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BACHELOR OF SCIENCE
IN MECHANICAL ENGINEERING

100% REPORT

STRIKER MECHANISM UPGRADE FOR THE
SPLIT-HOPKINSON PRESSURE BAR
EXPERIMENT

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This B.S. thesis is written in partial fulfillment of the requirements in EML 4905. The contents represent the opinion of the authors and not the Department of Mechanical and Materials Engineering.
2 ETHICS STATEMENT AND SIGNATURES

All the submitted work in this B.S. thesis is exclusively prepared by a team composed by Hector Di Donato, Jean Paul Garbezza, Alejandro Infante and Ricardo Lopez and it is unique. Extracts from others’ work have been clearly identified, their work acknowledged within the text and listed in the list of references. All of the engineering drawings, formulations, design work; prototype development, analysis and testing reported in this document are also original and prepared by the same team of authors.

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1. ABSTRACT

For our Senior Design requirement to fulfill a B.S. Degree in Mechanical Engineering from Florida International University (FIU), and at the behest of the Air Force Research Laboratory (AFRL), Munitions Directorate, our team’s goal is to develop a more effective striking system than that of last year’s group had put into place, as well as improve the diagnostics to review the test results. Using scholarly sources such as textbooks and research articles, knowledge of the general function of Split Hopkinson Pressure Bars (SHPB), as well as general formulas related to interpreting the data was obtained. Based on the assumption of One-Dimensional stress wave propagation, a compressed gas striking system was developed and calibrated to test material deformation at increased strain rates using the hoppy bar. A 200 MHz frequency oscilloscope was used to capture the signals from the strain gauges attached to the input and output bars. That wave profile signals obtained from the oscilloscope were subsequently converted into stress vs. strain data sets.

2. INTRODUCTION

2.1 PROBLEM STATEMENT

A new striking mechanism is to be designed and integrated to the existing SHPB apparatus to improve the consistency, striking speed and ability to produce a 1-dimensional stress wave. Ideally, the integration of the new striking system should not change the physical principles involved with the existing hoppy bar. A compressed gas, crossbow or spring-type mechanism is to be designed. Extensive analysis of the physical system was performed to gather as much information as possible to make educated engineering decisions. Also, the diagnostics system is to be improved, resulting in the implementation of an oscilloscope with a frequency
response of 100 KHz (minimum), as well as substitute the existing strain gauges if they are below the 100 kHz minimum frequency.

2.2 MOTIVATION

Experimentally, it has been shown that material properties such as yield stress and ultimate strength differ when loads are applied quasi-statically rather than dynamically. SHPB, also known as Kolsky Bars, are used characterize said properties of materials at high strain rates (dynamic loading); in the order of $10^2$–$10^4$ in/in/s. These high strain rates are typically found in impacts relating to dropping of personal electronic devices, sporting equipment, car accidents, and armed forces protective equipment. AFRL Munitions Directorate’s primary interest in presenting this project to FIU senior design team last year, was to implement the use of air bearings to reduce friction in the input and output bar. The air bearings replaced the linear bearings generally used in SHPB. However, the striking system currently in operation is primarily driven by gravity, which does not comply with the one dimensional stress wave criteria required. Aside from this the current striking system creates inconsistencies in the striking speed and force with which the striker bar is set into motion. Moreover, the diagnostics system was not appropriate to observe the characteristic square waves from the stress-strain diagram. Therefore, the goal of this design is to implement a compressed gas striking system and improve diagnostics in the existing SHPB.

2.3 LITERATURE SURVEY

2.3.1 SPLIT HOPKINSON PRESSURE BAR

The Split Hopkinson Pressure Bar is a device used for characterizing material properties submitted to dynamic loading, producing high stress and strain waves. John Hopkinson, in 1872, studied-for the first time-the behavior of iron wires by performing stress wave experiments. (Hopkinson, 1872; Chen, W. W., & Song, B, 2011). His work consisted of having an iron wire
fixed at one end and the free end loaded with a sudden impulse of a mass. After his experiments, the results yielded the strengthening of iron wires being used under different loading conditions. One of the most important findings of John Hopkinson was “the fixed point of a wire will break only with half the speed that it will take the wire to break at the point where the mass is loaded” (Hopkinson, 1872). His son, Bertram Hopkinson, continued experiments in the same field. Bertram was the first person to use a bar to measure an impulse wave generated by materials upon impact (Chen, W. W., & Song, B, 2011). After years of study, he came to the conclusion that the most important factor in the failure of materials was the velocity of impact. All of these experiments were conducted in 1914, and his observations were only qualitative. In his experiments, Bertram used a pendulum integrated with pencil and paper to record the movements of the rods as the pendulum would impact the target as seen in Figure1.

On the other hand, Davies, in 1948 led the study of a different technique; he used parallel plates and cylindrical microphones to electrically measure the propagation of those waves. Davies also discussed the propagation and dispersion of waves when they are traveling in long rods. Shown Figure 2 is Davies’ principle contribution to improving the HPB mechanism.
Davies made several other contributions that can be denoted as follows: he discovered that HPB could not accurately measure rapidly applied pressures—in the µs scales; the time it would take to create a pressure wave when an instantaneous force is applied, the wave will reach a constant value, that in the end, is related to Poisson’s ratio; while his final contribution was the determination of the length-radius relationship of the bar.

![Diagram of Davie's New Improved Design OF SHPB](Chen, 2010)

At the same time as Davies, a modification of this idea was done by Kolsky in 1949 (Chen, W. W., & Song, B, 2011). He introduced the concept of having two bars in order to study the dynamic behavior and the relationship of the stress-strain for different materials, and one dimensional wave propagations. Kolsky presented a complete experimental procedure for operating the SHPB. After the technique of using a SHPB to study the dynamic behavior of materials was introduced, it became widely used to test materials at high stress and strain (B.A. Gama, 2004) (R.L. Sierakowski, 1997). Kolsky held experiments using materials such as rubber,
copper, polythene and lead with a HPB. The so-called SHPB was introduced by Kolsky in his publication and it was known as the “Kolsky Bar” (kolsky, 1949).

![Figure 3: Typical Split Hopkinson Bar Configuration (Chen, W. W., & Song, B, 2011)](image)

In modern times, the SHPB does not use a parallel plate condenser; it uses strain gauges that are attached to the input bar and output bars. Those strain gauges are generally placed atop the center of the bars, and both of the bars are equal in length so it helps in the accuracy of the data collection. The stain gauges send electrical signals to a high speed data acquisition system called an oscilloscope. These types of experiments are also recorded with high speed cameras so an additional visual analysis can be applied for a more complete interpretation of the deformation process.

The time loading, $T$, produced in a SHPB is related to the length, $L$, of the striker bar as shown below.

$$T = \frac{2L}{C_{st}}$$

Where $C_{st}$ is the one-dimensional wave speed in the bar.
When the striker bar is the same material as the incident bar, the stress amplitude is directly affected by the striker bar’s velocity as shown in the formula below.

\[ \sigma_1 = \frac{1}{2} \rho_B C_B V_{st} \]

Where \( \rho_B \) is the density of the bar, and \( C_B \) the one-dimensional wave speed.

Or

\[ \varepsilon_1 = \frac{1}{2} \frac{V_{st}}{C_B} \]

If we assume that stress waves propagate in the incident bar and the striker bar without dispersion, the pulses generated by those waves can be recorded by the strain gauges, and will result in the following formulas:

\[ V_1 = C_B (\varepsilon_i - \varepsilon_r) \]

\[ V_2 = C_B \varepsilon_t \]

Where subscripts \( i, r \) and \( t \) represent the final pulse for the incident, reflected and transmitted bars, respectively. From the equations above, we can obtain the average engineering strain for the specimen by substituting them in the equation below:

\[ \varepsilon = \frac{v_1 - v_2}{L_s} = \frac{C_B}{L_s} (\varepsilon_i - \varepsilon_r - \varepsilon_t) \]

The equation above you can see that \( L \) is the length of the specimen. Therefore we can calculate the stresses at both ends of the specimen as shown below, where \( A_b \) and \( A_s \) are the cross sectional areas and \( E_b \) is the young modulus of the specimen.
\[ \sigma_1 = \frac{A_B}{A_S} E_B (\varepsilon_l + \varepsilon_r) \]

\[ \sigma_2 = \frac{A_B}{A_S} E_B \varepsilon_t \]

When the experiment sequence reaches the point of measuring the strain in the incident and transmitter bars, strain gauges are the most common devices to do so. Arranged in pairs, the strain gauges are placed on the bar surface, symmetrically across its diameter. The signals from the gauges are sent to the oscilloscope through a common electrical circuit called a Wheatstone bridge (W.). The voltage output from the Wheatstone bridge, in general, is of such a small magnitude—typically in the milli-volt order—that a signal amplifier is necessary to record such low voltage on the oscilloscope. The frequency response of all components in the data acquisition system must conform to the minimum of 100 kHz. Lower frequency responses in any of the components will result in distorted signals in the oscilloscope.

SHPB experiments generate stress waves upon impact of the bars. The stress wave originates in the incident bar in compression since it is impacted by the striker bar. That wave propagates through the incident bar until it reaches the interface of the incident bar and the specimen. The specimen has a limit of the amount of the wave it can absorb; upon reaching that transmission limit, the rest of the stress wave is reflected back into the incident bar as a tension wave. The transmitted wave in the specimen gets reflected back and forth due to wave impedance mismatch between the specimen and the bars. The reflections build up the stress level in the specimen and compress it. This stress wave interaction in the transmission/specimen interface builds the profile of the transmitted signal. Due to the thin specimen used, the stress wave propagation in the specimen is usually ignored by assuming equilibrated stress in the specimen (W.).
2.3.2 STRAIN GAUGES

Strain gauges are used to measure the strain history of the waves traveling through both of the bars-input and output. Strain gauges that have electrical resistance will be mounted on both bars. This is one of the most popular methods to obtain data due to their small size and ease of installation. Metallic strain gauges are made of fine wire or metallic foil. The area of the grid is always minimized in order to reduce the effect of shear and poison strain. These strange gauges are commercially available with nominal resistances in the range of 30 to 3000 ohms.

A very important parameter of strain gauges is the sensitivity to stain, which can be expressed quantitatively as the Gauge Factor. This is defined as shown below:

Figure 4: Typical Split Hopkinson Bar Output Voltage vs. Time [1]
Gauge Factors are typically assumed to be 2.

There are four types of setups for the strain gauges in order to obtain data. The two most common types of setups are the full bridge and the half bridge. For the purpose of this experiment, we are going to use is the full bridge setup. We are using a conditioner in order to stabilize the signal and also amplify the signal in order to obtain clean and accurate results. The way the strain gauge system works is by means of an excitation voltage running through the conditioner which will need to be regulated to balance the voltage through the Wheatstone bridge and bring it close to zero as much as possible. In this manner, we know that any voltage signal thereafter is due to the impact of the bars. The oscilloscope will receive the voltage output signal from the conditioner and give us the raw data.

This output voltage can also be calculated with the following formula:

\[ V_o = \left[ \frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2} \right] V_{EX} \]

In the data acquisition system, we will be retrieving the raw data as voltage vs. time; with this new voltage obtained, we will have to convert this raw data into something useful. The first step is to
calculate ratio of the voltage in order to simplify the final equation, so we will end up with the following formula:

\[ V_r = \frac{V_{o\,unstrained} - V_{o\,strained}}{V_{ex}} \]

Where \( V_0 \) stands for Voltage output

\( V_{ex} \) stands for the voltage excitement

This previous formula leads to the calculation of the final strain that is denoted with the formula shown below:

\[ \text{Strain} \quad \varepsilon = -\frac{V_r}{GF} \]

2.3.3 COMPRESSED GAS STRIKING MECHANISM

Our compressed gas striking mechanism is designed on the principal of a gas expanding isentropically and adiabatically from our capacitance reservoir into the barrel. Making these assumptions allows us to calculate the pressure, temperature, speed of the gas, density, etc. through our one-dimensional, hence constant area flow, using techniques developed in gas dynamics. The equations below give a ratio of the properties of the gas to the total properties in the capacitance reservoir with respect to the Mach number at that point in the flow field.

Nomenclature:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>Mach</td>
<td>( M )</td>
</tr>
<tr>
<td>Speed of sound</td>
<td>( a )</td>
</tr>
<tr>
<td>Gas constant</td>
<td>( R )</td>
</tr>
<tr>
<td>Specific heat ratio</td>
<td>( \gamma )</td>
</tr>
<tr>
<td>Velocity</td>
<td>( v )</td>
</tr>
<tr>
<td>Pressure</td>
<td>( p )</td>
</tr>
<tr>
<td>Temperature</td>
<td>( T )</td>
</tr>
<tr>
<td>Density</td>
<td>( \rho )</td>
</tr>
<tr>
<td>Area</td>
<td>( A )</td>
</tr>
<tr>
<td>Dynamic pressure</td>
<td>( q )</td>
</tr>
</tbody>
</table>
Mach Number:

\[(1) \quad M = \frac{v}{a}\]

Speed of Sound in Air:

\[(2) \quad a = \sqrt{\gamma \frac{p}{\rho}} = \sqrt{\gamma RT}\]

Pressure over Total Pressure:

\[(4) \quad \frac{p}{p_t} = \left( \frac{\rho}{\rho_t} \right)^\gamma = \left( \frac{T}{T_t} \right)^\frac{\gamma}{\gamma - 1}\]

Pressure over Total Pressure:

\[(6) \quad \frac{p}{p_t} = \left( 1 + \frac{\gamma - 1}{2} M^2 \right)^{\frac{-\gamma}{\gamma - 1}}\]

Temperature over Total Temperature

\[(7) \quad \frac{T}{T_t} = \left( 1 + \frac{\gamma - 1}{2} M^2 \right)^{-1}\]

Density over Total Density:

\[(8) \quad \frac{\rho}{\rho_t} = \left( 1 + \frac{\gamma - 1}{2} M^2 \right)^{\frac{-1}{\gamma - 1}}\]
3. DESIGN ALTERNATIVES

3.1 CONCEPTUAL DESIGN

In the selection of the striking system which we will design for the SHPB previously designed, different factors were taken into consideration. The previous team engineered a pendulum hammer driven by gravity. This system was found inadequate being that it introduced more dimensions than necessary in the propagation of the stress wave, and the striker bar did not have a constant velocity between shots. To overcome these factors, two different systems were taken into consideration; a cross-bow and a compressed gas mechanism. Of the preliminary concepts of energy storage, the crossbow design stored potential energy of a spring in the crossbows limbs. This energy would later be released and transmitted through the striker bar. The problem with using a spring to store the energy we need, would lie in the amount of energy called out in our requirements. Below, the general potential energy of a spring formula is given:

\[ PE_s = \frac{1}{2} Kx^2 \]

When calculating the potential energy of a spring, we multiply the K constant of a spring (K constants of springs are directly proportional to the amount of energy that can be stored in said spring) by the square of the displacement of the spring. In simple words, the potential energy of a spring lies in the K constant of the spring and the displacement it undergoes during...
the energy storage process. Our design requirements call for a very large amount of energy being stored (PE) and released, which leaves us with two variables to work with, K and X. Since X will be limited, the driving variable in this equation is the spring K constant. Upon formulating design principles, the conclusion was made that a cross-bow type system will have the same loss of force when hitting the striker bar due to losses in elasticity in the bow line. In order to achieve results with a one-dimensional stress wave through the SHPB and consistent impact force and speed, the striking system our team is designing is comprised of compressed gas stored in a pressure vessel. The potential energy of the compressed air will be rapidly released from the tank resulting in kinetic energy transferred to the striker bar. An air-actuated ball valve will be used to release the air from the tank in a controlled and consistent manner. A solenoid will direct the air through the valve as necessary by flipping a light switch fitted to it which allows an electric current to be passed through the solenoid, allowing the gas to flow from the tank. The valve is fully opened in 0.6 seconds. By replacing a regular valve with the air-actuated one, the system promotes less human error and having different shooting speeds between shots.

### 3.2 PROPOSED DESIGN

The striking system will consist of a compressed Nitrogen gas tank, a capacitance reservoir, air-actuated ball valve, steel barrel, and a striker bar. The diagnostic system will consist of strain gauges and an oscilloscope with a minimum frequency of 100 kHz.

For detailed information of individual components, refer to section 4.1, Major Components.
3.3 PROPOSED DESIGN, SECOND ITERATION

Upon researching our initial design, and performing the necessary engineering related calculations, we came to the conclusion that our design had to be revised yet again. We had also observed, through historical data, that the barrel diameter was too small to fit our needs. For a barrel slightly larger than our own, we observed a velocity calibration chart that indicated a flow through the barrel which was choked. This is a term widely used in the aerospace field, relating to gas dynamics, referring to how the mass flow rate of a gas through a nozzle, duct, etc. is capped when it reaches Mach 1 in the duct. In our case, we can assume the flow occurs so quickly that it is adiabatic, and we can assume our flow to be isentropic. Based on these assumptions, we can use the governing equations for the flow through a nozzle. Our flow is governed by the difference in our pressure inside the tank-p_t (total pressure)-and the back pressure, p, at an arbitrary point in our flow field, i.e. our barrel. Pressure flows from high to low, with the speed at which our gas may flow depending on the ratio between the back pressure and the total pressure. The compressibility of our fluid also determines how much mass we can flow through our barrel per second. Although the main factor governing our flow rate and speed of flow is pressure, once the flow reaches sonic conditions, we cannot pump anymore mass through our barrel–no matter how much we change the ratio of the back pressure to total pressure. The remedy to this problem
which we devised is to increase the diameter of the barrel to 1 inch, and add Delrin spacers to the striker bar to maintain the seal necessary to use gas as our energy source.

4. THEORETICAL ANALYSIS AND SIMULATIONS

4.1 ANALYTICAL ANALYSIS AND STRUCTURAL DESIGN

4.1.1 GENERAL GOALS

The SPHB is an experimental tool, most of the time longer than 15ft. This type of tool is very difficult to store because of its size, having said that, one will need more components such as air bearings and longer bars which will make the project very costly. Since our objective is to design the striking mechanism, this matter is also taken into consideration since the size of the striker can be long as well. That is one of the main constraints that we need to meet in this project by scaling it down. However the scaling is done very precisely in order to preserve the properties of the SHPB. All calculations will be done analytically as well as performed with computer drafting programs to run the appropriate simulations and verify the results.

4.1.2 SHPB COMPRESSED GAS STRIKER

As we have the information from the previous team that worked on the air bearing upgrade for this SHPB, it was analyzed and the modification to use air bearings was worthwhile. The team from previous year used a SHPB without air bearings and then they understood the properties they have to preserve in order to make the SHPB work under the same conditions (Danny Adames, 2012). After reading their report, we also understand all the properties that we have to preserve when changing from a hammer to compressed gas as a striking mechanism. This understanding made us aware of meaningful information that will help us preserve the principles for material testing and energy of the system during its use.

4.1.3 SHPB SCALING

In the analysis of SHPB for scaling, to get more information on the air bearing we referenced the report from the previous year (Danny Adames, 2012). For this redesigned striking mechanism, we need
to build a consistent way to impact the input bar to generate a one-dimensional stress wave. That is why we have chosen the compressed gas striking system to provide a clean and precise stress wave. The gun consists of a long barrel with porting holes in order to achieve a constant velocity of striker before hitting the input bar. The striker bar will leave the barrel with a pressure of 300 psi converting transmitting all of its kinetic energy to the input bar. This allows the system to have a very high impact velocity, transmitting the required force required to deform elastically copper.

4.1.4 NATURAL DEFLECTIONS

As we know, the SHPB experiment is considered to be one-dimensional; having said that, in theory, the bars must be perfectly aligned with each other, but in reality it is very hard to achieve that. Also, it is very hard to manufacture rods that are perfectly circular along the entire length of the bar. All of these constraints will no longer generate a one-dimensional wave which will change the data results slightly. A normal type of deflection that occurs on these bars is due to their own weight, but in this case that will be neglected for better analysis. Since that bar has already been designed and we will be using the same bar the dimensions have been already set as we can see the figure shown below.

![Figure 7: Transmitter bar and bearing location dimensions based on analytical calculations. Dimensions are in inches [8]](image)

The entire SHPB is supported on two supports; they are separated by 52.5 inches so we will have 15.75 inches to overhang the beam. The deflection of the beam was calculated by the previous year team
and it came to be located at the end of I beam and it is 0.000127 inches (Danny Adames, 2012). The figure below shows you a better idea of the setup of our SHPB.

**Figure 8: I-beam support spacing and dimensions based on calculations. Dimensions are in inches [8].**

4.1.5 Flow-Field Analysis

Using the equations from section 2.3.3 under the assumption the flow exiting the valve is adiabatic, and isentropic, the following values were obtained:

<table>
<thead>
<tr>
<th>after solenoid</th>
<th>in tank</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.719</td>
<td>in$^2$</td>
<td>pt</td>
<td>605.7373</td>
<td>psi</td>
</tr>
<tr>
<td>R</td>
<td>1.708</td>
<td>ftlb/(lbf·R)</td>
<td>Tt</td>
<td>549.12</td>
<td>°R</td>
</tr>
<tr>
<td>V</td>
<td>33.077</td>
<td>fps</td>
<td>pt</td>
<td>3.21798</td>
<td>lbm/ft$^3$</td>
</tr>
<tr>
<td>p</td>
<td>2.04</td>
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<tr>
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<td>fps</td>
<td>W$^*$</td>
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4.1.6 Wheatstone bridge

These types of circuit known as Wheatstone bridge are frequently used to determine the value of an unknown resistance to an electrical current. In a typical Wheatstone bridge, four resistors are located in a circuit designed in such a way that the current from power source splits, the current flows
through the sequence of resistors, and then it cancels out with the other negative current on the opposite side. There are three main ways to connect Wheatstone bridges: Quarter Bridge, Half Bridge and Full Bridge. On a Quarter Bridge a single active strain gauge element is mounted on the bar following the principal direction of axial or bending strain. For the half bridge configuration, two active strain gauges are mounted on the bar; one is mounted in the direction of axial strain, the other acts as a Poisson gauge and transverse to the principal axis of strain. Finally, on a Full bridge connection, which is the set up used in this experiment, four active strain gauges elements are connected. On one bar of the four gauges, two are parallel to each other on opposite sides of the bar and were aligned with an imaginary axis of the bar; the other two gauges are placed on opposite sides of the bar and were aligned 90 degrees to the first set of gauges.

Every time the striker bar hits in the incident bar the strain gauges installed on the incident and transmitted bar will measure the differential of voltage on running through the bar. The Wheatstone bridge converts the signal from the strain gauges, which is change in resistance so it reflects in changes of voltage, which we read through the oscilloscope, which is connected through the conditioner.

On our SHPB we decided to go with a Full Bridge setup in order to get more accurate readings. Our strain gauges are installed on a bar that has some noise, which means that our oscilloscope will be always reading noise. The change in voltage every time the bars are hit the change in voltage is minimal, and it can be easily confused with the noise, making it hard to reads. This is one of the main reasons we have chosen to install a strain gauge conditioner. Strain Gauge conditioners are devices that help with the completion of the Wheatstone bridge and also the amplification of the signal that goes into the oscilloscope. Another reason why a Full Bridge setup is better for our SHPB is because every time each strain gauge senses a change in voltage, it gets heat up. Any material that is heated increases the resistance, making a false reading of the change in voltage. When using four strain gauges, two of them
will compensate the temperatures changes and keep, a more precise reading even if heat is being present.

As mentioned before, the change in voltage that the strain gauges read is so minimal that is insignificant compare with the noise on the bars. That is where we need to incorporate the strain gauge conditioner. How a conditioner works it has an input voltage that is called excitation voltage. This excitation voltage is providing a constant voltage supply to the bridge. While there is no standard voltage level that is recognized industry wide, excitation voltage levels of around 3 and 10 V are recommended. While a higher excitation voltage generates a proportionately higher output voltage. The amplifier inside the conditioner amplifies that change in voltage to differentiate it from the existing noise.

4.1.7 Data Acquisition (Oscilloscope)

We chose for our design the Tektronix TDS2024C, 2GS/s Digital Storage Oscilloscope because it is a compact design and a very fast data acquisition system, needed for data recording for split Hopkinson pressure bars. The pulse length of our wave is calculated with the following formula.

\[ t_c = \frac{2L}{C} \]

Where:

\( t_c \) = pulse time length

\( L \) = length of striker bar (ft.)

\( C \) = Sound speed in steel
By doing this calculation based on the specifications for our set up we can calculate that our pulse is given by:

\[ L = 0.8 \text{ ft.} \]

\[ C = 20000 \text{ ft/sec} \]

\[ t_c = \frac{2 \times 0.8}{20,000} \]

\[ t_c = 8.0 \times 10^{-6} \text{ sec} \]

After calculating the pulse length we must set our oscilloscope on the time region of 80 micro seconds to 100 micro seconds so the actual wave can be seen on that range. The oscilloscope is capable of recording 2,500 data points per second. Knowing that amount of data points we need to set up our time period to be within the window of microseconds so we can record as many data points per each pulse wave. After doing the above calculations we know that for time increment of 2 microseconds the oscilloscope will record 25 data points, if the increment is 1 microsecond we will achieve 50 data points per pulse, if time increment is 0.5 microseconds it will record 100 data points for each pulse.

### 4.1.8 Data Analysis

The following procedures will describe the data analysis used to interpret wave profile signals from the Split Hopkinson Pressure Bar (SHPB) and convert these signals into stress versus strain data sets. While the data reduction technique itself is general to any configuration of a SHPB, the specific considerations for this analysis will reflect the design and physical assembly of the SHPB located Florida International University, Engineering Center.
4.1.8.1 Overview of the Analysis

As seen on the image below the wave profiles for the reflected and transmitted signals in a SHPB, these data consist of several wave reflections, but we are only interested on the first reflected wave that is on the incident bar (Red Line), and also on the signal from the transmitter bar (blue line), see below figure 1.

![Wave profiles from a SHPB experiment on Al-6061-T6 (R.L. Sierakowski, 1997)](image)

The oscilloscope will provide the wave forms data in an excel spreadsheet. These data will be manipulated to create the specimen true strain and true stress. Some of the required parameters such as geometries and material constants are given in a table below. Note that all dimensions are given in English units. It is predicted that given the initial raw data, the formulas below with the table of data would allow for the deduction of the SHPB into a true stress versus true strain curve. In the Excel spreadsheet it should be the data points for the two wave profiles (incident and transmitter bar) from
the strain gauges mounted on each bar. The data points where the first reflected and first transmitted wave starts are the data points to actually use in the analysis. Note that the voltages will have different signs, the reflected signal on the incident bar will be positive, the transmitted signal is negative.
Table 2: Parameters used for Analysis of the SHPB

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<th>Value</th>
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<td>Gauge Factor</td>
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<td>$GF$</td>
<td>no units</td>
</tr>
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</table>

4.1.8.2 Preliminaries

The SHPB analyzed in this report has a 0.501 inch diameter for all three bars (Striker, Incident, and Transmitter). The strain gauges are mounted at the same distance from the specimen, so the pulsation will get to the two strain gauges locations simultaneously. In the case they are not mounted at the same distance, the analysis will be the same but the time of comparison will be shifted by when the, i.e., the first wave and its time, will not be the same for the wave on the transmitted pulse. In the data file provided the specimen was made from Al-6061-T6. The specimen geometry was 0.2 inch in length and 0.2 inch in diameter.

4.1.8.3 Strain Gauge Analysis

Strain gauges have been installed on the bars using a Wheatstone bridge configuration to obtain time and voltage data. In this SHPB, the incident bar has 4 strain gauges and the transmitter bar has 4 strain gauges. On one bar of the four gauges, two are parallel to each other on opposite sides of the bar
and were aligned with an imaginary axis of the bar; the other two gauges are placed on opposite sides of the bar and were aligned 90 degrees to the first set of gauges. All four are wired into a strain gauge conditioner as a full Wheatstone bridge circuit that counts compensation for bending loads. With this configuration the following formulas are used to convert voltage into strain.

\[ \varepsilon = \frac{2V_{out}}{GF(1+\nu) V_{excitation}} \]  

(1)

Where:

\( \varepsilon \) = Strain on the Bar (Incident/Transmitted)

\( V_{out} \) = Output voltage from the Wheatstone bridge

\( GF \) = Gauge Factor

\( \nu \) = Poisson’s ratio (Bar Material)

\( V_{excitation} \) = Excitation Voltage

4.1.8.4 Strain Analysis

The local displacements at the specimen/bar interfaces can be analyzed to give the following relationship

\[ \dot{\varepsilon} = \frac{2 C_b \varepsilon_r}{L_s} \]  

(2)

Where:

\( \dot{\varepsilon} \) = Sample Strain Rate
C_b = Sound Speed in the Bar

\( \varepsilon_r = \text{Reflected Strain in the Incident Bar} \)

L_s = Length of the Specimen

If equation number 2 is integrated, we can derive, \( e_s \), which is the engineering strain in the sample.

\[
e_s = \int de = \frac{2C_b}{L_s} \int \varepsilon_r \, dt
\]  \hspace{1cm} (3)

Using trapezoidal rule we can get an approximating of the integral in Equation 3.

Finally, the true strain, or natural strain is the value needed so the strain on the previous equation must be changed to obtain True Strain as seen below:

\[
\varepsilon_s = \ln(1 + e_s)
\]  \hspace{1cm} (4)

Where:

\( \varepsilon_s = \text{Specimen True Strain} \)

Ln = Natural Logarithm

Knowing that tension is positive and compression is negative, the sign of the engineering strain will take care of itself in Equation 4. (Please note regarding sign the true stress and true strain quantities in compression would both be negative terms, but in order to plot these in the 1st quadrant of a graph each term will be multiplied by negative 1.)

4.1.8.5 Stress Analysis

The stress in the specimen will obtained from the following formula:
\[ \sigma = \frac{A_B E \varepsilon_t}{A_S} \]  \hspace{1cm} (5)

Where:

- \( \sigma \) = True Stress
- \( A_B \) = Area of the Bar
- \( A_S \) = Instantaneous Area of the Specimen (\( A_S = f(t) \))
- \( E \) = Young’s Modulus of the Bars

Solving the true stress in Equation 5 is a simple calculation. The \( A_S \) is the parameter that is not simple and straightforward to calculate since it is changing as a function of time, and must be described with variables that are already known. A correlation between the initial geometry and the current geometry can be calculated assuming constant volume and gives:

\[ A_0 l_0 = A l \]  \hspace{1cm} (6)

Where:

- \( A_0 \) = Initial Area of Cylindrical Specimen
- \( l_0 \) = Initial length of Cylindrical Specimen
- \( A \) = Current Area
- \( l \) = Current Length

Leaving \( A \) alone we obtain:
\[ A = \frac{A_0 l_0}{l} \]  \hspace{1cm} (7)

\( l_0 \) is related to \( l \) by

\[ l = l_0 + \Delta l \]  \hspace{1cm} (8)

If dividing both sides of Equation 8 by \( l_0 \) becomes

\[ \frac{l}{l_0} = 1 + \frac{\Delta l}{l_0} = 1 + \varepsilon_s \]  \hspace{1cm} (9)

Equation 9 can be used to replace the lengths in Equation 6 with the specimen engineering strain that is known and the equation will become:

\[ \frac{A_0}{1+\varepsilon_s} = A_s \]  \hspace{1cm} (10)

Now combining Equations 5 and 10 will obtain

\[ \sigma = \frac{A R E \varepsilon_t}{A_o} (1 + \varepsilon_s) \]  \hspace{1cm} (11)

The stress versus strain plot can now be generated plotting the results of Equation 11 in the y axis and the results of Equation 4 will be the x-axis, see Figure 2. Please note that the final values of, \( \sigma \) and \( \varepsilon_s \), need to be positive in order to plot in the first quadrant.
5. PROTOTYPE OVERVIEW AND FABRICATION

5.1 MAJOR COMPONENTS

5.1.1 STRESS GENERATING SYSTEM

The stress generating system of our compressed gas striking system includes a main supply nitrogen tank, a capacitance reservoir, an air-actuated ball valve, barrel, and striker bar – most of which are depicted in figure 5. This striking system is also a major part of the overall hoppy bar, whose major components consist of the incident bar, transmitter bar and momentum catch.

The compressed Nitrogen will be employed due to the low weight requirement for the gas being used. Once released, the gas must expand quickly to set the striker bar in motion. Other options for the expanding gas are air and carbon dioxide (CO$_2$).
The reason for having the capacitance reservoir is that we must have a quantifiable and consistent amount of gas being disbursed during subsequent iterations of experiment shots. The reservoir will be rated at 600 psi. Although the static pressure is 600 psi, the output pressure setting the striker bar in motion will be approximately 320 psi. The holding reservoir will be a 2 gallon tank with 5 outlet fittings allowing the tank to be filled, have a relief valve, pressure gauge, and air outlet simultaneously.

The launch barrel material used is comprised of 316 stainless steel so it will withstand the pressure of the expanding gas impacting the striker bar. The barrel has a 1 inch diameter and a wall thickness of 0.25 inches. Porting holes will be drilled 18 inches from the breech side to allow the expanded gas to vent to the atmosphere. Prior to venting, the gases accelerate the striker to its final velocity. Subsequent to the venting of the expanding gases, the striker bar is traveling at a constant velocity. Velocity measurements are made prior to impacting the incident bar using two remote optical sensors at a set distance from each other plugged into a tachometer. The barrel will be held in place with barrel mounts machined from aluminum which are clamped to the I-beam.

The striker bar is adopted from last year’s senior design team, although certain modifications will have to be made to tailor it to our design objectives. It is a hardened steel bar, 0.5 inches in diameter and 10 inches in length. The necessary modifications to this bar are the two delrin spacers added to be able to increase the barrel diameter.

The impact of the striker and the incident bar must occur on a plane normal to the direction of stress propagation to maintain wave propagation that is one dimensional. The stress wave initiated by the striker bar travels across the incident bar until it reaches the incident bar/specimen interface, in which the part of the wave not transmitted to the specimen is reflected back into the incident bar. Since the initial
stress wave propagated through the bar in tension, the stress wave which is reflected propagates through the bar in compression; this is due to Newton’s third law, which states that every action must have an equal and opposite reaction. The specimen is thus compressed in between the incident and transmitter bar.

5.1.2 STRESS DETERMINING SYSTEM

This system is the other major component in the SHPB. It is made up of strain gauges, strain gauge conditioners and an oscilloscope.

The strain gauges read the stress waves initiated and reflected through the incident bar, the specimen, and the transmission bar. The voltage read from the strain gauges is typically so low that voltage amplifiers are needed to raise the signal amplitude seen by the oscilloscope.
Strain Gauge Conditioners are low cost solutions for strain measurements needs. The conditioners are integrated circuit boards that amplify and complete the Wheatstone bridge configuration, which is the typical configuration for strain gauges readings. The conditioners can work in several different configurations, such as quarter bridge, half bridge and full bridge as seen in the following figure (Gray, 2002).

![Figure 12: Display of 3 possible set ups by strain gauges. (Gray, 2002)](image)

Strain gauge conditioners can also amplify the gain which can be controlled manually or by programing via standard protocol inside the unit. (See appendix B for references). Another advantage that this unit has it that it can be directly connected to the analog LabVIEW DAQ or the oscilloscope. The main applications of signal conditioners are for strain gauge measurement, and load cells.
Figure 13: Strain Gauges Set up with Oscilloscope

Figure 14: Strain gauge conditioner set up in Quarter Bridge
In order to confirm our calculated speed of the striker bar, we drilled two holes four inches apart at the muzzle end of the barrel, and setup two remote optical sensors attached to a tachometer. The sensors have L.E.D.’s which get reflected back through reflected tape thus giving a constant voltage. The tachometer will be set in the single capture mode, so when the striker bar passes the set of sensors, it cuts off the signal being reflected in turn changing the voltage seen by the sensors. The speed of the striker bar is calculated by setting the distance between each L.E.D. sensor in the tachometer and thus the device can internally determine the speed by dividing the distance over the time between the two changes in voltage from the sensors.

Having this tachometer in the striking system will verify the analysis of our calculations and, assure the theoretical speed will match the actual speed required to deform different types of specimen.

![ACT 3X Tachometer and LED sensors](image)

**Figure 15: ACT 3X Tachometer and LED sensors**

### 5.2 STRUCTURAL DESIGN

The main gas supply tank is an industrial size 292 cubic foot tank. This gas supply is fed through a high pressure hose which fills the auxiliary reservoir while the valve is closed. The reservoir is fitted with a ball valve which allows the compressed gas to expand through the barrel. Along the barrel, at a given distance from the rear-or “breech” end-when the striker bar has reached the velocity required to
produce the desired strain in the specimen, the expanded gases will be vented from the barrel through an array of equidistant drilled holes. This is done to allow the striker bar to reach a constant velocity before it impacts the incident bar. Furthermore, the inside diameter of the barrel is slightly greater than the striker bar; this assists in the reduction of losses in potential energy of the gas. The striker bar will also be fitted with bearings or metallic O-rings which will also serve to hinder the escape of gas. The thickness of the barrel will be approximately an inch to account for mechanical stability which provides a straighter surface for the striker bar to travel.

5.3 PROTOTYPE SYSTEM DESCRIPTION AND PLANNED TESTS

The prototype shall be made to half scale of the actual system, using a lower tolerance to ensure a low cost model of the conceptual design. By having a scaled down model of the system we will be able make adjustments to any clearance, fabrication, etc. issues we may foresee in the fabrication of the actual system. The prototype shall be made of lower grade material, and shall not include any of our actual full-scale system components. This will further reduce the cost of the prototype, which is a requirement we developed being that the prototype will serve as a reference for providing fit and safety checks as well as fabrication assistance.

While the actual system will consist of precision instruments including, air bearings, oscilloscopes, strain gauges, etc., the prototype will include reference markers in their place. Reference markers will allow us make adjustments to positioning for any high precision instrument, saving us time when working on the actual system. What we will be maintaining in our prototype to ensure its accuracy is proportion to the actual system. This part of the prototype system is crucial in order to produce a viable prototype; we will achieve this proportion by setting the scale to one half of the actual system. For example, our conceptual system calls for a 60-inch steel barrel. Our prototype’s barrel will include a 30-inch PVC pipe for the barrels substitution. The choice of PVC lies in few major factors; fit, form, and
function. The PVC allows us to represent the barrel to the correct scaled dimension, while maintaining its function as a prototype.

Our prototype, though made of different materials, will still be required to hold pressure. We will be listing this as a requirement to further increase the prototypes accuracy in regards to the original model. While holding pressure much lower than actual testing pressure, the prototype will allow our team to practice proper safety procedures while operating pressurizes vessels. This detail is critical to ensure a safe working environment for testing under high pressure loading.

5.4 PROTOTYPE PARTS AND FINITE ELEMENT ANALYSIS
Figure 16: Exploded View

Figure 17: Section External View of Main Components
Figure 18: Air Bearings and Incident Bar

Figure 19: Striker and Barrel view
Figure 20: Rear end

Figure 21: Outlined perspective
Figure 22: Barrel Support

Figure 23: Sawhorses
Figure 24: Exhausts holes for Compressed Gas

Figure 25: Compressed gas tank
Figure 28: SHPB System
Figure 30: Isometric View of Final Components of Design

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<tr>
<td>11</td>
<td>Socket Head Cap Screw Al</td>
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</table>
Figure 31: Back View of Gas Gun Set Up
Figure 32: Striker bar Assembly
The above image displays the exhaust holes at the end of the barrel; the reason for having this in the design is to help the gases to be released from the system. This will help the striking bar to achieve a constant velocity ending with a steady velocity that will give consistency for our design.

Figure 33: SolidWorks static analysis of transmitter bar deflection under gravity for 0.25 in mesh size (Danny Adames, 2012) Shown

Figure 34: SolidWorks static analysis of transmitter bar deflection under gravity for 0.125 in mesh size. Shown with a deformation scale factor of 3000 (Danny Adames, 2012)
Figure 35: Stress created by force applied to 3 bars

Figure 36: Strain of Incident Bar
Figure 37: Final displacement of input bar

Figure 38: First deformation created by von Misses analysis
Figure 39: Second von Misses analysis with Smaller applied force will cause less deformation.

Figure 40: Displacement of the striker and incident bar
Figure 41: Striker bar shows large amount of stress due to high friction with barrel

Figure 42: Linear dynamic Displacement
On these pictures we can appreciate some simulations made on SolidWorks. These simulations are made only with four components consisting of the striker bar, incident bar, the specimen and transmitted bar. Simulations were based on a force of 4500 N. applied to the striker bar, creating a one dimensional lineal motion. All of our simulations show that all the bars can resist the applied forced. The striker bar is the one that shows more stress. As you can see on figure 25 and 26 the striker bar has some red color on the bottom, which means the bar is suffering stress on that part.
For the Von Misses analysis, the bar look that is bended, but the actual resultant numbers and the color of the analysis show that bar with resist the impact without braking or bending. The URES analysis, as shown in figure 23 and 24, shows the displacements the bars are making. Since, the design used for the simulation does not have a wall at the end of the bars, it will make the transmitted bar not to stop, so it shows a larger displacement. We did not add this wall to our design because our main concern is prove that our bar will resist the impact without deforming plastically and, also to see how different specimens will affect the forces applied to the bars.

We decided to make this simulation with only the components needed not including the rest of components because SolidWorks takes a large amount of time to run the simulation if more components are added.

5.5 STRAIN GAUGE INSTALLATION

In order to install strain gauges properly, the following items are needed.

- Acetone
- Gauze sponges
- 150 C Sand paper
- 400 C Sand paper
- Glass plate
- Tweezers
- KFG-5-120-C1-11L1M2R Pre-Wired Strain Gauges
- Scotch tape
- Loctite 401 Instant Adhesive
- Clean protective plastic film
- Black electric tape
Prior to performing the installation, the surface of the incident bar and transmitter bar needs to be properly prepared for bonding, at the area where the strain gauges will be installed. Be sure to check the expiration date on the adhesive.

Hands should be washed before proceeding to clean the surfaces. The first steep is to clean the bar with acetone using the gauze sponges, making sure that all the grease is removed. With 150C sand paper, sand the area where the strain gauges will be installed, following sand the bar with the 400 C sand paper. This will leave the surface clean and will remove all the particles that can interfere on the readings. The last steep of the cleaning stage is to clean another time the bar with acetone using the gauze sponges. To prevent contamination always use clean gauze sponges.

Using the tweezers carefully remove the strain gauges from the packing, the bottom surface of the strain gauge should never touch any dirty surface, this will contaminate it, and we result on transmitting wrong signals. Grabbing the gauge from one corner without touching the grid area place it on the clean plastic film with the bounding side down, when properly oriented connected the cables should be on the top of the strain gauge. Use a 3 inches peace of scotch tape to transfer the gauge to the bar. Place the tape on top of the gauge making sure that its complete surface area is being covered by the tape. Wipe trough with the side of your thumb to allow contact. Separate the tape from the plastic film by lifting the tape at a shallow angle making sure that the strain gauge stays attached to the tape. Carefully position the gauge on top of the bar at the area where that sanding was applied. Remove and re-position the tape at a perfect angle if needed. The strain gauge should be positioned parallel to the bar. Lift the tape at a shallow angle to expose the bonding side of the gauge and an additional ¼ inch. Next apply the adhesive by placing a drop right beside the tape. Align the gauge tape assembly over the bar, wipe the tape in order to spread the adhesive all over the gauge. Applied immediate firm thumb pressure for one minute. After waiting another two
minutes remove the tape very carefully make sure that the strain gauge stays glued to the bar. Cover the strain gauges with black electric tape.
6. PROJECT MANAGEMENT AND COST ANALYSIS

6.1 TIMELINE

Below is a Gantt chart that illustrates the major task to be performed during fall and spring semesters. The times below are just an estimated time frame for completing all tasks and they may change along the semester.
Figure 48: Time Line Gantt chart
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<td>Alejandro Infante</td>
<td>Prototype System Description</td>
<td>3</td>
<td>Prototype Cost Analysis</td>
<td>3</td>
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<td></td>
<td>Literature survey (Striking Mechanism)</td>
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<td>Plan for Tests on Prototype</td>
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<td>Structure Design</td>
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<td>Structure Implementation</td>
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<td>Strain Gauge Installation</td>
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</table>

**total hours** | **92.5**
6.2 PROTOTYPE COST ANALYSIS

Our initial system concept consists of a main supply tank that supports up to 292 cubic feet of compress air connected with ¾ pipes outlets, from this tank we will be receiving all the air that feeds the system, this tank comes with a valve that let us control when we want the air released in order to fill out a reservoir with compress air. We chose this type of tanks because it is the best way to obtain compress air for the lowest price.

The reservoir is the tank where we will be collecting the compressed air from the main supply tank. The reservoir will hold the air until a bottom on the solenoid is pressed. For this tank our team chose a Pure Energy N2 Tank that holds up to 68ci at 3000 psi. This tank was chosen because for its size is the one that holds the most cubic inches, since most of the tanks in the market only holds 32 ci. This reservoir will be connected through a T ¾ pipe DURA 4 in. Schedule 40 PVC Tee SxSxFPT.

In order to shoot the same amount of air into the striking bar after the reservoir a solenoid will be connected. After researching different types we selected an Alcon - 04EZ003A1-1ECA - Solenoid Valve, 2 Way, NC, Delrin, 3/4 in. this solenoid can open the valve as fast as 38 millisecond. Every time the button is pushed.

All this components will be attached one from the each other with a ¾ pipe Thick-Wall (Schedule 80) Dark Gray PVC Threaded Pipe Nipples 4” 3/4 Pipe Size.

The striker bar will be inside of the last ¾ pipe waiting for air to be released to be shoot through the apparatus.
## Table 4: Final Design Cost Analysis

<table>
<thead>
<tr>
<th>Item #</th>
<th>Part Name</th>
<th>Vendor</th>
<th>Description</th>
<th>Part Nbr.</th>
<th>Unit Price</th>
<th>Qty.</th>
<th>Total Price</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Ball Valve &amp; Actuator</td>
<td>McMaster-Carr</td>
<td>High-Pressure Air-Driven 316SS Ball Valve Air-to-Open/Air-to-Close, 1&quot; NPT Fem, Direct Mount</td>
<td>7554T26</td>
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<td>2</td>
<td>Striker Barrel</td>
<td>McMaster-Carr</td>
<td>Thick-Wall Stainless Steel Threaded Pipe Nipples and Pipe</td>
<td>48395k96</td>
<td>$236.55</td>
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<td>3</td>
<td>Accessory Hoses</td>
<td>McMaster-Carr</td>
<td>Air and Water Hose W/Brass Male Both Ends, 1/4&quot; ID, 200 PSI (3ft Hose)</td>
<td>5304K82</td>
<td>$12.70</td>
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<td>$25.40</td>
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<tr>
<td>4</td>
<td>Accessory Hoses</td>
<td>McMaster-Carr</td>
<td>Air and Water Hose W/Brass Male Both Ends, 1/4&quot; ID, 200 PSI (10ft Hose)</td>
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<td>Three-Way Aluminum Manifold</td>
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<td>7</td>
<td>Quick Disconnect (Air Bearing)</td>
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<td>Industrial-Shape Hose Coupling Sleeve-Lock Sckt Brass, 1/4&quot; NPTF Fem, 1/4 Cplg</td>
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<td>Total Price</td>
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<td>Multipurpose Gauge Steel Case, Dual 2-1/2&quot; Dial, 1/4 Bottom Conn</td>
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<td>Tank Bushing Adapter</td>
<td>McMaster-Carr</td>
<td>Type 304 Stainless STL Threaded Pipe Fitting 3/4 Male X 1/4 Fem, Hex Reducing Bushing, 3000 PSI</td>
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<td>McMaster-Carr</td>
<td>Steel Regular Duty C-Clamp 4&quot; Max - 0&quot; min Opening, 4100# Holding Capacity</td>
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<td>$299.04</td>
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<td>11</td>
<td>High Pressure Quick Release (Sleeve)</td>
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<td>Multipurpose Aluminum (Alloy 6061) 1&quot; Thick X 3&quot; Width X 3' Length</td>
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<td>Iron Shims</td>
<td>McMaster-Carr</td>
<td>Iron Leveling Shim 5/16&quot; Screw Size, 3/8&quot; Hole Diameter, 1&quot; Square, Packs of 25</td>
<td>91151A030</td>
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<td>High Pressure Gauge (0-1000)</td>
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<td>Stainless Steel-Case Gauge 4&quot; Dial, 1/4 NPT Male Bottom, 0-1000 PSI</td>
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<td>Copper Samples</td>
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<td>ultra Conductive Copper (Alloy 101) Rod, 1/4&quot; Diameter, 3' Length</td>
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<td>Nylon Spacer</td>
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<td>Wear-Resistant Nylon Sheet 1/2&quot; Thick, 12&quot; X 12&quot;</td>
<td>8539K18</td>
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<td>L-Brackets</td>
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<td>Steel Bracket Corner, Galv, 1-59/64&quot;, 3-1/2&quot; L of Sides, 2-3/8&quot; W</td>
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<td>Strain Gauges</td>
<td>Omega</td>
<td>Package of 10, pre-wired strain gages, 5 mm grid, 120 ohms, matched to steel</td>
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<td>Super Steel Sawhorse Legs</td>
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<td>Relief Valve</td>
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<td>SS High-Pressure Proportional Relief Valve, 1/4 in. MNPT x 1/4 in. FNPT, Manual Override Handle</td>
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<td>Tacuna</td>
<td>Strain Gage Adhesive</td>
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<td>FHQ</td>
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<td>Tachometer</td>
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<td>31</td>
<td>Hose to tank inlet adapter</td>
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<td>$370.36</td>
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<td>External Retaining Rings</td>
<td>McMaster-Carr</td>
<td>Cadmium-Plated Steel MIL Spec Retaining Ring External, for .5&quot; Shaft Dia</td>
<td>96363A553</td>
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<td>Delrin Spacers</td>
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<td>36</td>
<td>Connecting Pipe</td>
<td>McMaster-Carr</td>
<td>Thick-Wall 304/304L SS Threaded Pipe Nipple 1 Pipe Size X 2&quot; Length</td>
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<td>Regulator Bushing</td>
<td>Airgas</td>
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<td>38</td>
<td>Purge Regulator</td>
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<td>Radnor® Model TPR250-500-580</td>
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<tr>
<td>39</td>
<td>High Pressure Hose (Nitro tank to Reservoir)</td>
<td>Airgas</td>
<td>Western® 6' 1/4&quot; NPT Female X 1/4&quot; NPT Female 304 Stainless Steel Braid Flexible Pigtail</td>
<td>WESP-4-72</td>
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<td>Nitrogen Tank</td>
<td>Airgas</td>
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</table>

Total: $3,235.87

7. CONCLUSIONS

Upon collaborating with Dr. House of the Air Force Research Laboratory to obtain a clear picture of what was expected and researching scholarly sources, a compressed gas striking system was engineered. This striking system encompasses the expectations of the client, AFRL, and the Industrial Advisory Board. The systems expectations were to be integrated to the existing hoppy bar, produce a consistent striking velocity, and upgrade the diagnostics equipment utilized.

The newly upgraded hoppy bar produces a consistent and reproducible striker bar velocity up to 120 fps which furnishes strain rates up to 104 in./in/sec. The diagnostic system implemented upgraded the frequency response of all the components to 100 kHz. This minimum frequency required to interpret the data clearly without any distortion in the oscilloscope recordings is driven by the loading duration in the specimen. Unknowingly, the previous design team had problems viewing the characteristic square strain waves due to the low frequency response of the data acquisition system.

In conclusion, the crossbow-type striker demonstrated excessive losses in striking force, leading to inconsistent striker bar velocities, which would have resulted in inconsistent data. Therefore, the compressed gas striking system proved to be the most reliable conceptual system.
8. REFERENCES


(Benson, 2008)
9. Appendices:

9.1 Appendix A: Hand Calculations

9.2 Appendix B: Strain Gauge conditioner Reference Manual
Embedded Strain Gauge and Load Cell Signal Conditioner/Amplifier

1 DESCRIPTION

The embedded strain gauge signal conditioner board is a low cost solution to your strain measurement needs. This miniaturized board accepts or completes a single Wheatstone bridge arranged in quarter, half, or full bridge configuration. In full bridge mode, it can also accept a standard load cell. Gain and offset adjustment can be controlled manually or programmably via standard SPI protocol. Easily interface with your microprocessor or ADC for reliable and low cost measurement of strain signals or any other application that requires a differential amplifier. Additionally, this board can be interfaced directly with any analog LabVIEW DAQ or other data acquisition system.

2 APPLICATIONS

- Strain gauge measurement
- Load cell measurement
- Bridge sensor amplifier
- Thermistor measurement
- General differential amplifier

3 FEATURES

- Optional 6 V - 16 V or 5 V only power supply options
- 5 V Bridge excitation
- Flexible on-board bridge completion resistor options (sold separately)
  - Through hole
  - Surface mount (0805 package)
  - Prototyping DIP socket (plug-gable)
- Precision gain (0.1% tolerance)
- Manual or programmable gain: 110, 220, 550, 1100, 2200, 5500, 11000
- Gain can be customized at time of order 1/11 to 2 times gain range above
- Manual or programmable calibration offset
  - Manual: Potentiometer controlled
  - SPI controlled
- Noise elimination filters
  - Factory default low-pass: -3 dB at 180 Hz
  - Factory adjustable, per request
- Small profile (1.3” x 3.3”)

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4 AVAILABLE OPTIONS

The EMBSGB can be configured with several options including manual or serial control as well as different style terminal blocks for the input and output signal headers. Please refer to the table below to determine the available configurations.

<table>
<thead>
<tr>
<th>Model #</th>
<th>Gain Control</th>
<th>Offset Control</th>
<th>Connectors</th>
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<td></td>
<td>Manual</td>
<td>SPI</td>
<td>Manual</td>
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<tr>
<td>EMBSGB-M</td>
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<td>X</td>
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<td>EMBSGB-S</td>
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<tr>
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<tr>
<td>EMBSGB-SO</td>
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<td></td>
<td>X</td>
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</table>

- (*) Standard versions feature pluggable terminal blocks on both ends of the amplifier. This version is shown above.
- (*) OEM versions feature unsoldered header pins to be configured by the user.
- Overall amplifier gain can be modified to users specifications (contact Tacuna Systems). Gain can be scaled 1/11(0.0909)-2 times the gain specified in the description or in Section 9.1.

5 ELECTRICAL SPECIFICATIONS

The input and output electrical specifications for the EMBSGB are listed in the table below.

<table>
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<th>Parameter</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
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<td>16</td>
<td>V</td>
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<td>-</td>
<td>1.5</td>
<td>V</td>
</tr>
<tr>
<td>SPI/logic high</td>
<td>3.5</td>
<td>-</td>
<td>-</td>
<td>V</td>
</tr>
<tr>
<td>Analog Out</td>
<td>0</td>
<td>-</td>
<td>5</td>
<td>V</td>
</tr>
<tr>
<td>Current (w/ 120 ohm bridge res)</td>
<td>52</td>
<td>100</td>
<td>mA</td>
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</table>
6 QUICKSTART

6.1 Manual quarter bridge

- Using ESD precautions, unpack and connect a strain gauge to the inputs of the EMBSGB (quarter bridge example seen below).

- Place correct value bridge completion resistors (if needed for non-quarter bridge).

- Apply a 6V to 16V DC power across pins 7 and 8 (Note the polarity). The green LED will indicate correct power to the system.

- Set the desired gain with the gain select switch 9.1.

- Connect a voltmeter or other measurement device to the analog output pin 9.

- While reading the analog output with the system unloaded, adjust the potentiometer until the voltage reaches approximately 2.5V.

- Now the EMBSGB is properly set up and adjusted, you can now calculate strain from the output of the amplifier - see section 11 for more information.

![Quarter Bridge Diagram]

6.2 Manual full bridge/load cell

- Using ESD precautions, unpack and connect a strain gauge bridge or load cell to the inputs of the EMBSGB (full bridge/load cell example seen below).

- Apply a 6V to 16V DC power across pins 7 and 8 (Note the polarity). The green LED will indicate correct power to the system.

- Set the desired gain with the gain select switch 9.1.

- Connect a voltmeter or other measurement device to the analog output pin 9.

- While reading the analog output with the system unloaded, adjust the potentiometer until the voltage reaches approximately 2.5V.
• Now the EMBSGB is properly set up and adjusted, you can now calculate strain from the output of the amplifier - see section 11 for more information.

Use shielded cable to minimize noise - connect drain wire to Shield

No bridge completion resistors required
8 BLOCK DIAGRAM

![Block Diagram Image]

Figure 1: Amplification Stage

*Low pass filter default is 180 Hz, but can be customized to the desired corner frequency.
9 MANUAL CONTROL

In the manual version, gain is controlled by the three gain control switches and the offset is controlled through the offset adjustment potentiometer.

9.1 MANUAL GAIN CONTROL

The gain of the second stage amplifier is fixed at 11. However, the gain of the primary stage amplifier can be controlled by the three gain control DIP switches. The total gain of the amplifier board is calculated by multiplying the gain of the two amplifiers together. The total gain of the amplifier board is listed in the following table.

<table>
<thead>
<tr>
<th>G2 (MSB)</th>
<th>G1</th>
<th>G0 (LSB)</th>
<th>Total Gain (G_{AMP1} \times G_{AMP2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>110</td>
</tr>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>220</td>
</tr>
<tr>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>550</td>
</tr>
<tr>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>1100</td>
</tr>
<tr>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>2200*</td>
</tr>
<tr>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td>5500*</td>
</tr>
<tr>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
<td>11000*</td>
</tr>
<tr>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>DO NOT USE</td>
</tr>
</tbody>
</table>

*Gains above 1000 are not recommended without careful consideration of noise and might require additional shunt resistors to prevent the first stage amplifier from saturating.
9.2 MANUAL OFFSET CONTROL

For most applications, use the offset potentiometer to adjust the output voltage to near the middle of the range for \( V_{\text{out}} \) (Approx 2.5 V). Adjusting the output voltage to 2.5 V allows for maximum range of both positive and negative strain. If your strain gauge is known to only flex in one direction, you may find it more useful to adjust the output voltage closer to the top or bottom of the \( V_{\text{out}} \) range so you can get maximum resolution from your ADC.

*NOTE*

The offset potentiometer will need to be readjusted for each gain alteration and/or bridge configuration.
10.1.2 Gain Control (Register bits 0:2)

The three gain control bits allow for the selection of seven different gains:

<table>
<thead>
<tr>
<th>G2 (MSB)</th>
<th>G1</th>
<th>G0 (LSB)</th>
<th>Total gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>110</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>220</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>550</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1100</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2200*</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>5500*</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>11000*</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>DO NOT USE</td>
</tr>
</tbody>
</table>

*Gains above 1000 are not recommended without careful consideration of noise, and might require additional shunt resistors to prevent the first stage amplifier from saturating.

10.1.3 Frequency Compensation (Register bits 3:5)

The gain-bandwidth compensation is set to one of five levels under program control. The amount of compensation can be decreased to maximize the available bandwidth as the gain of the amplifier is increased. The compensation level is selected by setting bits COMP[2:0] of the control register with 000b, 001b, 010b, 011b, or 1xxb. Frequency Compensation (Register bits 5:3) shows the bandwidths achieved at the selectable gain and compensation settings. Note that for gains 110X and 220X, the recommended compensation setting is 000b. For the gain setting 550X, compensation settings may be 000b and 001b. Gain settings 1100X and 2200X may use the three bandwidth compensation settings 000b, 001b, and 010b. At gains of 5500X and 11000X, all bandwidth compensation ranges may be used. Note that for lower gains, it is possible to under compensate the amplifier into instability.

<table>
<thead>
<tr>
<th>Gain</th>
<th>Bandwidth Frequency Compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>930 kHz n/a n/a n/a 74 kHz</td>
</tr>
<tr>
<td>220</td>
<td>385 kHz n/a n/a n/a 37 kHz</td>
</tr>
<tr>
<td>550</td>
<td>160 kHz 460 kHz n/a n/a 16 kHz</td>
</tr>
<tr>
<td>1100</td>
<td>80 kHz 225 kHz 640 kHz n/a 8 kHz</td>
</tr>
<tr>
<td>2200</td>
<td>38 kHz 95 kHz 195 kHz n/a 4 kHz</td>
</tr>
<tr>
<td>5500</td>
<td>16 kHz 40 kHz 85 kHz 130 kHz 1.5 kHz</td>
</tr>
<tr>
<td>11000</td>
<td>8 kHz 22 kHz 50 kHz 89 kHz 0.8 kHz</td>
</tr>
</tbody>
</table>

10.1.4 Input Multiplexer and Polarity Switch (Register bits 6:8)

The input multiplexer allows for additional control in many situations that will not be used and should therefore be fixed to 0,0. The polarity switch can reverse the input polarity from
the Wheatstone bridge to the input of the first stage amplifier, this can be useful for high gain situations if the minimum offset compensation has pushed the output voltage beyond the desired operating region. This can also be useful to quickly change the sign of strain measurement.

<table>
<thead>
<tr>
<th>MUX0 (LSB)</th>
<th>MUX1 (MSB)</th>
<th>POL</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Normal polarity, S+ to pos input &amp; S- to neg input of amplifier (*Recommended)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>Reverse polarity, S- to pos input &amp; S+ to neg input of amplifier</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>x</td>
<td>DO NOT USE</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>x</td>
<td>DO NOT USE</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>x</td>
<td>DO NOT USE</td>
</tr>
</tbody>
</table>

10.1.5 Shutdown Enable (Register bit 9)

When the SHDN bit of the LMP8358 register is set to 1b the part is put into shutdown mode.

<table>
<thead>
<tr>
<th>SHDN</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Active mode</td>
</tr>
<tr>
<td>1</td>
<td>Shutdown mode</td>
</tr>
</tbody>
</table>

10.2 PROGRAMMABLE OFFSET CONTROL

Programmable offset control is made available from a 16 bit digital to analog converter, the AD5662 from Analog Devices [http://www.analog.com/static/imported-files/data_sheets/AD5662.pdf](http://www.analog.com/static/imported-files/data_sheets/AD5662.pdf). Excerpts are taken directly from analog devices.

10.2.1 Serial Control

The write sequence begins by bringing the CS line low. Data from the SDI line is clocked into the 24-bit shift register on the falling edge of SCK. The serial clock frequency can be as high as 30 MHz, making the AD5662 compatible with high speed DSPs. On the 24th falling clock edge, the last data bit is clocked in and the programmed function is executed, that is, a change in DAC register contents and/or a change in the mode of operation. At this stage, the CS line can be kept low or be brought high. In either case, it must be brought high for a minimum of 33 ns before the next write sequence so that a falling edge of CS can initiate the next write sequence. Since the CS buffer draws more current when VIN = 2.4 V than it does when VIN = 0.8 V, CS should be idled low between write sequences for even lower power operation. As mentioned previously it must, however, be brought high again just before the next write sequence.
The output voltage from the DAC will depend on the 16 bit number passed into the register. In decimal form the number can range from 0 to 65,536. Representing a range from 0 to 5V. The output voltage can be calculated below.

\[ V_O = \frac{D}{65,536} \times 5 \]  

10.2.2 Power Down Modes

The AD5662 contains four separate modes of operation. These modes are software-programmable by setting two bits (DB17 and DB16) in the control register. Below is the state of the bits corresponds to the devices mode of operation.

<table>
<thead>
<tr>
<th>DB16</th>
<th>DB17</th>
<th>Operating Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Normal Operation</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>Power-Down (1 k(\Omega) to GND)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>Power-Down (100 k(\Omega) to GND)</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Power-Down (Open/floating)</td>
</tr>
</tbody>
</table>

When both bits are set to 0, the part works normally with its normal power consumption of 250 \(\mu\)A at 5 V. However, for the three power-down modes, the supply current falls to 480 nA at 5 V. Not only does the supply current fall, but the output stage is also internally switched from the output of the amplifier to a resistor network of known values. This has the advantage that the output impedance of the part is known while the part is in power-down mode. The outputs can either be connected internally to GND through a 1 k\(\Omega\) or 100 k\(\Omega\) resistor, or left open-circuited.
11 BRIDGE CONFIGURATION

The bridge can be configured in many ways and can be completed by on board bridge completion resistors. To complete the bridge you can use 0805 surface mount resistors or standard through hole resistors placed in the DIP socket shown in the board diagram.

The simplified schematic of the bridge completion circuit is shown below, the two types of resistors (surface mount and through hole are wired in parallel).

Shielded wire should be used to minimize EM noise.
11.1 Quarter Bridge

Quarter bridge utilizes the three wire configuration to minimize the effect of wire resistance. In addition all three bridge completion resistors are required.

\[ V_{S,\text{quarter}} = \frac{V_E G F \epsilon}{4} \] (2)

11.2 Half Bridge

Half bridge only uses the two left side bridge completion resistors.

\[ V_{S,\text{half}} = \frac{V_E G F \epsilon}{2} \] (3)
11.3 Full Bridge

A load cell or a full bridge require no completion resistors.

\[ V_{S,\text{half}} = V_2 G F \epsilon \]  

(4)
### 12 STRAIN AND GAIN ACCURACY

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st stage amp. gain error</td>
<td>0.03</td>
<td>0.15</td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>2nd stage amp. gain error</td>
<td>0.02</td>
<td>0.1</td>
<td></td>
<td>%</td>
</tr>
</tbody>
</table>
13 TROUBLESHOOTING

No LED power indication

Check connections, the power plug is the large connector. With the large connector on the right and the small connector on the left (component side up) the pins count increasingly from top to bottom.
Check power requirements, the supply voltage requires a minimum voltage of 6 V and a maximum of 16V along with a maximum of 100 mA of current.

Saturated low or high output signal

Saturated high

Check that wheatstone bridge is well balanced, if not use shunting resistors to correct any errors.
Check if amplification gain is too high, using correct MSB to LSB orientation.
Progressively high gain requires a further balanced wheatstone to prevent saturation.

Check if potentiometer (Manual mode) or DAC (SPI) reference voltage is too high.

Check connections, the gauge input/load connects to the small connector. With the large connector on the right and the small connector on the left (component side up) the pins count increasingly from top to bottom.

Saturated low

Check that wheatstone bridge is well balanced, if not use shunting resistors to correct any errors.
Check if amplification gain is correct, using correct MSB to LSB orientation.
Progressively high gain requires a further balanced wheatstone to prevent saturation at low or high rails.

Check if potentiometer (Manual mode) or DAC (SPI) reference voltage is too low.

Check connections, the gauge input/load connects to the small connector. With the large connector on the right and the small connector on the left (component side up) the pins count increasingly from top to bottom.
Appendix C: Reference Manual Speed Sensors and ACT3X Tachometer
ACT-3X
Tachometer / Totalizer / Ratemeter
User Manual and Reference Guide
1.0 GENERAL OVERVIEW

The ACT-3X digital panel meter is an extremely versatile instrument. The user has complete control of the unit configuration. Power may be either 115 - 230 Vac (50/60 Hz), or optionally, 12 Vdc or 24 Vdc. Input signals are accepted (on Channel 1) from optical, proximity, magnetic, infrared or laser sensors, or direct TTL or external AC sources. A second auxiliary input (Channel 2) may be used for instrument control and remote resetting. There are several remote communication options – RS232, USB or Ethernet and the optional remote software can be used to program the unit or display data locally. The unit is suitable for panel mounting or bench top use, with convenient screw terminal connections on the rear panel of the instrument.

When the instrument is turned on, it displays all 8x, then “3 rx.x”, where 3 is the unit type (ACT3) and rx.x is the software revision level, before entering the normal mode of operation.

The display will show “- - - -” when a measurement is over range.

2.0 INSTALLATION

The instrument is intended to operate in the following environment: Indoor Use Only

<table>
<thead>
<tr>
<th>Environment</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation Category II</td>
<td>IEC 664</td>
</tr>
<tr>
<td>Measurement Category I</td>
<td>IEC61010-1</td>
</tr>
<tr>
<td>Temperature</td>
<td>-10 °C to +50 °C operating per IEC61010-1</td>
</tr>
<tr>
<td>Humidity</td>
<td>Maximum relative humidity 80% for temperatures up to 31°C decreasing linearly to 50% relative humidity at 40°C</td>
</tr>
<tr>
<td>AC Mains Supply</td>
<td>100 - 240 Vac - 5% 50/60 Hz 8 VA</td>
</tr>
<tr>
<td>DC Supply (Option)</td>
<td>12 or 24 VDC±10% 6 Watts (DC Option)</td>
</tr>
</tbody>
</table>

**NOTE:** The instrument is designed to be panel mounted and as such should be considered as fixed equipment or permanently connected. If permanently connected, disconnection from the supply must be possible via a customer supplied switch or circuit breaker rated at 120V or 240V (dependent on local voltage supply) 5A minimum when connected to an AC supply or 30V 1A minimum when connected to a DC supply. This disconnection device must disconnect all current-carrying conductors. It must be included in the panel installation and should be clearly marked, in close proximity to the Unit and easily accessible to the operator.

The ACT3X is a 1/8 DIN enclosure requiring a 3.58” wide by 1.74” high (91x44 mm) mounting hole. Approximately 5” (127 mm) will be required behind the panel. Refer to Figure 1 below.

![Panel Cutout](image)

**Figure 1 Dimensions In Inches [Millimeters]**

**WARNING:** Do not use this instrument in any manner inconsistent with these operating instructions or under any conditions that exceed the environmental specifications stated.

2.1 Noisy Environments

These instruments are highly responsive. They have input ranges up to 999,990 RPM and 250,000 Hz. They therefore have extremely fast input circuitry that may respond to spurious noise. It is important to provide a clean source of power to the units, either AC or DC, and to ensure that the input to the unit is free of spikes or any other high frequency noise. In noisy environments, it may be necessary to supply power through a filter, or alternate source. The inputs may also need to be
damped, to suppress high frequency noise. It is always a good idea to use shielded cable for input signals and ensure the shield is properly grounded.

**NOTE:** The common on the inputs is **NOT** a ground.

Another source of noise is spikes generated by the alarm relay contacts. It may be necessary to suppress the contacts externally. This is particularly true when the internal relays switch other external relays that do not have spike suppression. Always ensure that all sources of spikes or noise are adequately suppressed from the environment.

### 2.2 Adjustments

Since the instruments are crystal controlled, there are no user calibration adjustments. Any of the programmable parameters, such as scaling, limits, analog out, and so on must be set up using the menu options.

### 2.3 Connections

All connections are via the rear panel of the instrument – power, sensors, alarms, analog output, and communication. The rear panel is shown below and may vary slightly depending on what options are in the unit.

![Figure 2 ACT-3X Rear panel with Analog Output and USB Option](image)

#### 2.3.1 Power Connections

Power to the unit is connected to the terminals under the sections labeled **POWER** on the rear panel. Be sure the power supplied matches the specification indicated on the rear panel. Refer to **Figure 2** above.

- **AC powered** (115 - 230 Vac), connect the Live (Hot) wire to the terminal marked L and the Neutral (Return) wire to the terminal marked N. **NOTE:** The ground connection is not required as the unit is fully isolated from the mains.
- **DC powered**, connect the dc supply Positive to the terminal marked “+” and the dc supply Negative or Common to the terminal marked “-”. **CAUTION:** Ensure the dc voltage does not exceed the rating on the unit (12V ±10% or 24V ±10% as marked).

#### 2.3.2 Sensor Connections

A speed sensor (not included) can be connected to the terminals under the section labeled **IN** on the rear panel. Refer to **Figures 2** and 3.

Connections and their functions are as follows:

- **+VA** Positive Supply Output. Used to provide power to optical, laser, infrared or amplified magnetic sensors. Voltage out is +24Vdc, +12Vdc or +5Vdc (factory selected). Maximum load is 30mA from the 24V supply or 60mA from the 5 or 12V supplies.
- **PX+** This output is for use with two wire proximity sensors. It has internal current sensing. Maximum load for proper operation with two wire sensors is 20 mA.
- **SIG** Signal Input. Positive input signal from the speed sensor. Accepts TTL pulses or ac signals, unipolar and bipolar, from 1.1 Vac to 50 Vac. Connect the signal wire from the wire sensor or the positive side of two wire magnetic sensors to this terminal. Typical input impedance is 10 Kohns.
- **COM** Common or Negative Terminal. Common or Negative connection for both signal and power.

Refer to **Figure 3** on the following page for connection of Monarch standard sensors. The connections are typical for these types of sensors.
2.3.3 Analog Output

The Analog Output is an option. The Output option is marked on the back of the unit to the right of the connector—refer to Figure 2.

2.3.3.1 Current Output

The current output is 4 to 20 mA. This output is a current source and has a 12 Volt dc internal compliance voltage. (Optional 24 Vdc may be ordered.)

Typical connection is as follows: (See Figure 4.)

Connect the Positive side of the load to the OUT terminal marked “+” and the other side of the load to the terminal marked “-“. With the internal 12 Vdc compliance voltage the maximum load for the current loop is 500 Ohms. If the optional 24 Vdc compliance option is ordered the maximum load will be 1000 Ohms.

2.3.3.2 Voltage Output

The analog output is 0 to 5 Vdc @ 5mA.

Connect the Positive side of the load to the OUT terminal marked “+” and the return side of the load to the terminal marked “-“. (See Figure 4.)

The output full scale and zero scale values are programmed via the front panel or remotely through the communication port.

2.3.4 Auxiliary Input (AUX- Channel 2)

The Auxiliary Input is also referred to as Channel 2 (CH-2) and will accept a TTL input or any signal up to 12Vdc. It has a weak pull up internally and can be used with a set of potential free contacts. The AUX input is programmed via the front panel or remotely via the communication port. Refer to Figure 2 and figure shown right—the AUX input is connected to the input marked AUX (+) and COM (-).

2.3.5 Pulse Output

The Pulse Output provides a pulse out for each pulse in. It is a TTL pulse switching between +5V and ground. Refer to Figure 2 and figure shown right—the connection is to the PO (+) terminal and the COM (-) terminal.

2.3.6 Alarm Relay Outputs

The Alarm Relay Outputs are potential free Form C contacts (Change Over) capable of carrying 1A at 250Vac or 30Vdc.

The contacts are marked NCx where NC is the Normally Closed Contact, x = 1 or 2 depending on which relay you are using. CM is the Common and NO is the Normally Open Contact.

CAUTION: Relay contacts may be wired to external high voltage potentials—ensure all power to the contacts are off before attempting any wiring.

CAUTION: During programming of the device, relay contacts may make or drop out intermittently.

Page 3
2.3.7 Serial Communications

There are three serial communication options – Ethernet, USB and RS232. The Ethernet option will have a standard RJ45 connector, the USB option will have a type B female connector, and the RS232 option will have a male DB9 connector on the rear panel. The connections of the Ethernet and USB are generic. The connection of the RS232 DB9 is shown here:

<table>
<thead>
<tr>
<th>Pin</th>
<th>Description</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Receive data</td>
<td>In</td>
</tr>
<tr>
<td>3</td>
<td>Transmit Data</td>
<td>Out</td>
</tr>
<tr>
<td>5</td>
<td>Common (GND)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Request to Send RTS</td>
<td>Out</td>
</tr>
<tr>
<td>8</td>
<td>Clear to Send CTS</td>
<td>In</td>
</tr>
</tbody>
</table>

All other pins are not used. Communications are at the preset Baud Rate, 8 bits, No Parity and 1 stop bit.

3.0 FRONT PANEL

Refer to the first page for a photo of the front panel.

The front panel of the instrument has 5 push buttons, five 0.56” 7 segment light emitting displays, and six single light emitting diodes (LED’s), marked LIM 1, LIM 2, GATE, MIN, MAX and RPM. Some of these LED’s may not be visible; it depends on the mode the unit is in.

3.1 Status LED’s

3.1.1 LIM 1 and LIM 2 (Alarm) LED’s

The LIM 1 and LIM 2 (Alarm) LED’s indicate the status of the limits, particularly of the alarm output relay. When an alarm trips, the corresponding LED blinks at a rate around 1 flash per second. When the alarm resets, the LED goes out. These LED’s also go on continuously to indicate when and which limit is being set or adjusted. If the LED’s are on continuously, the value on the display is a set point value, not the input value.

3.1.2 GATE LED

The GATE LED is an indication of the instrument’s input trigger signal from a sensor. It is triggered on by the falling edge of an input pulse, and goes off about 150 milliseconds later (unless there is another input pulse). It is more useful at slow speeds, as it appears to be on continuously at higher inputs. It gives an indication that a valid input trigger signal is present.

3.1.3 MAX and MIN LED’s

The MAX and MIN LED’s indicate to the user that a maximum or a minimum is being displayed. If either one of these LED’s is on, the display is a stored value, not the input value.

3.1.4 RPM LED

The RPM LED indicates that the RPM Mode (frequency x 60) has been selected, which can only be used when the input is one pulse per revolution. The RPM LED is off in all other modes. In the Scale Mode the read outs may be in RPM, but the RPM LED will be off.

**NOTE:** For applications where there is more than one pulse per revolution, the Scale Mode must be used.

3.2 Push Buttons

The five push buttons on the front panel have multiple functions. The following sections cover the function of the buttons under normal operating conditions.

3.2.1 SET BUTTON

The SET button enters the Menu and allows the user to view the current settings in the unit. Refer to Section 5.0.

3.2.2 RESET BUTTON

The RESET button, when pressed, resets the Alarms, assuming they have tripped. It is the only way to reset a latching alarm other than via the serial interface.

**NOTE:** If an alarm set point is exceeded when the reset button is pressed, the alarm will immediately trip again on the next data acquisition cycle.

If the user holds the RECALL button and then presses the RESET button, the minimum and maximum values (and the TOTAL if the unit is in the Totalizing mode) are reset.

In the Single Event Capture (SECAP) Mode, pressing the RESET button signals the instrument to take a reading at the next trigger as well as its normal functions.

When in the Menu, the RESET button reverts back one level without saving any changes (Exit) or exits the Menu.
3.2.3 UP (▲) and DOWN (▼) BUTTONS

The UP (▲) and DOWN (▼) buttons can be used to view the current settings of the alarms. Press the UP (▲) button to view LIMIT 1 or the DOWN (▼) button to view LIMIT 2. The display will revert back to normal after a few seconds.

When in the Menu, the UP (▲) and DOWN (▼) buttons are used to scroll through the menu options or edit data within the options.

3.2.4 RECALL BUTTON

The RECALL button toggles between the maximum and minimum readings. The display will revert back to normal after a few seconds. The RECALL button, when used with the RESET button, also resets the maximum and minimum readings or total (when in Totalizing mode).

When in the Menu, the RECALL button reverts back one level without saving any changes (يدل الملاحظة على أنه هو الملاحظة الثاني) or exits the Menu (الشاشة من الشاشة).

4.0 OPERATION

4.1 Modes of Operation – Channel 1

There are a number of different modes of operation. These modes determine what is shown on the display for any given input to the instrument. Basically, it determines what computation is performed on the input. The input signals are on Channel 1 (Signal inputs). The user can set the sense of the input, positive or negative. The AUXillary input (Channel 3) can be used to control the signals on Channel 1. Refer to Section 5.0 for details on changing modes.

NOTE: The instrument is programmed from the factory in the RPM Mode for one pulse per revolution.

4.1.1 RPM Mode

In the RPM Mode the unit behaves like a tachometer displaying revolutions (revs) per minute (RPM) from an input of 1 pulse per revolution. The instrument effectively multiplies the input frequency (pulses per second) by sixty to derive RPM. In this mode, the range of the unit is 5 to 999,999 RPM. The RPM LED on the bottom right of the display area illuminates to indicate the RPM mode is programmed. The AUXillary input (Channel 2) can be used to inhibit (disable) the signal into the unit.

NOTE: For applications with more than one pulse per revolution, the Scale Mode (see below) must be used to display RPM or other rates.

4.1.2 Frequency Mode

In the Frequency Mode, the unit displays input pulses per second or more commonly, Hertz (Hz). This is the most basic mode of operation. The range of measurement in this mode is 0.0033 to 250,000 Hz. The AUXiliary input (Channel 2) can be used to inhibit (disable) the signal into the unit.

4.1.3 Scale Mode (Ratemeter)

In the Scale Mode of operation, the input frequency (pulses per second) is multiplied by a constant, which is set by the user, and displayed. This allows the user to scale the input to obtain a readable in any units required: RPM, inches per second, meters per hour, yards per fortnight, and so on. The scale factor may be set anywhere from 0.001 to 9999.9. The AUXiliary input (Channel 2) can be used to inhibit (disable) the signal into the unit.

4.1.4 Single Event Capture (SECAP) Mode

The SECAP (Single Event Capture) Mode is just like the Scale Mode except that only one reading is made. The RESET button is pressed to start each new measurement. The unit will then use the next input pulse to start a measurement, then the next input pulse will end the measurement. In the other tachometer modes, the unit will keep acquiring pulses until 32 mS (or 4mS) has passed so it can give an accurate reading. The SECAP Mode sacrifices accuracy as measurements get shorter than 32 mS (or 4mS), but it is the only way to measure single (non-repeating) events. The AUXiliary input may be used for the second pulse input if two sensors are used, the first pulse on Channel 1 will start the process and the second pulse on Channel 2 (AUX) will stop the process. Refer to Appendix C – Using the Single Event Capture Mode.

4.1.5 Rate of Change (ROC) Mode

In the Rate of Change Mode, the unit displays the rate of change of the input frequency (pulses per second). The unit measures the input frequency times the scale factor set by the user. A moment later it measures the input frequency again. The difference of these two, scaled frequencies is divided by the time interval between the two measurements. Several measurements are averaged then displayed.

The scale factor allows the user to scale the input to obtain a readable in any units required: RPM per Minute (RPM/M), inches per second per second, meters per hour per second, and so on. The scale factor may be set anywhere from 0.0001 to 9999.9.

In this mode:

- The display is updated up to once every two seconds with the average Rate of Change.
• The throughput of the max/min, analog outputs, and relays is up to twice a second.

• The display will show a positive number when the frequency is increasing and a negative number when the frequency is decreasing.

Remember that even a small change in RPM over a short time will cause a large Rate of Change (average acceleration) to be displayed. The gate time for each measurement is about 1/3 of a second. For instance, if you use a digital function generator to change from 3000 RPM to 3001 RPM, the change will happen all at once. You will see that it happens within 1/3 of a second. So 1 RPM change in 1/3 of a second is 180 RPM over one minute or 180 PRPM acceleration.

4.1.6 Totalizing Mode

In the Totalizing Mode, each input pulse causes the display to be incremented by a constant value that is set by the user. This enables the user to scale the input to obtain a readout in any measure required: number of inches, number of miles, number of revolutions, and so on. The scale factor may be set anywhere from 0.0001 to 99999.9 Total can be reset using the RESET and RECALL buttons pressed together on the front panel. The AUX input (Channel 2) can be set to reset the totalizer and turn the unit into a batch counter or to inhibit the input signal (see Section 4.2.4).

4.2 Modes of Operation – Channel 2

Channel 2 is the AUXiliary input and is basically used to control the input to Channel 1, or can be used as an external reset for the input channel or the Alarms. The user can set the sense of the input, positive or negative. The input has a weak pull-up resistor internally so it can be used with a potential free contact. All modes are mutually exclusive – only one mode may be active at any time. Refer to Section 5.0 for details on changing modes.

NOTE: The instrument is programmed from the factory with the AUXiliary input disabled (OFF).

4.2.1 Off

When programmed OFF this input has no effect.

4.2.2 Inhibit

If programmed as an inhibit pin, it will disable the signal input when asserted (high or low depending on the sense programmed). It acts as a gate preventing the input signal from updating the unit.

4.2.3 Single Event Capture

When programmed as Single Event Capture (SECOR) this input acts as the second input for the external signal – see Section 4.1.4 above.

4.2.4 External Reset – Input Totalizer

If programmed as External Reset for Inputs (+5V in), when asserted (high or low depending on the sense programmed), it will reset the display (count) to Zero. Used in the Totalizer Mode (see Section 4.1.6) to enable the unit as a batch counter.

4.2.5 External Reset – Alarms

If programmed as External Reset for Alarms (+5V-RL), when asserted (high or low depending on the sense programmed), it will reset any Alarms and drop out any Contact closures. Note: The alarms need to be set up correctly (see Section 4.4).

4.3 Decimal Point

The decimal point on the display may be fixed from 1 to 3 places, or may be set to none (only whole number displayed). As the display increases the unit will automatically drop decimals to show whole number values. Note that for values larger than 99999 all decimal points light indicating the current reading is x10.

4.4 Alarm Limits

The ACT-3X has two independent alarm set points, referred to as LIMIT 1 and LIMIT 2 (Set 1 and Set 2 on the menu). These limits are fully programmable by the user (unless the write protect option has been set). The limits may be set as high or low with an option of low limit lockout, latching or non-latching at any value. The limits are accurate to better than ±0.1% of the set point value. Refer to Section 4.7.2 for the limit response time. The dead band (hysteresis) is also programmable at any value from 0.0001 to 99.9999% of the set point value. The actual output from these alarms is a set of form C, dry contacts, accessible via barrier strip screw terminals on the rear panel. These contacts are capable of switching 1 A at 250 Vac. When the unit is making measurements, the limits can be viewed by pressing the UP (+) button for LIMIT 1 or the DOWN (-) button for LIMIT 2. The display will return to normal after a few seconds. The relays may also be set to be Fail Safe, which inverts the sense of the relay so that they are energized under normal condition. In the event of a power failure the contacts will drop out as they would during an alarm condition. Refer to Section 5.0 to set limit set points.

4.4.1 Latching vs. Non-Latching Limits

A Latching Limit is one which, when the alarm trips, remains in this condition regardless of what the input may do. This tripped limit needs to be manually reset by the operator to restore it back to its normal position. Reset is via the front panel RESET button or remotely using Channel 2 Auxiliary input if programmed. A Non-Latching Limit, on the
other hand, will automatically reset itself when the input no longer exceeds the set point, either high or low. The user can program each limit to be Latching or Non-Latching. Refer to Section 5.0.

4.4.2 Dead band (Hysteresis)

Dead band is only applicable to non-latching limits. Dead band is a value that is added to the set point (in the case of a low limit) or subtracted from the set point (in the case of a high limit) so that this new value (set point ± dead band) becomes the reset point for the alarm. The primary purpose of this function is to prevent the alarm relays from chatter when the input value remains very close to the set point. Dead band is set in absolute engineering units. For example, if the limit is set to 200 RPM as a High limit and the dead band is set to 20 RPM, the alarm will trip when the input is greater than 250 but will not reset until the input goes below 180 PM. Without the dead band feature, the alarm relays would chatter on and off if the input varied from 199 to 201, which is undesirable. The user can set the hysteresis to any value from 0.0001 to 9999. Refer to Section 5.0.

NOTE: The Dead band needs to be less than the setpoint.

4.4.3 Low Limit Lockout

The Low Limit Lockout is a feature that prevents a low alarm from tripping when the input starts from zero. The low alarm essentially is locked out and will not operate until the input exceeds the low limit, at which time the low alarm is enabled and will trip when the input goes below the set point. This feature enables a motor that has a low speed cut out (low alarm) to start from rest without having to short out the normally closed relay contacts externally. This feature may be enabled or disabled by the user. Refer to Section 5.0.

4.4.4 Fail Safe

The Fail Safe option reverses the sense of the relays, essentially energizing them under normal conditions. When an alarm is set, the relays will drop out (become de-energized). Thus in the event of a power failure the relays will drop out by default creating the equivalent of an alarm condition.

4.5 Analog (AO) and Current (I0) Output

The ACT-3X has options for voltage (0 to 5Vdc) or current (4 to 20mA) outputs.

The analog outputs are derived from a 15-bit digital to analog converter. This means that the output voltage (or current) changes in steps. The standard analog output has ~32,000 steps from zero to full scale. This implies that each step size is 1/32,000 of the full-scale value or about 0.003% of full scale. The user can set the actual full-scale value anywhere from 1 to 999,999. This full-scale value is the value at which the analog outputs are at a maximum, 5 Vdc or 20 mA.

The zero and full-scale range is usually set to give a reasonable working range for the analog output. For example, if you are measuring the RPM of a motor that typically runs at 1700 RPM, you may want to set the zero scale (offset) for 1000 and the full-scale for the analog output at 2000. Note that the zero and full-scale ranges are always set in the units you choose to display, RPM in this case. The output voltage will then be 5 Vdc (20 mA) for an input of 2000. It will be linear between 1000 (zero scale) and 2000 (full scale). Thus, at 1700 RPM the output will be:

\[
\frac{(1700 - 1000)}{(2000 - 1000)} \times 5 \text{ Vdc} = 3.5 \text{ Vdc}
\]

Resolution = \[
\frac{(2000 - 1000)}{32,000} = 0.03 \text{ RPM}
\]

NOTE: For any input below the zero scale setting, the outputs will be at 0 Vdc or 4 mA. For any input above the full-scale setting, the outputs will be at their maximum value, 5 Vdc or 20 mA.

4.6 Maximum and Minimum

The unit tracks and saves the maximum and minimum values. These values are continuously updated and can be viewed at any time by pressing the RECALL button on the front panel. The first time this button is pressed the MAXimum is shown, indicated by the MAX light to the right of the display. Pressing the RECALL button a second time shows the MINimum.

The user can also reset these values by pressing and holding the RECALL button and then pressing the SET button. The next reading will always update both values. This will keep the minimum value from showing zero unless there was a zero reading after the RECALL and SET buttons were pressed.

Thus, if you start a motor, for example, from zero, the minimum will start recording with the first reading. Usually the user will reset the minimum once the motor is up to speed. When slowing to a stop, the minimum will naturally tend to zero, but the maximum will be retained.

4.7 Throughput

Throughput is a measure of how fast the instrument processes data. The rate at which the instrument acquires data is a function of the "Gate Time" and the input frequency. The instrument gets a start pulse then it continues to get pulses until the Gate Time elapses. The next pulse ends this measurement and starts the next. At frequencies slower than the Gate Time, the update rate is equal to the period of the input frequency. Eventually, the instrument has to make the decision that the input is zero, because theoretically it could wait forever for the next pulse. This Low-End timeout is programmable.
4.7.1 Display Update Rate

Although the instrument can update up to 244 times a second, to display the data at this rate would result in a totally erratic display. Therefore, the instrument limits the display update rate to once every 1½ second. Obviously if the input pulses are spaced more than ½ second apart, the instrument will not have any new data until the next pulse comes along, and the time to update will be greater than ½ second. The point at which the update rate becomes longer than every ½ second is when the period of the input (time between pulses) is greater than ½ second, which is 2 Hz or 120 RPM. Thus, for an input greater than 2 Hz or 120 RPM, the update rate is twice a second.

For very fast inputs, the unit averages the readings between display updates so that the value displayed is an average of the total number of acquisitions since the last update.

4.7.2 Internal Update Rate - GATE

The rate at which the limits are checked, the analog output is updated, and the minimum and maximum are updated, is at the maximum rate at which the instrument acquires data. This is set by the GATE menu item. The Gate Time can be set to 32.756 mSecs (STD) or 0.096 mSecs (FAST). See Section 5.1.6 for more details.

The STD setting is slower (up to 31 readings per second) but gives more accurate readings especially for the maximum and minimum readings. Below 31 Hz or 1676 RPM, the internal update rate is the period of the input frequency. Thus, the response of the alarms, etc can be seen to be a function of the input. Above an input of 31 Hz, the alarms respond within 66 milliseconds. Below this input they respond within (1 + input frequency) seconds.

The FAST gate time is faster (up to 244 readings per second) but is less accurate (about 0.025% of reading worst case at high frequencies). Below 244 Hz or 14,640 RPM, the internal update rate is the period of the input frequency. Thus, the response of the alarms, etc can be seen to be a function of the input. Above an input of 244 Hz, the alarms respond within 9 milliseconds. Below this input they respond within (1 + input frequency) seconds.

At input frequencies below 31 Hz or 1676 RPM there will be no difference in the two settings.

The instrument has a special feature to allow it to quickly respond to rapid deceleration and still measure down to 5 RPM with 1 pulse per revolution. (To measure to 1 RPM, 5 pulses per revolution are required). After receiving no input pulses for about 67 milliseconds for the Standard gate mode or 37 mSecs for the Fast gate mode, the instrument will calculate a reading as though an input pulse had just occurred. If this new reading is less than the last reading, the instrument uses it. Until an input pulse is detected or the Low-End timeout is reached, the instrument will “force” another reading every 33 milliseconds. These “forced” readings will update the analog output, limits, and the max/min.

The last “forced” reading of every ½ second will be displayed every ½ second. The Low-End timeout can be set to 12, 1 or 0.5 seconds. Refer to Section 5.1.3 for details.

4.7.3 Low End

Low End is applicable to RPM, FREQ, SCALE, and SECAP Modes only. Low End selects how many seconds may elapse between input pulses before the unit displays the reading zero. There is a tradeoff between the fastest reading available and how quickly the unit responds when the input pulses stop and displays 0. There are three values: 12 seconds, 1 second, and 0.5 seconds. In the RPM mode, with one pulse per revolution, these settings correspond to the lowest RPM reading of 5, 60 and 120 RPM respectively.

4.8 PULSE OUTPUT

The Pulse Repeater Output provides a conditioned TTL positive going 5 V pulse out for each pulse in. The sense of the output, high pulse or low pulse, is programmable by the user. See Section 5.9.

5.0 USING THE MENU

To enter the MENU Mode, press the SET button. The display will show the first top-level menu item, which is CH. 1 for Channel 1 setup. Continuing to press the SET button will cycle through all options and show the current settings. At any point press the RESET button to back out (Abort) the current setting. Pressing RESET again will eventually exit from the Menu.

Once in the MENU Mode, with CH. 1 displayed, press the UP (△) or DOWN (▼) buttons to cycle through the top-level menu options.

The top-level menu choices are:

- **CH. 1** - Channel 1 - Set up parameters for Channel 1 – the primary input channel
- **CH. 2** - Channel 2 - Set up parameters for Channel 2 – the Auxiliary Input Channel
- **dECPT** - Decimal Point - Set the number of Decimal Points displayed on the unit
- **SEEl.** - Set point 1 - Set up parameters for Alarm 1
- **SEEt.** - Set point 2 - Set up parameters for Alarm 2
- **dAC.** - Digital Analog Converter 1 - Set up parameters for the Analog Output (Option)
APPENDIX C – USING THE SINGLE EVENT CAPTURE MODE

This is how to calculate a scale factor and to show sources of measurement error.

In this example, the distance between sensors is 1 inch and we want the readings displayed in Miles Per Hour (MPH). The fastest measurement we intend to make is 130 MPH.

First calculate the scale factor. With a scale of one, the tachometer will display readings in pulses per second.

The scale factor can be calculated as:

\[
\text{1 Pulse} \times \frac{1 \text{ Inch}}{1 \text{ Foot}} \times \frac{3600 \text{ Seconds}}{1 \text{ Hour}} \times \frac{1 \text{ Mile}}{5280 \text{ Feet}} = 0.05681818 \text{ Miles} \text{ Hour}^{-1}
\]

There will be an error because scale factors can only be five digits. Therefore, the scale factor is rounded to 0.0568.

You will also have an error in the placement of the sensors. The tape edges won’t be exactly 1 inch apart. Assuming the edges were really 1.01 inches apart there would be 1% error. So at 130 MPH your reading would be 129.7 MPH.

The internal clock inside the tachometer runs at 2 MHz. All measurements are synchronized to this internal clock giving a ±0.5 microsecond uncertainty. As RPM, MPH, etc increase, the measurement time decreases. As the measurement time decreases, the small measurement uncertainty becomes a larger percentage of the measurement.

At 130 MPH there would be 0.000478703706 seconds between pulses. (Seconds = scale factor / 130 MPH.) This is equal to about 874 clock cycles for a 2 MHz internal reference clock.

873 clock cycles = 130.16666 MPH
875 clock cycles = 129.87013 MPH

Therefore, we have an error of ±0.148765 MPH from the clock resolution at 130 MPH. The sensors must be placed further apart for better resolution.