting the square wave pulse at 500 cycles/sec, approximately 700 travel times were collected, and used to compute the travel time variance as follows:
\[ \tau^2 = \langle (t_i - \langle t \rangle)^2 \rangle \]  

(4.5.2)

where the brackets surrounding each parameter indicate averaging over the data set.

![Figure 4-11 – Correlation of sent and received signals e1 and e2](image)

taken from Andreeva and Durgin (2003)

The CompuScope 82G DAQ card was used to sample and store data corresponding to the two signals, sent and received, along with a sampling time marker for each wave. This data acquisition card featured 2 channels with monolithic A/D converters each running at 1 GS/s, 400 MHz band width, 8 bit resolution, and was designed to allow maximum separation of analog and digital grounds, thereby providing high immunity to digital noise. The card, manufactured by GaGe Applied Science Inc., is controlled through a LabView interface called Gage Sample Oscilloscope.vi which was
supplied with the board. From this module, the sampling rate, trigger type, number of
data points collected, clock speed, sent and received signals, etc. were monitored and
controlled. All acquired data was recorded and saved automatically by the system as a
tab delimited text file for each test run.

Figure 4-12 - Data Flow Diagram

Thus, Fig. 4.12 is a graphical representation which summarizes the flow of acquired data
through hardware and system components. Likewise Fig. 4.13 illustrates all hardware
interconnections.

The primary data analysis was conducted using LabView 5.1, and the following
describes the details of the data acquisition software.
4.5.2 Acquisition System Software

All of the hardware data acquisition systems were controlled using LabView 5.1 programs. The Function Generator.vi program was used to trigger the Hewlett Packard 3314A programmable function generator. This program, as illustrated in Fig. 4.14, enabled the exact instance that each ultrasonic wave was sent to be determined with a high degree of accuracy and precision.
The Gage Sample.vi program was used to control the CompuScope 82G high speed data acquisition card. This program, as illustrated in Fig. 4.15, controlled the signal sampling rate and channel voltages.
An integral part of this program was a sub vi (virtual instrument) called CSScope.vi, developed by Gage to configure and initialize the data acquisition card. A detailed view of the CSScope.vi is presented in Appendix A.