A DATA ACQUISITION SYSTEM EXPERIMENT FOR GAS TEMPERATURE AND PRESSURE MEASUREMENTS ON A LIQUID-NITROGEN-POWERED VEHICLE

THESIS

Presented to the Graduate Council of the University of North Texas in Partial Fulfillment of the Requirements For the Degree of

MASTER OF SCIENCE

By

Samson Sze-Sang Lui, B.B.A.

Denton, Texas

May, 1998

A data acquisition system was set up to measure gas temperatures and pressures at various points on a liquid-nitrogen-powered vehicle. The experiment was attempted to develop a data acquisition method for applications on engines that use liquid air as the fuel. Two thermocouples and a pressure transducer were connected using data acquisition instruments interfaced to a laptop computer to acquire data. The experiment is believed to be successful and applicable.

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TABLE OF CONTENTS

LIST OF TABLES .............................................................................................................. v
LIST OF ILLUSTRATIONS ............................................................................................ vi

Chapter

1. INTRODUCTION ....................................................................................................... 1
   Background
   Liquid-Nitrogen Powered Vehicle
   Data Acquisition Experiment
   Objective

2. LIQUID NITROGEN VEHICLE DESCRIPTION ............................................... 3
   Fundamental Concepts
   Liquid Nitrogen Powered Vehicle
   Performance Based on Gas Temperature and Pressure

3. DATA ACQUISITION CONCEPTS ........................................................................ 8
   Fundamental Processes
   The Computer Interface
   Transduction
   Signal Conditioning
   Pre-processing
   Digitization
   A general data acquisition system

4. SENSOR CONCEPTS ............................................................................................... 18
   Thermocouples
   Transducers

5. INSTRUMENT AND SENSOR SELECTIONS .................................................... 29
   SigLab Hardware
LIST OF TABLES

Table

1. Thermocouple Types and Temperature Ranges........................................21
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The Cool N2 Car</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>A Close-up of the Pneumatic Motor and Other Components</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>An Overview of the Liquid Nitrogen Engine System</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>Differential Amplifier</td>
<td>11</td>
</tr>
<tr>
<td>5</td>
<td>The Functional Diagram of a Data Acquisition System</td>
<td>16</td>
</tr>
<tr>
<td>6</td>
<td>Basic Thermocouple Circuit with Instrument</td>
<td>18</td>
</tr>
<tr>
<td>7</td>
<td>T-Type Thermocouple, Seebeck Voltage</td>
<td>19</td>
</tr>
<tr>
<td>8</td>
<td>T-Type Thermocouple Connecting to Signal Conditioner</td>
<td>22</td>
</tr>
<tr>
<td>9</td>
<td>Reference Junction Thermocouple Circuit</td>
<td>23</td>
</tr>
<tr>
<td>10</td>
<td>Software Compensation</td>
<td>24</td>
</tr>
<tr>
<td>11</td>
<td>Hardware Compensation</td>
<td>25</td>
</tr>
<tr>
<td>12</td>
<td>The SigLab 20-22</td>
<td>30</td>
</tr>
<tr>
<td>13</td>
<td>A Typical PC-Interfaced SigLab Data Acquisition System</td>
<td>30</td>
</tr>
<tr>
<td>14</td>
<td>The Virtual Oscilloscope</td>
<td>33</td>
</tr>
<tr>
<td>15</td>
<td>Channel Setup</td>
<td>34</td>
</tr>
<tr>
<td>16</td>
<td>Input Voltage Range</td>
<td>34</td>
</tr>
<tr>
<td>17</td>
<td>Timebase Setup</td>
<td>35</td>
</tr>
<tr>
<td>18</td>
<td>Sampling Period</td>
<td>35</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

Background

By the year 2003, 10% of the automobiles sold in California must be zero emissions vehicles due to state regulations to control air pollution. Recent developments in the automobile industry have been focusing on the possibility of manufacturing zero emission vehicles powered by other sources of energy other than fossil fuels, such as electricity, solar energy, or liquefied air.

Liquid-Nitrogen Powered Vehicle

The use of liquefied air as fuel to power pneumatic motors provides an additional alternative for the zero-emission vehicles. An experiment had been successfully conducted using compressed nitrogen gas as a combustionless fuel to drive an air motor. The experiment operated using the concept of a “cryogenic heat engine”, which used a cryogenic substance to produce useful energy. The liquid nitrogen was stored in a pressurized tank. A heat exchanger vaporized and then heated the nitrogen under pressure using atmospheric heat and produced compressed nitrogen gas. The compressed gas was sent to a pneumatic motor to drive the vehicle.
Data Acquisition Experiment

A data acquisition system was set up using sensors to measure and record gas temperatures and pressure. The data acquisition hardware was carefully selected according to the needs for this process. Two temperatures and one pressure were measured. Instruments and sensors were set up in such a way that they measured relatively accurate data. At the same time, the experiment also achieved a cost-effective data acquisition goal for this first-phase experiment.

Objective

The objective of this experiment is to develop a method of temperature and pressure measurements at different points on engines that use liquefied air as the fuel. This method uses data acquisition instruments combined with temperature and pressure sensors to measure and record data. The experiment is intended to be a prototype for quantitative analysis to determine the performance of the engine. This objective can be extended by developing the current method for further experiments on more complex machines.
CHAPTER 2

LIQUID NITROGEN VEHICLE DESCRIPTION

Fundamental Concepts

The CooLN2Car (Figure 1), as it was named, was a "zero-emissions" car that ran on liquid nitrogen. The operation of the vehicle was based on the concept of a "cryogenic heat engine", which used a cryogenic substance, in this case, liquid nitrogen, to produce useful energy. The cryogenic medium liquid nitrogen was employed as a heat sink (the cold reservoir), while the atmosphere served as a heat source (the hot reservoir).

Figure 1. The CooLN2Car
Refrigeration of air created the cold reservoir for the cryogenic heat engine, which was used afterward by the heat engine to do work. The cryogenic heat engine was able to operate by utilizing the temperature difference between the cryogenic medium (liquid nitrogen at 77K) and the ambient temperature in the atmosphere. Thus, both the refrigerator and the cryogenic heat engine combined to produce a system for energy storage and extraction. Compressed nitrogen gas from the heat exchanger was sent through a pneumatic motor. The pneumatic motor provided its necessary torque to accelerate the vehicle.

The liquid-nitrogen-based heat engine used atmospheric heat to vaporize super-cooled, compressed liquid nitrogen and produced compressed nitrogen gas. The compressed gas was used to drive a pneumatic motor, and released to the atmosphere afterwards. The process was similar to that of the steam engine. A major difference between the gasoline-powered engine and the nitrogen-powered engine is that the combustion engine produces pollutants while the CoolN2Car produces pure, clean, breathable air. Ideal for this experiment, nitrogen is an abundant resource, constituting 78 percent of the atmosphere. It is mined in its gaseous form from the air, then cooled and compressed into a liquid.

Liquid Nitrogen Powered Vehicle

An experiment had been conducted successfully using liquid nitrogen as fuel to power a converted 1973 Volkswagen for operation. The system consisted of a pressure-regulated liquid nitrogen storage tank (a Taylor-Wharton XL-45 180 L tank with internal vaporizer), which provided nitrogen gas to two parallel connected external heat
exchangers (Thermax D8.3 vaporizers). The tank had a volume of 47.6 gallons, which could hold 124 kg of liquid nitrogen, was mounted at the back of the car along with the two vaporizers. The heat exchangers heated the nitrogen gas and sent it through a pneumatic motor. The 9-hp Gast 16AM-FRV-13 vane-type pneumatic motor was mounted in place of the gasoline motor (Figure 2). Pressure in the tank and vaporizers was maintained at 1.2 MPa (170 psi) by the tank’s internal vaporizer circuit. Before the pneumatic motor, a pressure regulator reduced the pressure to 0.7 MPa. Between the pressure regulator and the pneumatic motor, a throttle consisting of a butterfly valve was mounted and connected to the accelerator pedal. For an overview of the whole system, please refer to Figure 3.

Figure 2. A Close-up of the Pneumatic Motor and Other Components
Performance Based on Gas Temperature and Pressure

The mass of the vehicle with a full tank was 700 kg (1540 lbs.). The maximum speed of the converted automobile was found to be 11 m/s (25 mi./hr). The maximum speed was limited by constricted gas flow through two stainless steel transfer lines, which connected the tank to the vaporizers. The driving range without refueling the automobile was found to be approximately 24 km (15 mi.) while travelling at about 9 m/s (20 mi./hr).

The performance of the car in terms of driving range, for example, depended on the specific energy of liquid nitrogen\(^1\), which in turn depended on the flow rate,

\(^1\) Nitrogen Characteristics: Molar mass: 28.013kg/kmol; \(R\): 0.2968kJ/(kg \cdot K); Critical Temperature: 126.2K; Critical Pressure: 3.39MPa; Critical Volume: 0.0899m\(^3\)/kmol
temperature, and pressure of the inlet gas to the motor. The specific energy produced in terms of these factors has the following relationship:

$$\varpi = 2 \pi f \tau / m$$

where:

- \( \varpi \) is the specific energy produced
- \( f \) is the rotation speed in rps (revolution per second);
- \( \tau \) is the torque in N·m;
- \( m \) is the mass flow rate in kg/s.

By the ideal gas law, the mass flow rate at the air motor inlet is \( m = PV/(RT) \), where:

- \( P \) is pressure in Pa;
- \( V \) is volume flow rate in \( m^3/s \);
- \( T \) is temperature in K;
- \( R = 0.2968 \) kJ/kmol·K is the gas constant for Nitrogen.
CHAPTER 3

DATA ACQUISITION CONCEPT

Fundamental Processes

Data acquisition is a process of collecting data in physical variable forms such as temperature, pressure, and electric current or voltage from some signal sources. These signal sources include, but are not limited to, humans, animals, plants, or industrial equipment. In data acquisition applications, any physical variables carrying information is called a signal, which could be classified according to their sources or their physical nature. In this application, we are collecting both the environmental signals (nitrogen gas pressure) and instrumental signals (thermocouple temperature changes) under the first category, and electric voltage under the second category.

Sensors are used in combinations with signal conditioning equipment and the computer to measure and acquire these data. The data acquisition system takes the voltage signals produced by temperature sensors, pressure transducers, flowmeters, etc, which are usually functions of time, and converts them into voltage. The acquired data can be saved in files and retrieved later for further analysis.

The Computer Interface

In many instances, measuring devices are directly interfaced to a computer, eliminating the need for the intermediary data storage and transfer of data from the acquisition system to the computer. This "on-line data acquisition" process offers
greater speed since it eliminates delay from the necessity of storing data in a medium and reading them back afterwards. Data is directly fed from the real world environment to the computer environment. The data gathered can be monitored, displayed and analyzed in the computer. The computer can also accurately control the acquisition processes for maximum efficiency if the acquisition system has output capabilities. Output data is sent directly to any industrial or laboratory apparatus in "real-time" through the output channels to control their operations as a function of the input data. The application of using data acquisition instruments in a control system is a good example. Furthermore, data can be saved for later analysis as well as displayed in different formats such as spreadsheet tables, histogram charts, pie charts, and, line plots. Analysis can be done by the computer using methods such as transforms and curve fitting.

To determine the performance of the nitrogen gas that powers the gas engine of the CoolLN2Car, this project measured two temperatures and a pressure of the gas using a data acquisition system that interfaced with a computer. The data acquisition system took the signals from two thermocouple sensors and a pressure transducer, and converted them through a built-in A/D converter in the data acquisition module into computer understandable signals. The result was saved and displayed in different formats for further analysis.

Transduction

Transduction is the use of a sensor such as a transducer to sense either the absolute value of, or changes in, a physical quantity and converts such information into useful signals for the data acquisition processing system. The result of the transduction
process is the variation of the information’s amplitude or frequency produced by the data acquisition system in accordance with the experimental data.\textsuperscript{10} Some transducers require a precise source of energy (e.g. the reference signal) to operate properly. This is called excitation. Excitation works by altering the reference in accordance with the information contained within the experiment or process.\textsuperscript{11} The pressure transducer used in the data acquisition process for the CooLN2Car experiment required some external excitation. This will be discussed in further detail in later chapters.

**Signal Conditioning**

Transducers must be provided with an electrical environment in order to function correctly. “Passive transducers” require a stable constant current or voltage supply and possibly additional resistors to complete a null bridge arrangement. Some sensitive energy-conversion-type transducers need to be coupled to a high-input impedance amplifier, which amplifies the signal to improve resolution. For example, it is desirable to condition low-level signals near the signal source to prevent signal degradation due to noise. Conditioning low-level signal requires amplification by using devices such as a differential amplifier (Figure 4).\textsuperscript{12} Some signals may contain noises that need to be eliminated by limiting the frequency content of the information. Many transducers also require calibration before use. Raw data gathered by these sensors also need to be converted to engineering data. Signal conditioning is the method of comprising all these operations that are subsidiary to the proper functioning of the transducers, as well as extracting appropriate information or eliminating noises.\textsuperscript{13, 14} The signal conditioning
components form the interface between the sensor/transducer and the A/D converter or preprocessing circuitry. These components "shape" the signal for further processing. Such transformations are usually achieved using operational amplifier (‘op amp’). ii

\[ E_0 = G (E_1 + E_2 - E_2) = E_1 G \]

(G is the amplifier gain.)

Figure 4. Differential Amplifier

A signal conditioner is a unit used to carry out the process of signal conditioning. To function properly, a signal conditioner also needs a stable operational amplifier having a defined gain with high input and low output impedance, and a stable constant voltage (or current) power supply. The signal conditioner performs many different functions, which differ according to the type of signal being measured and the transducers used.

The CooLN2Car experiment used two thermocouple signal conditioners from Omega Engineering, Inc. to amplify the thermocouple millivolts signals to large voltage signals. The pressure transducer, also from Omega, had its own signal conditioning capabilities built in. They will be discussed in later chapters.

ii An ‘op amp’ is an electronic circuit that generates linear as well as non-linear signals in response to input signal. They are used with components such as resistors, capacitors, diodes, and transistors.
Pre-processing

In data acquisition, input signals are sampled within an interval of time. The precision of the sampled data at discrete time intervals in representing the original continuous signals is decreased. The desired signal could also be mixed with unwanted background noise or discrete frequency component. These may require a separation process.\(^{17}\)

Therefore, prior to analysis, there is the need to carry out signal amplification and frequency filtering as well as other forms of modification, such as trend removal, decimation and calibration. These pre-processing operations are nearly always carried out at the time of data acquisition.\(^ {18}\) Amplification is the most important element in pre-processing, situating in between the transducer and the processing or recording device. The amplifier provides an impedance-matching function by its operational amplifier, which is a high-gain, solid-state device being able to operate down to zero frequency (D.C. level). It provides gain for low-level signals, using high input impedance to minimize loading on the signal source.\(^ {19}\) Of the different types of amplifiers, differential amplifiers have better drift and stability, as well as less affected by noise.

Filtering is used for applications of signal-to-noise ratio improvements, smoothing of data, bandwidth reduction and avoidance of aliasing effects. The aliasing effect is the existence of high frequency and low frequency components in a sampled signal. These components, if mixed in the sampling process, will become indistinguishable within the summated waveform.\(^ {20}\) A filter is thus any frequency-selective device, which transmits a certain range of frequencies, known as the pass-band, or rejects all frequencies in a range
known as the stop band. The process reduces the number of data points, eliminating or reducing some of the noise.  

During the filtering process, the original data are retained in a one-dimensional array. Each set of arbitrary consecutive points is replaced by a single point, which is the sum or average of its neighboring points. If noise in the data is randomly distributed, then the noise will be reduced (approximately) by the square root of the number of points within the set. The reduced data are retained in an array, and can be applied in processes that are either on-line or off-line. Continuous or analog filtering is especially necessary preceding digitization if the distorting effects of aliasing are to be avoided. Analog filters are traditionally designed from passive electrical elements, i.e. resistors, inductors and capacitors. A digital filter may be realized by suitably interconnecting electronic logic elements or by programming a digital computer.  

Decimation, a data compression procedure, involves the selection of a subset of some arbitrary samples of the digitized data at intervals spaced uniformly throughout the data sequence. This process reduces the quantity of data to be analyzed to a realistic minimum to improve data recording or processing efficiency, as well as attenuating nonlinear time-data results.  

Sometimes there is the need to remove a signal when its deviation falls outside a permitted value. Trend removal is the process of removing unwanted value added to the required signal, which could decrease the signal sensitivity as a function of temperature or time. In many occasions, trend removal can be combined with filtering as a whole process.
“Calibration” is the process taken to assure that data are accurate and meaningful. Calibration carried out prior to the recording of the data is called pre-experiment calibration. It relates the characteristic of the transducer to the parameter being measured, e.g. converting pressure in pound per square inch to volts output. Real-time calibration is carried out during the recording of data. It checks any changes that may have occurred during the actual period of recording, e.g. amplifier drift, change of transducer characteristics, etc. Sometimes calibration is carried out after the data has been recorded. This is called post-experiment calibration.

In addition, calibration also checks the linearity, gain, dynamic range, frequency response, etc., of the system following the transducer.

Preprocessing could be done in an external device such as a single-chip computer. Such purpose is to reduce time for the computer to handle the major portion. In the CooLN2Car experiment, preprocessing was handled by several different components in the data acquisition system (SigLab 20-22 data acquisition module). The thermocouple signal conditioners as well as the pressure transducer itself provided signal amplification, while the SigLab 20-22 data acquisition module filtered noises from the input signals. Calibrations of the sensors were done at the manufacturer’s site. The thermocouples were calibrated as NIST (National Institute of Standards and Technology) T-type standard, and the pressure transducer was calibrated to measure linearly 0 – 150 psig, output from 1 – 5V.
**Digitization**

Any process of data acquisition must involve some approximation. Sampling is the process of measuring a signal at a discrete set of moments, while quantisation is the process of approximating the actual signal at each moment by a finite-digit representation. Sampling involves setting up intervals between successive values, the sampling intervals, where there will be a minimum number of data points per period time. Quantisation works as a code conversion process. It provides corresponding discrete or 'digital' data either on a single line (serial output) or on several lines (parallel output) from continuous or 'analog' information. Devices used are commonly called as analog-to-digital converters, or A/D converters. These two processes (sampling and quantisation) convert analog signals into digital signals as input for the computer, and the whole conversion process is called digitization. This process must be able to digitize a given signal in such a way that it minimizes cost without introducing unacceptable values.

The SigLab 20-22 has a built-in sigma delta A/D converter which allows such an analog-to-digital data conversion.

Figure 5 shows a functional diagram of a data acquisition system.
A general data acquisition system

Data acquisition systems can be categorized as data display system, data recording system, data processing system, and integrated data system. Data display systems measure and display signal information immediately in a form suitable for human inspection. Real-time monitoring of plant activities is required. Such systems consist of signal measurement devices at one end and output devices reproducing the information at the other end. Examples of the display mechanism are alarm bells, meters, or oscilloscopes.

Data recording systems contain both analog and digital recording processes. Digital recording offers higher accuracy and easier handling of the recorded data. This higher accuracy is due to the ease of correcting errors in digital information through the control of noise signal and interference in the processes of sampling and quantisation. Digital recording also allows data to be converted from one form to another very easily, depending on the purposes of the usage and devices in use.
Processing systems transform measured signals into new information suitable for a particular application as well as reduce its quantity. This process includes preprocessing, which extracts existing signals from the raw data by eliminating noise, calibration errors, etc., and the data processing itself.\footnote{33}

Integrated data systems apply some control function on the input signals and produce output signals to be sent immediately to devices under the control of the data system. It can be interpreted as that the present behavior of the system, as measured by the data acquisition unit, is being used to control its future behavior.\footnote{34}

The data acquisition for the CooLN2Car experiment can be considered as a combination of both a data display and recording system. The SigLab 20-22 provides a windows-based GUI display using real-time data acquisition process, and allows digital recording for further purposes.
CHAPTER 4

SENSOR CONCEPTS

Thermocouples

It is very common to measure temperature by conduction at the junction of 2 dissimilar metals of a thermocouple. A thermocouple is created whenever two dissimilar metals touch and the contact point produces a small open-circuit voltage as a function of temperature. This thermocouple voltage is known as the Seebeck voltage, named after the German physicist Thomas Seebeck, who discovered it in 1821. Figure 6 shows the Seebeck Effect, which states that when two wires composed of dissimilar metals are joined at both ends is heated, there is a continuous current which flows in the thermoelectric circuit.

![Diagram of a thermocouple circuit]

Figure 6. Basic Thermocouple Circuit with Instrument
If this circuit is broken at the center, the net open-circuit voltage (the Seebeck voltage) is a function of the junction temperature and the composition of the two metals. Figure 7 shows a T-type thermocouple that was used in the CooLN2Car experiment, which has as its two metals as copper and constantan respectively. One end of the two joined metals is heated to temperature $T$, the resulting Seebeck voltage $V$ at the other end can be measured. All dissimilar metals exhibit this effect. This resultant voltage is nonlinear with respect to temperature. This non-linearity is due to the Peltier effect. A French physicist, J.C. Peltier discovered in 1834 that when electrical current is caused to flow across the junction of two dissimilar metals, heat is either absorbed or liberated, resulting in a change in temperature.

![Diagram of a T-type thermocouple](image)

**Figure 7. T-type Thermocouple, Seebeck Voltage**

The change in temperature due to this effect is proportional to the quantity of electricity crossing the junction.\(^{36}\) To minimize current flow, the thermocouple is associated with high-input impedance methods of measuring the electromotive force across the junction.\(^ {37}\) However, for small changes in temperature the Seebeck voltage is approximately linearly proportional to temperature: $\Delta V = \alpha \Delta T$, where:
\( \alpha \), the Seebeck Coefficient, is the constant of proportionality;

\( \Delta V \) is the induced voltage;

\( \Delta T \) is the change in temperature;

The nonlinearly voltage-temperature relationship is due to the varying value of \( \alpha \) with changes in temperature. Several thermocouple types are available, they are designated by capital letters that indicate their composition according to American National Standards Institute (ANSI) conventions. For example, a T-type thermocouple has one pure copper wire for the positive conductor and a constantan (a copper-nickel alloy) for the negative conductor. These low-cost T-type thermocouples are excellent for use in measuring subzero temperatures because of their high resistance to corrosion from atmospheric moisture or moisture condensation. Copper-Constantan thermocouples are generally more accurate than other commercially available thermocouples for measuring temperatures between approximately \(-300^\circ F\) to \(+300^\circ F\), which is very suitable for this CoolLN2Car experiment. The T-type thermocouple has a maximum temperature of 350°C since copper oxides above 350°C, and it has an output of about 60 \( \mu V/\circ C \). Please refer to Table 1 for the corresponding operating temperature ranges and conductor combinations of different thermocouple types.

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iii The Seebeck coefficient for T-type thermocouple is 38\( \mu V/\circ C \) @ 0°C
<table>
<thead>
<tr>
<th>ANSI Code</th>
<th>Alloy Combinations</th>
<th>Range, F</th>
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</thead>
<tbody>
<tr>
<td>J</td>
<td>IRON + LEAD, CONSTANTAN COPPER-NICKEL</td>
<td>-346 to 1400 F</td>
</tr>
<tr>
<td>K</td>
<td>CHROMEL NICKEL-CHROMIUM + LEAD, ALUMEL NICKEL-ALUMEL</td>
<td>-454 to 2500 F</td>
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<tr>
<td>T</td>
<td>COPPER + LEAD, CONSTANTAN COPPER-NICKEL</td>
<td>-454 to 752 F</td>
</tr>
<tr>
<td>E</td>
<td>CHROMEL NICKEL-CHROMIUM + LEAD, CONSTANTAN COPPER-NICKEL</td>
<td>-454 to 1832 F</td>
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<tr>
<td>R</td>
<td>PLATINUM-13% RHODIUM + LEAD, PLATINUM</td>
<td>-58 to 3214 F</td>
</tr>
<tr>
<td>S</td>
<td>PLATINUM-10% RHODIUM + LEAD, PLATINUM</td>
<td>-58 to 3214 F</td>
</tr>
<tr>
<td>B</td>
<td>PLATINUM-10% RHODIUM + LEAD, PLATINUM-6% RHODIUM</td>
<td>+212 to 3300 F</td>
</tr>
<tr>
<td>N</td>
<td>OMEGA-P™ + LEAD, OMEGA-N™</td>
<td>-454 to 2372 F</td>
</tr>
</tbody>
</table>

**Table 1. Thermocouple Types and Temperature Ranges**

To measure thermocouple voltage, a voltmeter is connected to the two metal wires of thermocouple, but the voltmeter leads themselves will create a new thermoelectric circuit. Consider the circuit illustrated in Figure 8 in which a T-type thermocouple is in a heat source that has a temperature to be measured. The two thermocouple wires are connected to the copper leads of a temperature-measuring device, such as a DAQ board or a thermocouple signal conditioner. Notice that the circuit now contains three dissimilar metal junctions – J1, J2, and J3. The thermocouple junction, J1 generates a Seebeck voltage proportional to the temperature of the heat source. J2 (a copper-to-constantan junction) and J3 (a copper-to-copper junction) each will have its own Seebeck coefficient and generates its own thermoelectric voltage proportional to the
temperature at the DAQ terminals. To determine the voltage contribution from J1, one needs to know the temperatures at junction J2 and J3 as well as the voltage-to-temperature relationships for these junctions. One can then subtract the contribution of the parasitic thermocouples at J2 and J3 from the measured voltage.

![Diagram of a T-Type Thermocouple Connecting to Signal Conditioner](image)

**Figure 8. T-Type Thermocouple Connecting to Signal Conditioner**

Since junction J3 is a copper-to-copper, it creates no thermal EMF ($V_3 = 0$), but J2 is a copper-to-constantan junction which will add an EMF ($V_2$) in opposition to $V_1$. If a reference with a known temperature is established for one of the junctions (e.g. J2), the emf as read by the indicating instrument will vary directly and only with the unknown temperature at J1. A cold reference junction is usually used to compensate for the unwanted parasitic thermocouples. The term cold junction comes from the traditional practice of holding this reference junction at $0^\circ$C in an ice bath. For example, the copper-to-constantan junction J2 can be physically put into an ice bath, forcing its temperature to be $0^\circ$C and establishing it the reference junction (Figure 9). Since both voltmeter terminal
junctions are now copper-to-copper connections, they create no thermal emf and the
reading V on the voltmeter is proportional to the temperature difference between J1 and
J2. Therefore the voltmeter reading (Signal Conditioner) is $V = (V_1 - V_2)$.

![Reference Junction Thermocouple Circuit](image)

**Figure 9. Reference Junction Thermocouple Circuit**

Before proceeding to find the voltage at J1 and converting it to its equivalent
temperature, two possible errors in measuring the hot junction temperature must be
considered. First, when an instrument is used to measure the emf, it is necessary to
introduce additional metals into the circuit. This could mean that the emf developed by
the thermocouple would be modified and any calibration done to the thermocouple could
be damaged. However, the introduction of this third metal into the circuit may pose no
effect upon the emf generated so long as the junctions of the third metal with the other
two are at the same temperature. This is the Law of Intermediate Metals.  

Another possible error is the possibility for the reference temperature to drift or
change over the course of time. This drifting effect could be minimized by terminating
the two output leads on an isothermal block. Thus, as long as the metals inside the
instrument connected to the thermocouples in the thermoelectric circuit are kept at a uniform temperature, the net emf generated by the thermocouple itself will be unaffected. This isothermal block is indicated as the isothermal region in Figure 9.

In practical applications, it is more convenient to physically remove the ice bath from the thermocouple circuit. To determine V2, the absolute temperature at J2 has to be determined. This can be done by adding a thermistor to the thermocouple circuit. As shown in Figure 10, the ice bath is replaced by putting the junctions between the third metal from the signal conditioner (copper) and the two thermocouple metals within an isothermal block. The isothermal block is an electrical insulator but a good heat conductor. These junctions are thus held at the same temperature and the whole block can be treated as the reference junction. The absolute temperature at J2 (reference junction) is determined by measuring the thermistor's resistance at and converting this resistance to its corresponding temperature. The temperature is then corrected to its equivalent reference junction voltage V2. After subtracting voltage V2 from the measured voltage V, voltage V1 is determined and can be corrected to temperature value for the hot junction J1.

Figure 10. Software Compensation
Instead of measuring the temperature of the reference junction and computing its equivalent voltage as we did with software compensation described above, we could use electric cold junction to simulate a reference temperature. A variable voltage source is inserted into the circuit to cancel the parasitic thermoelectric voltages. The variable voltage source generates a compensation voltage according to the ambient temperature, adding the correct voltage to cancel the unwanted thermoelectric signals. When these parasitic signals are canceled, the only signal the DAQ system measures is the voltage from the thermocouple junction of the reference junction. Another way of electric cold junction can be achieved by mounting another type of temperature sensor (e.g. thermistor) on the isothermal block, as shown in Figure 11. The temperature sensor inside is used to measure the actual cold junction temperature, then applies an appropriate correction factor to the cold junction reference circuit. The thermocouple signal conditioners used in the CooLN2Car experiment had such electric cold junction circuit built in, and were coupled with signal amplification function.

Figure 11. Hardware Compensation
Thermocouples are very rugged and inexpensive and can operate over a wide temperature range. In fact, they have the widest temperature range of the measurement transducers. Their small mass also gives them a good response and sensitivity. Since thermocouples are very easily corroded, it is sometimes necessary to protect them using chemically inert and vacuum tight metal ceramic tubes.

The following is a list of advantages and disadvantages for using thermocouples:

Advantages:

1. **High Temperature**: can measure high temperature compared to thermistors or wire-type sensors.
2. **Small Size**: made of fine wire and are able to measure temperature at a particular point.
3. **Linearity**: provide outputs temperature linearity of under 1 percent over a wide range.
4. **Low Cost**: widely available at low cost and can be self-made quite easily.

Disadvantages:

1. **Cold Junction Compensation**: in all applications a thermocouple does not measure the temperature at a junction, but rather the difference in temperature between the measuring junction and a reference junction (i.e. ambient temperature)
2. **Low-level Output**: 5.28 millivolts at 100°C for the most sensitive iron-constantan thermocouple, change in output is 5.4 microvolts/0.1°C, compared to a wire-sensor bridge of over 100 times as great, thus need a very sensitive amplifier.
3. **Limited Accuracy**: thermocouple curves taken from published tables could contain a margin of error.

4. **High-impedance Instrumentation**: thermocouples are pure potential devices and give accurate readings only when used in a potentiometer circuit where the current approaches zero to avoid the Peltier effect.

5. **Special Lead Wire**: need special compensating lead wire to keep circuit resistance low and avoid unwanted thermal junctions.

**Transducers**

Transducers are elements that convert one form of energy into another.\(^4^6\) A transducer accepts a non-electric signal and outputs an electric current or voltage that reproduce the information in the signal. Transducers can measure displacement, acceleration, and velocity through linear and angular measurements. Most transducers produce a continuous (analog) output, although there are some that are designed to produce directly a digital output.\(^4^7\) They can be classified as active, passive, and feedback transducers.\(^4^8\) Active (or self-generating) transducers, convert energy directly from one state to another without any external power source or excitation. A good example is a thermocouple, which converts temperature difference into voltage. Passive transducers do not convert energy directly. They produce varying output signals which correspond to changes of measured values, and whose output signals require some excitation coming from some other source. Feedback transducers are characterized by a feedback loop of which an opposing electrical quantity balances out the input physical quantity, where the force to achieve this equilibrium equals the physical quantity being measured. The
pressure transducer used in the CooLN2Car experiment belonged to the second category. It operated by causing some output voltage changes in response to changes in the physically measured pressure, while requiring some 10-30V DC voltage source to generate the output signal at the same time.

The transducer is usually the first element in a measurement system. It may be installed inside the measuring instrument, or installed remotely from the instrument in applications under harsh environment. In many occasions, a signal conditioner is used to modify the signal from the transducer by amplification or wave shaping to suit the requirements of the output device.

Transducer characteristics usually include, but are not limited to, sensitivity, repeatability, accuracy, resolution, time constant, response time, linearity, hysteresis, input excitation requirements, output signal type etc. Please refer to the glossary section at the end of this paper for their corresponding definitions.
CHAPTER 5

INSTRUMENT AND SENSOR SELECTIONS

SigLab Hardware

The DSPT SigLab\textsuperscript{iv} 20-22 (Figure 12) is a lab-quality dynamic signal and system analyzer with customizable signal conditioning abilities. SigLab provides all the functions of the high priced instruments. It communicates over a SCSI bus with a desktop PC running MatLab,\textsuperscript{v} a numeric computation and visualization software. SigLab 20-22 provides with the benefits of portability, expandability and MatLab integration (Figure 13). Its ruggedness and lightweight allows its convenient usage for field operation. SigLab collects real-world physical measurements such as time-domain data or power spectra directly into the MatLab environment. It also performs advanced dynamic system analysis such as transfer function estimation and system characterization in terms of s or z-plane models.

\textsuperscript{iv} DSPT SigLab is a registered trademark of DSP Technology, Inc.
\textsuperscript{v} MatLab is a registered trademark of the MathWork, Inc.
Figure 12. The SigLab 20-22

Figure 13. A Typical PC-interfaced SigLab Data Acquisition System

SigLab 20-22 has integrated multifunction signal-generation ability. Its hardware uses sigma-delta data conversion technology\(^{\ddagger}\) and three on-board, high performance DSP chips to deliver dynamic signal and system analysis over the 0 to 20 kHz range. A dedicated DSP processor filters and decimates the A/D data stream providing a selection of 13 alias-protected sampling rates down to 5 Hz. Triggering circuitry provides slope control and 17 selectable threshold levels. The trigger source can be an input channel, an output channel, or a rear panel digital input.

\(^{\ddagger}\) Data converter: 18-bit sigma delta A/D
SigLab provides better than 90dB spurious free dynamic range. The on board real-time signal processing provides 90dB alias protection at all 13 user selectable bandwidths, and real-time frequency translation (zoom) capabilities for narrow band measurements. A floating point TMS320C31 DSP performs all dynamic signal/systems analysis including FFT, windowing, cross and auto spectrum and coherence computations. The C31 responds to commands from MatLab and returns results to the host PC through the SCSI interface. SigLab 20-22 is constructed in a notebook form factor with an internal battery for portable operation. SigLab can operate from an external 12 V input or from its internal NiCad battery. A universal ac-line to 12 V adapter is used to power SigLab and charge the internal battery. Extended remote operation is possible from a 12 V source such as a car battery.

SigLab 20-22 comes with a ready to use Windows-based measurement and analysis software, coded in MatLab. Set up and control of all measurements are through point and click graphical user interfaces (GUIs). No programming or knowledge of MatLab is required. Once all parameters are set, data acquisition can take place. Results are viewed in real-time using MatLab's extensive graphics visualization capabilities. Measurements can easily be viewed, controlled and stored for further analysis.

The SigLab 20-22 is a fully alias-protected two-channel data acquisition system in one small enclosure. Each SigLab 20-22 module has two differential signal analysis input channels and two signal generation output channels, supporting up to 20kHz sample rates. The differential inputs have ten full-scale ranges allowing measurement of signals from ±20 millivolts to ±10 volts in 6dB steps. These inputs are protected up to 30 volts
rms (differential). AC/DC coupling as well as DC offset can be specified. Additionally, optional signal conditioning circuitry can be inserted in SigLab beneath the top cover access panel. The SigLab 20-22 can be expanded beyond 2 channels using daisy-chaining up to a total of 8 units, combining to provide a maximum of 16 fully time-synchronized 20 kHz bandwidth measurement channels. Each SigLab module is linked by way of an external cable providing synchronous multi-channel capability. This subsystem manages the synchronization of all sampling clocks and trigger signals for the input and output channels.

**SigLab Software**

The following software GUIs, each defining a different instrument or measurement utility, are supplied with the SigLab hardware:

- Function Generator (including arbitrary output)
- Oscilloscope
- Spectrum Analyzer
- Network Analyzer - Broad Band Transfer Function and Coherence estimation
- Swept-Sine Network Analyzer - Narrow Band Transfer Function and Coherence
- System Identification - System Modeling in Z or S planes

These are called virtual instruments as they are not physically instruments but they are programs that have the same functions as the traditional instruments. The Oscilloscope was used in this experiment for data recording and display. The following is a brief
description of its basic operations. They will be divided into Channel Setup, Timebase, Processing, and Triggering groups. Figure 14 is a sample picture of the VOS.

![Figure 14. The Virtual Oscilloscope](image)

The "channel setup" (Figure 15) group provides access to the channel parameters. The Channel Select popup allows a particular channel to be selected for parameter adjustment. The number of available channels depends on how many SigLab modules are physically connected to the system. It ranges from a minimum of 2 to a maximum of 16 channels. The Full Scale Range popup (Figure 16) sets the maximum input voltage range, with ten full-scale selectable voltages from 20 mV to 10V in 6dB steps. The Channel Enable toggle button determines if the channel will be part of the measurement set. If it is

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vii A control containing a list of options
set to off, data will not be acquired for the channel. The *AC/DC Coupling toggle button* sets the input coupling. When AC is selected, the DC Offset capability is disabled. Adjustable DC Offset can be added to the input signal. Each channel can have its own unique label set by the *Channel Label edit control*. Engineering Units can also be applied to the data by the *Engineering Unit Toggle button*.

![Figure 15. Channel Setup](image)

![Figure 16. Input Voltage Range](image)

The "timebase group" (Figure 17) deals with the sampling and filtering parameters which are common to all channels. The *Sampling Period popup* (Figure 18) provides thirteen selections of the sampling period, ranging from 7.8μS per sample to 78.1mS per sample. The *Anti Alias Filter control* enables or disables the digital AA filters in the input subsystem (executing in the AD2105 DSP chip). The *Acquisition Record length control* determines the number of samples to be acquired, displayed, and (potentially) averaged. Allowed record lengths range from 64 to 8192. In the *Frequency Translation (Zoom Off / Zoom Center Freq) toggle button*, the digital low pass filters are
transformed to digital band pass filters which produce a complex valued time history, the real component of which is plotted in the display. This feature is useful in studying narrow band signals and systems.

In the “processing group” (Figure 19), signal averaging can be performed during the acquisition of data. When the “Avg” (Figure 20) button is pressed, successive data records are averaged together which will lead to a reduction of the random components of the signal. This processing requires triggering to be used so that successive records are identical (except for the random components which are to be reduced). Averaging modes include Additive, Exponential, Peak Hold, and Adaptive.
The "triggering group" is used to control trigger parameters common to all input channels. Trigger Mode selections include Off (Free Run), Every Frame, First Frame, Manual Arm, and First Manual Arm trigger modes. The Off Trigger Mode was used in the CooLN2Car experiment. When the "AVG" button is pressed (Figure 20), data records are simply continually acquired, with averaging, up to the 8000 sample size as specified.

**Thermocouple**

Two Omega SA1-T self adhesive T-type thermocouples (Figure 21) were used to measure gas temperatures entering into and coming out of the air motor. These sensors are manufactured from 30 AWG Teflon-coated thermocouple wire, with a flattened bead secured between a high temperature polymer and a high temperature, fiber reinforced polymer for good thermal conductivity and fast response. The thermocouples output
millivolts signals to the two Omega signal conditioners, DRN-TC-C, which amplified them to 0-5 volts as output signals to the SigLab 20-22.

To effectively measure the temperatures, the measuring heads of the thermocouples were inserted into the inlet pipe and the exhaust pipe for measurement. This was done by cutting away each thermocouple’s adhesive polymer, allowing the front part of the thermocouple wire with the flattened bead to be easily inserted in a 1-inch portion of a small, hollow plastic tube. Approximately half of this section was then inserted into the pipe through a small drilled-hole. High-strength epoxy was filled inside and outside the hole as well as inside the plastic tube to firmly secure the thermocouple to the pipe. The front portion of the thermocouple with its flattened bead was exposed to the air, so that gas temperature inside the pipes could be accurately measured. Please see Figures 22 and 23.

![Figure 21. The Omega SA-1 T-Type Thermocouple](image-url)
Since the DSP SigLab 20-22 accepts only voltage input signals, the non-compatible input signals provided by the thermocouples must be interfaced with the two Omega signal conditioners to provide high level voltage input signals for the data acquisition system. The isolated DRN rail mount signal conditioners represent state-of-the-art signal conditioning technology, and are ideal for all process and power monitoring applications. These models feature 3-way isolation, high accuracy input and programmable outputs. The conditioners have a Step Response to 99% in 1 second.

Their operating ambient temperature range is between -5 to 55°C (23 to 131°F), and their storage temperature range is between -40 to 85°C (-40 to 185°F). They can be mounted on 32 and 35 mm DIN rail (Figure 24). Their dimensions measure 75 H x 22.5 W x 121 mm D (2.95" x 0.89" x 4.77").
Figure 24. The Omega Din-Series Signal Conditioners

The signal conditioners are excellent front-end interfaces for programmable logic controllers or data acquisition systems. The DRN-TC has a built-in amplifier that amplifies the small voltage signal to the output voltage or current, sending out measured analog outputs that are proportional to the input signals. These signal conditioners provide a non-electrical connection between input and output. Because there is no electrical connection, the data acquisition system is protected from any excessive voltages. These isolated signal conditioners are rated for as high as 1800V-peak power supply.

The DRN modules accept nine different thermocouple types. The required power supply for the DRN module is from 10 to 32 Vdc. The output can be user-set for 0-10 V, 4-20mA or 0-20mA. Complete input-output scaling is configured over a Windows-based setup program, the DRN-CONFIG. Calibration of the signal conditioner is done via an RS-232 link to the computer. Once configured, the settings may be stored in the non-volatile memory within the unit, and the unit can then be disconnected from the PC.

The configuration consists of five sections:
1. *Input Range*: All thermocouple types are available. Line frequency can be chosen between 50 and 60 Hz (Figure 25).

![Input range or configuration](image)

**Figure 25. Input Range**

2. *Input/Output Mode Selection*: Options for the temperature units are Celsius, Fahrenheit, or Kelvin. The analog output mode can be set to voltage or current, and hardware cold junction can be activated or deactivated (Figure 26).

![Input/output mode selection](image)

**Figure 26. Input/Output Mode Selection**
3. *Filter Time Constant*: No filtering, as well as filter time constants of 2, 4, 8, 16, 32, 64, and 128 are available (Figure 27).

<table>
<thead>
<tr>
<th>Filter time constant:</th>
</tr>
</thead>
<tbody>
<tr>
<td>No filtering</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>16</td>
</tr>
<tr>
<td>32</td>
</tr>
<tr>
<td>64</td>
</tr>
<tr>
<td>128</td>
</tr>
</tbody>
</table>

*Figure 27. Filter Time Constant*

4. *Resolution*: Temperature readings are within 1, 0.1, or 0.01 degree in precision (Figure 28).

<table>
<thead>
<tr>
<th>Resolution:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>0.1</td>
</tr>
<tr>
<td>0.01</td>
</tr>
</tbody>
</table>

*Figure 28. Temperature Measurement Resolution*

5. *Analog Output Scaling*: The user is allowed to arbitrarily set the lower and upper limits for both the temperature degrees and voltage or current output (Figure 29).
Analog output scaling:

<table>
<thead>
<tr>
<th>Input 1</th>
<th>Desired output 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>00.0000 °F</td>
<td>00.0000 Volt</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Input 2</th>
<th>Desired output 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 °F</td>
<td>5 Volt</td>
</tr>
</tbody>
</table>

Figure 29. Analog Output Scaling

The calibrations for the two Omega signal conditioners were the same and are as follows:

1. Thermocouple was set to T-type, line frequency 60 Hz.
2. Fahrenheit was chosen as the temperature unit, analog output mode set to voltage, and hardware cold-junction compensation activated.
3. No filtering was used.
4. Temperature reading precision was set to within 0.01 degree.
5. The temperature range for measurement was set to between 0 and 100°F, while the output voltage was between 0 and 5 volts.

Pressure Transducer

The pressure transducer used in the CooLN2Car experiment was an Omega PX613 (Figure 30) thin film pressure transducer. It measured the gas pressure before entering the pneumatic motor. The rugged stainless steel construction PX613 is an amplified voltage pressure transducer with an output of 1 - 5 VDC (3 wire) and accepts
10-30VDC unregulated excitation. In the CooLN2Car experiment, a 12-V automobile battery was used to produce the excitation. The PX613 has built in pressure sensors (a 17-4PH stainless steel diaphragm and thin film polysilicon strain gages) coupled with compensation networks. It is fully compensated over the operating temperature range both at zero and full pressure to be stable. At zero pressure (atmospheric) reading, there is still some voltage through the unit, this is called the null offset or null voltage. The PX-613 has a null voltage of one volt, and it represents the beginning point of the transducer response graph.

![DIMENSIONS IN INCHES](image)

**Figure 30. PX613 Side View and Dimensions**

**Calibration**

All commercial thermocouples have been calibrated to produce the correct voltages to their corresponding temperatures by carefully controlling the constituent components. Please refer to the NIST ITS-90 Thermocouple Reference Tables for further

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\[\text{Accuracy (Linearity, Hysteresis, and Repeatability) at } \pm 0.4\% \text{ BFSL; Hysteresis at } \pm 0.2\% \text{ FS; Repeatability at } \pm 0.05\% \text{ FS, Thermal Zero Effect and Thermal Span Effect at } \pm 0.04 \text{ FS}/\degree F.\]
detail calibration information. These tables can be found at the following web address on the Internet: <http://www.omega.com/techref/tctables/temperl11.html>

The Omega-SA1 is calibrated according to the NIST table as standard T-type Copper-Constantan thermocouple. The PX-613 pressure transducer is also calibrated and requires no calibration as is described in the product certificate provided by Omega.
CHAPTER 6

EXPERIMENT PROCEDURES

SigLab

Two SigLab units were linked by connecting their Multi-Box Synchronizing Signals connectors and at the same time daisy-chained by a SCSI cable connecting their SCSI connectors at the back to form a 4-channel system (Figures 31 and 32). The SigLab unit that was not terminated was connected to the Bus Toaster PCMCIA SCSI II Adapter of a Toshiba laptop using a SCSI cable. Both the laptop and the other SigLab unit were terminated according to the SCSI standard. The unit not terminated was assigned a SCSI device address 4, while the terminated unit was assigned address 5. The laptop had an address 7. SigLab automatically assigned the two channels of the unit with lower address channels 1 and 2, while the channels of the unit with the higher address were assigned as channels 3 and 4 respectively.
This 4-channel SigLab 20-22 system became the component in the data acquisition that performed most of the pre-processing procedures such as filtering, decimation, and digitization. The first two input channels were used to measure intake and exhaust gas temperatures respectively. The third channel was not connected with any sensor and was set inactive during the acquisition process, while the fourth channel was connected with the pressure transducer to measure gas pressure entering the motor. The virtual oscilloscope (VOS) was employed as the software program for this data acquisition process (Figure 33). All active input channels had a 0-5 volts input voltage range. The two temperature channels (1 and 2) measured a temperature range from 0 to 100°F, averaging 20°F per volt. The pressure channel (4) measured a pressure range from 0 to 150 psig, averaging 30 psig per volt. All input channels were DC-coupled without any DC offset. Channel 1 was labeled Intake, channel 2 Exhaust, and channel 4 Pressure.
Sampling period was set at 7.8ms/sample (51.2 Hz) for 8000 samples to yield to a 62.4-second record length. During the acquisition process, the anti-alias (AA) filter\textsuperscript{ix} was turned on to reduce noise. Since this experiment was intended to simply acquire data continually, only Free Run triggering method was employed. The additive averaging processing method combined successive records with equal weighting, reducing random components of the signals. The data collected with VOS was stored in standard MatLab

\textsuperscript{ix} The Anti Alias Filter control enables or disables the digital AA filters in the input subsystem (executing in the AD2105 DSP chip). The filter code is executed for all sampling periods except the fastest (19.5 μs). When the filter code is disabled, the DSP chips simply decimate the input data stream from the A/D converter by 2, 5, 10, 20, 50, etc. (determined by the sampling period selection). A 4 pole analog low pass filter and the digital filter inherent in the sigma-delta converter are always active, therefore the anti-alias filters cannot be disabled when sampling at a 19.5 μs period (51200 Hz).
arrays. All the setup information was saved in VOS data files, under standard MatLab.MAT format.

**DRN-TC-C Thermocouple Signal Conditioner**

A standard 12-volt car battery (Figure 34) was used to provide the necessary power source for the two Omega DRN-TC-C thermocouple signal conditioners. Each conditioner drew approximately 166mA current from the battery at 12Vdc.

![Figure 34. 12-V Car Battery and Wires](image)

Two Omega SA-1 T-type thermocouples were connected to the two signal conditioners (Figure 35). Each thermocouple’s red copper wire was connected to the conditioner’s positive input terminal, and the brown constantan wire to the negative terminal. To allow signals to be sent from the conditioner to the SigLab input channel, a “pigtail” cable with a male BNC connector at one end was connected to the female BNC connector (Figure 36) at the Siglab input channel. The other end of the pigtail cable consisted of two wires, which were hard-soldered to a pair of wires coming out from the conditioner’s analog-out terminals. All terminals on the DRN modules were screw type
terminals and all wiring connections used 20-gage copper wires, except the thermocouples, which were made of 30AWG Teflon-coated wires.

Figure 35. Thermocouples Connected to the Signal Conditioners

Figure 36. SigLab BNC Input Channel Connectors
Pressure Transducer

Unlike thermocouples, the Omega PX-613 (Figure 37) pressure transducer did not need an external signal-conditioning interface. It was designed to send out a compatible voltage signal directly to the meter, which, in this experiment, the SigLab. It had built-in signal conditioning capabilities and the internal amplified voltage signals could travel up to medium distances and were much better in immunity to stray electrical interference than millivolts signal generated by a thermocouple. However, since the Omega PX-613 pressure transducer was a passive transducer, it required an external power source to provide it with necessary excitation to generate output voltage signals according to changes from the input pressure signals. The standard 12-V car battery provided such excitation for the transducer.

![Figure 37. Pressure Transducer](image)

To connect the pressure transducer to the car battery and the SigLab, an Omega 4-contact-hole PT06F-8-4 rugged aluminum shell female connector (Figures 38 and 39) was installed at the back of the pressure transducer. The solder contacts between the
connector and the transducer provided positive connections for signal and power circuitry. The built-in 4-pin solder type contact connector at the back of the transducer was tightly mated with the PT06f-8-4 when they were twist-locked. This connection provided a pressure tight seal.

![PT06f-8-4 Connector](image)

**Figure 38. Omega's PT06f-8-4 Connector**

**Figure 39. Front View of PT06f-8-4**

Wire connections between the pressure transducer, SigLab, and the battery are shown in Figure 40. A positive excitation wire was soldered to pin A of the transducer, connected to the positive terminal of the power supply. Another wire was soldered to pin D as a common wire connecting to both the negative terminal of the power supply and to the negative signal output. A third wire was soldered to pin B connecting the positive terminal of the power supply. Note that pin C was left open. A male BNC pigtail cable was connected in between the SigLab input channel (channel 4) and the two signal output wires, which were also hard-soldered together.
Figure 40. Pressure Transducer PX613 Wiring

Please refer to Figure 41 for an overall connection diagram of all the instruments and components in the data acquisition system.

Figure 41. The CooLN2Car Data Acquisition System Connection Diagram
CHAPTER 7

THE EXPERIMENT AND RESULTS

The data acquisition experiment aimed at developing a method of measuring temperatures and pressure at different points on engines that use liquid air as fuel (figure 42). The liquid nitrogen vehicle powered by its 9-hp air motor was chosen to accomplish this purpose. The major maneuvers to be tested at this stage were mainly acceleration, gear-change, and the general phenomenon of gas temperature and pressure under normal driving conditions.

![Intake Pressure](image)

**Figure 42. Measurements at Different Points**

We expected to see gas temperatures between intake and exhaust to diverge as energy was extracted from the working gas. Thus, we expected that we would be measuring some lower exhaust gas temperature compared to that of the intake. We also
expected to see pressure to drop as we continued operating the vehicle. This was due to the many flow restrictions and lines that provided the pressure. During gearshifts, we expected to see small “spikes” from the pressure and temperature readings. As was mentioned earlier in the paper, a throttle consisting of a butterfly valve was connected to the accelerator pedal. During gearshifts, the accelerator pedal was momentarily released, closing the butterfly valve and restricting gas flow. As the gas was stopped from flowing into the air motor, it heated up because no cold air was provided during that moment. Gas temperature automatically went up. In the same manner, the restricted gas-flow in the flow system allowed pressure to build up, yielding to the increase from the pressure readings.

As the experiment went on, we also expected that the heat transfer components would become colder the longer the vehicle was driven. This was because the cold liquid nitrogen gas worked to cool down the temperature of the flow system, and would even cause the system to build up frost due to condensation.

Two driving experiments were conducted at different times. The first experiment took place on a cold and cloudy winter day at 42°F ambient temperature. The experiment collected data from three driving tests, each lasted for approximately 62.4 seconds. Due to the cold weather condition on that day, the heat transfer components built up frost very soon just as we had expected. What we did not expect was that the exhaust gas had reached below 0°F in less than approximately 2 minutes of driving (Figures 43 - 48). Further accurate temperature readings for the exhaust as well as the intake later were not available on that day, since the temperature had gone below the lower limit 0°F calibrated
for the signal conditioners. Frost formed on the tank and the external heat exchangers.

We were surprised to find that frost also covered components such as the gas filter, pressure regulator, oiler, the Gast air motor, and all the pipes that provided the nitrogen gas flow (Figure 49).

Figure 43. Test 1 Temperature

Figure 44. Test 1 Pressure
Figure 45. Test 2 Temperature

Figure 46. Test 2 Pressure

Figure 47. Test 3 Temperature

Figure 48. Test 3 Pressure
A second driving experiment was conducted about a month later. It was a sunny and warm Spring day at around 62°F ambient temperature. Data was successfully collected from three driving tests. Gas temperatures were able to maintain above 0°F this time, and there was not as much frost as was seen than the first experiment. Note that Figure 50 shows that the author was covering himself and the laptop screen with a jacket to allow images on the screen to be seen during the acquisition process.
Figures 51 - 56 display all the data acquisition results of the second experiment. From the tests results, it can be seen that both the intake and exhaust gas started at temperatures close to the ambient temperature during the first test. At this time, all the heat transfer components were at ambient temperature. As the vehicle was started and continued running, the exhaust temperature began to drop, while the intake temperature remained relatively stable. Results from the first test show that the exhaust gas dropped to 31.24°F, while the intake temperature was staying at around 62°F.

As the second test began, starting temperature for both intake and exhaust dropped a few degrees. This could be explained by the fact that the cold nitrogen gas running in the heat exchange system helped cool down the components. The intake temperature again showed relatively little change overall, but the exhaust temperature continued to drop to as low as 19.57°F. The third test followed pretty much the same rule as was found in tests 1 and 2. Both temperatures started at around 53°F and both were
showing a dropping trend. At the end of this test, the exhaust gas reached a low record of 7.9°F. It is believed that if further driving tests continued, temperature readings could drop below 0°F again.

Results of the pressure readings showed some fluctuating pattern, but the average performance of the gas pressure over the three tests was quite consistent. Based on the limited equipment, the only pressure phenomenon explainable was the spikes shown on the graph, which took place during gearshifts as was explained above. Further experiments using more sensors at different points may be needed to explain such complex phenomenon.

Figure 51. Test 1 Temperatures

Figure 52. Test 1 Pressure
Figure 53. Test 2 Temperatures

Figure 54. Test 2 Pressure

Figure 55. Test 3 Temperatures

Figure 56. Test 3 Pressure
CHAPTER 8

CONCLUSIONS

This paper has presented a data acquisition experiment on a liquid-nitrogen-powered vehicle. The experiment measured gas temperatures and pressure to determine the performance of the compressed nitrogen gas on a pneumatic engine. The purpose of the experiment was to develop a method of temperature and pressure measurements at different points on engines that use liquefied air as the fuel. Such a method uses data acquisition instruments combined with temperature and pressure transducers to measure and record the data. The whole acquisition system is interfaced to the computer to provide on-line display as well as direct recording. This method has been proven to be successful and applicable. It serves as a prototype for quantitative analysis method to determine the performance of the engine. Further experiments on more complex engines applications can be conducted by extending this current method.
CHAPTER 9

RECOMMENDATIONS

This first-phase experiment has successfully developed a data acquisition method to measure and record the gas temperatures and pressure. Further study and experiment are recommended for a quantitative approach to determine how the gas temperatures and pressure affect the performance of the engine. Future experiments may involve methods to quantitatively measure and analyze data. In addition to the current sensors and transducers that are used, more can be added at different points of the system to determine how the behavior of the gas temperatures and pressure change according to acceleration or other maneuvers.

For example, a force sensor can be installed at the accelerator pedal to determine how gas temperatures and pressure change as the accelerator pedal is pressed or released. Another pressure transducer may be used to measure gas pressure directly coming out of the gas tank to determine if any internal effect inside the tank will affect the measured gas pressure. It is also recommended that pressure transducers used in future experiments should contain no null voltage effect so that zero pressure will start at true zero voltage reading.

During the data acquisition process, accurate readings can be taken by using the appropriate averaging method to reduce noise. Environmental errors must be considered. Such errors are due to effects of changes in temperature, humidity and
pressure vibration, or of electric or magnetic fields on the performance of the instrument. It is also necessary to consider any limiting errors caused by the limits on the accuracy of the components which make up the system. To reduce electrostatic noise, use short cables and keep cables and connectors neat. If it is necessary, shield signal-carrying wires by wrapping them in a conductor that is grounded.
GLOSSARY

Accuracy: The closeness of an indication or reading of a measurement device to the actual value of the quantity being measured. Usually expressed as ± percent of full scale output or reading.

Aliasing Effect: The existence of high frequency and low frequency components in a sampled signal. These components, if mixed in the sampling process, will become indistinguishable within the summated waveform.

Analog-to-Digital Converter (A/D Converter): A device or circuit that outputs a binary number corresponding to an analog signal level at the input.

Amplifier: A device which draws power from a source other than the input source and which produces as an output an enlarged reproduction of the essential features of its input. Amplifiers are commonly constructed from discrete solid state devices (e.g. transistors) or integrated circuits.

Amplitude: A measurement of the distance from the highest to the lowest excursion of motion, as in the case of mechanical body in oscillation or the peak-to-peak swing of an electrical waveform.

Bandwidth: The difference between the minimum and maximum frequencies for which an instrument has been designed. A wider bandwidth improves response time, but it also makes the system more prone to noise interference.
Burst Pressure: The maximum pressure applied to a transducer sensing element or case without causing leakage.

Calibration: The process of adjusting an instrument or compiling a deviation chart so that its reading can be correlated to the actual value being measured.

Compensation: An addition of specific materials or devices to counteract a known error.

Cryogenic: Term applied to low-temperature substances and apparatus.

Cryogenic Heat Engine: A device that employs a cryogenic medium as a heat sink and the atmosphere as a heat source.

Data Acquisition System: A product and/or process used to collect information to document or analyze some phenomenon.

Digitization: The whole conversion process of converting analog data to digital data. The process includes sampling and quantisation.

Excitation: The external application of electrical voltage current applied to a transducer for normal operation.

Filter: An electronic circuit which attenuates signals of certain frequencies while passing others.

Frequency: The number of cycles over a specified time period over which an event occurs. The reciprocal is called the period.

Gain: The ability of an amplifier to boost a signal. It is the ratio of the input voltage or current to the output voltage or current. Normally expressed in decibels (dB).

GUI: Graphical user interface.
Heat Engine: A device which converts heat to work. It has heat-only interactions with two or more objects and which, in consequence, does work spontaneously.

Heat Exchanger: A device where two moving fluid streams exchange heat without mixing.

Heat sink: A reservoir that absorbs energy in the form of heat.

Heat Source: A reservoir that supplies energy in the form of heat.

Hysteresis: The difference in output when the measurand value is first approached with increasing and then with decreasing values. Expressed in percent of full scale during any one calibration cycle.

Impedance: The total opposition to electrical flow (resistive plus reactive).

Input Impedance: The resistance of a panel meter as seen from the source.

Linearity: The closeness of a calibration curve to a specified straight line. Linearity is expressed as the maximum deviation of any calibration point on a specified straight line during any one calibration cycle.

NIST: National Institute of Standards and Technology.

Noise: An unwanted interference on the desired signal. Noise can be of mechanical, such as vibration, of electrical, such as electrostatic fields, and of magnetic, such as magnetic fields. Noise could also be generated internally in the measuring instruments.

Null: A condition, such as balance, which results in a minimum absolute value of output.
Operating Temperature: In pressure transducer application, the operating temperature defines the upper and lower temperatures that the transducer can withstand without any subsequent changes in performance.

Oscilloscope: The most frequently used instrument. It shows the shape of a wave form as well as gives a reading of its amplitude. The X control is usually time, thus the display consists of the amplitude of the wave against time.

Output: The electrical signal which is produced by an applied input to the transducer.

Output Impedance: The resistance as measured on the output terminals of a pressure transducer.

Peltier Effect: When a current flows through a thermocouple junction, heat will either be absorbed or evolved depending on the direction of current flow. This effect is independent of joule $I^2R$ heating.

Precision: How exactly or sharply an instrument can be read, or how closely identically performed measurements agree with each other.

Proof Pressure: The specified pressure which may be applied to the sensing element of a transducer without causing a permanent change in the output characteristics.

Quantisation: At each discrete moment during the sampling process, the actual value of the signal is approximated by a finite-digit representation.

Reference Junction: The cold junction in a thermocouple circuit which is held at a stable known temperature. The standard reference temperature is $0^\circ C (32^\circ F)$. However, other temperatures can be used.
Repeatability: The ability of a transducer to reproduce output readings when the same measurand value is applied to it consecutively, under the same conditions, and in the same direction. Repeatability is expressed as the maximum difference between output readings.

Reservoir: A body with a relatively large thermal energy capacity (mass × specific heat) that can supply or absorb finite amounts of heat without undergoing any change in temperature.

Resolution: The smallest detectable increment of measurement.

Response Time: The length of time required for the output of a transducer to rise to a specified percentage of its final value as a result of a step change of input. Time constant is a term commonly used to describe the time required by a sensor to reach 63.2% of a step change in temperature under a specified set of conditions. Five time constants are required for the sensor to stabilize at 100% of the step change value.

RS-232: A serial bus introduced in 1962 to connect computers to their peripherals.

Sampling: The process to measure a signal at a discrete set of moments.

Seebeck Effect: When a circuit is formed by a junction of two dissimilar metals and the junctions are held at different temperatures, a current will flow in the circuit caused by the difference in temperature between the two junctions.

Seebeck Voltage (EMF): The open circuit voltage caused by the difference in temperature between the hot and cold junctions of a circuit made from two dissimilar metals.
Sensitivity: The ratio of the output signal, or response of the instrument, to the input signal or measured variable. In other words, sensitivity is the smallest change of the variables to which an instrument is susceptible.

Signal: An electrical transmittance (either input or output) that conveys information.

Signal Conditioning: To process the form or mode of a signal so as to make it intelligible to, or compatible with, a given device, including such manipulation as pulse shaping, pulse clipping, compensating, digitizing, and linearizing.

Signal Conditioner: A circuit module which offsets, attenuates, amplifies, linearizes and/or filters the signal for input to the A/D converter.

Thermistor: A temperature-sensing element composed of sintered semiconductor material which exhibits a large change in resistance proportional to a small change in temperature. Thermistors usually have negative temperature coefficients.

Thermocouple: The junction of two dissimilar metals which has a voltage output proportional to the difference in temperature between the hot junction and the lead wires (cold junction).

Transducer: A device (or medium) that converts energy from one form to another. The term is generally applied to devices that take physical phenomenon (pressure, temperature, humidity, flow etc.) and convert it to an electrical signal.
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