Final Design Specification

EML 4551C – Senior Design – Fall 2011 Deliverable

Team # 19

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Google Mobile App for Compressor Performance (GE)

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Compressor Performance Application

Majority of technical issues for a compressor are on flow, not achieving.

Looking to design a simple flow measurement system that could be externally mounted on the inlet/outlet pipe to the compressor, the sensor(s) would transmit the information back to a Android phone where data could be stored/plotted.

-As specified by Todd Hopwood (GE)

Design Product Specification

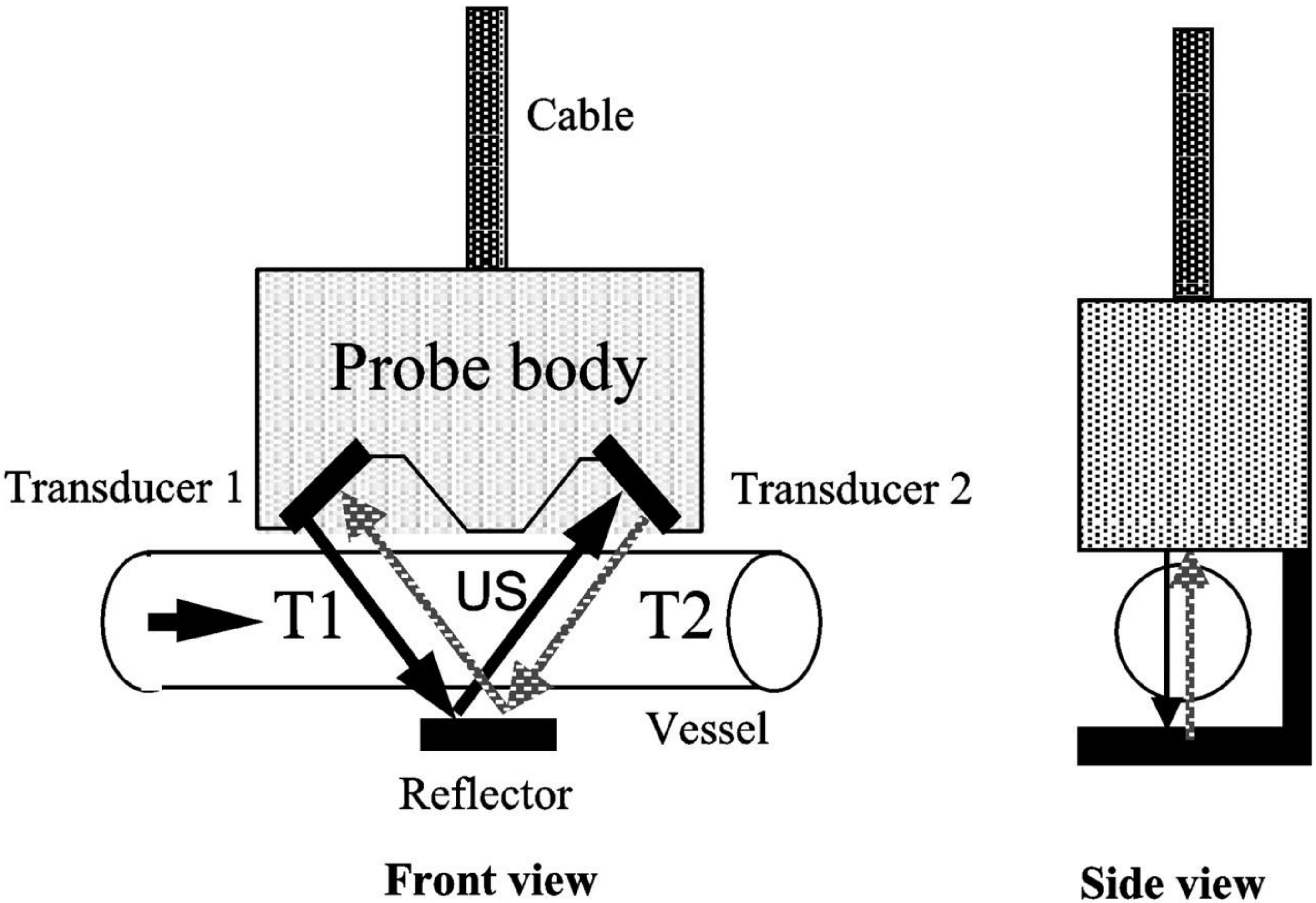
1. Data transferred through Wi-Fi or ? To an Android phone.
2. Setup time on the compressor less than 5 minutes, prefer 120 seconds or less.
3. No modifications allowed to the piping going to the package.
4. Software capturing data should be able to store the data and plot live.
5. Working Demo

As specified by Todd Hopwood (GE)

What Are Ultrasonic Transducers?

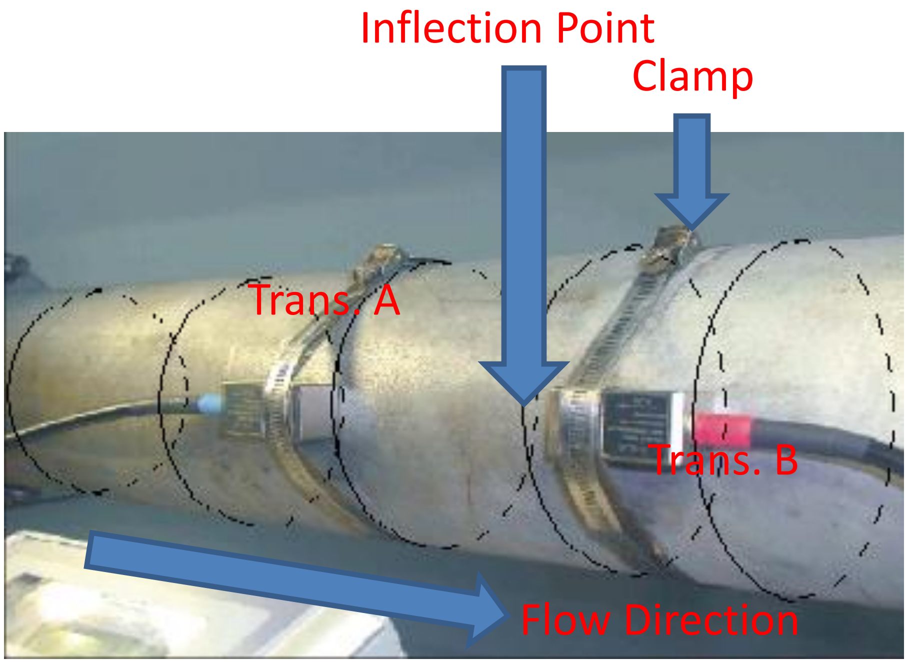
- Generate frequencies
  18 kHz and above by turning
  electrical signals into sound
- The rate these waves are slowed is dictated by the properties of the medium, including its motion
- This slowing can be calculated using several methods

Transit-Time Flow Concept



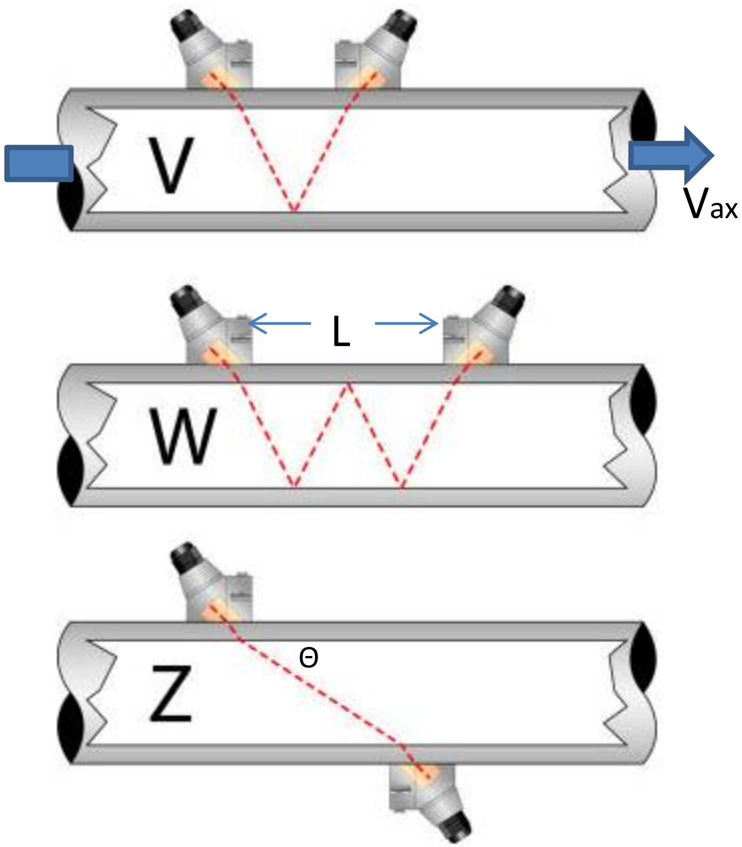
Transit-Time Flow Concept

- Ultrasonic waves exit emitter A. and are reflected off the inflection pt. into emitter B.



- Signal is slowed based on fluid properties and velocity of flow
- Fluid will flow faster in the direction of the flow

Transit-Time Flow Concept



(1) $$V_{ax} = \frac{L}{2\cos\Theta} \times \frac{\Delta t}{t_{up} \times t_{down}}$$

Where:

V_{ax} = the axial liquid velocity along the acoustic path

L = straight line distance between the centers of the faces of the upstream and downstream transducers

Θ = the path angle of transmission relative to the fluid at rest

t_{up} = the upstream transit-time

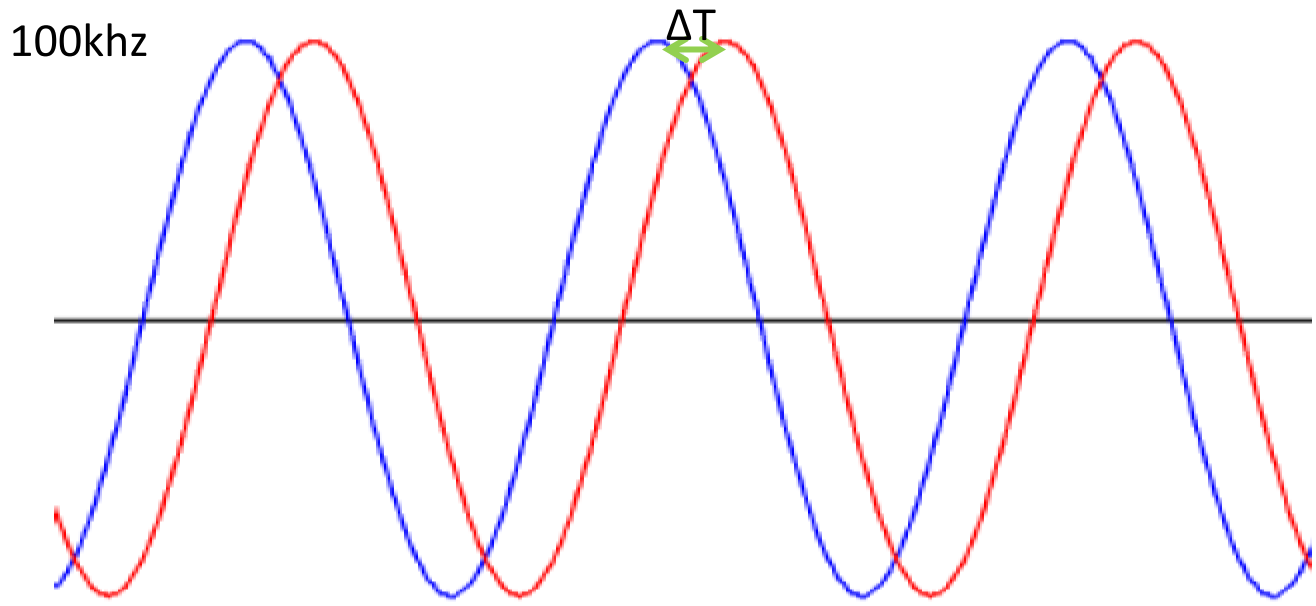
t_{down} = the downstream transit-time

$\Delta t = (t_{up} - t_{down})$ = the differential transit-time

Choice Methods of Deducing ΔT

- Cross Correlation
  - Find phase shift between two sine waves using signal reconstruction for cross correlation
    - Only requires two samples per waveform
- Signal Burst
  - Send out bursts of ultrasonic signal and timestamp when it is received

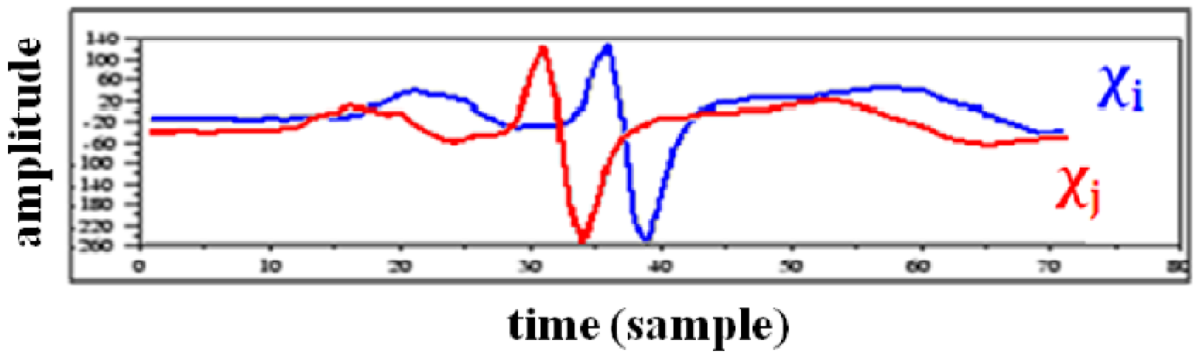
Cross Correlation Method



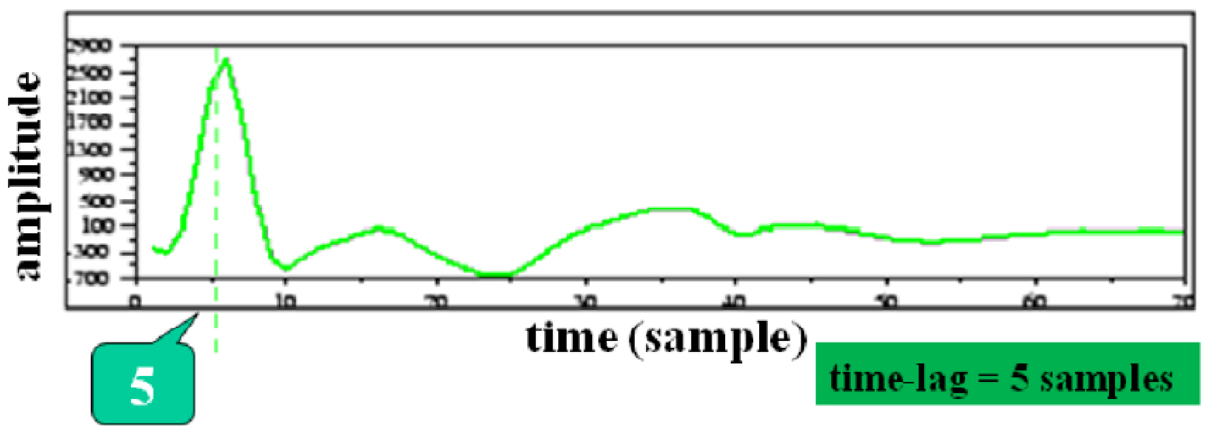
- The transit time is calculated by finding the phase shift between the original sine wave sent out and the sine wave received.

Cross Correlation Method

2 unlined signals [merge plot]



Cross correlation results

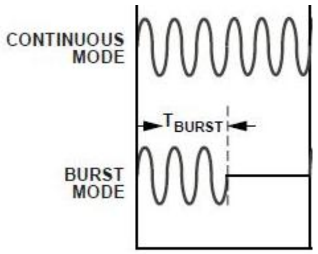


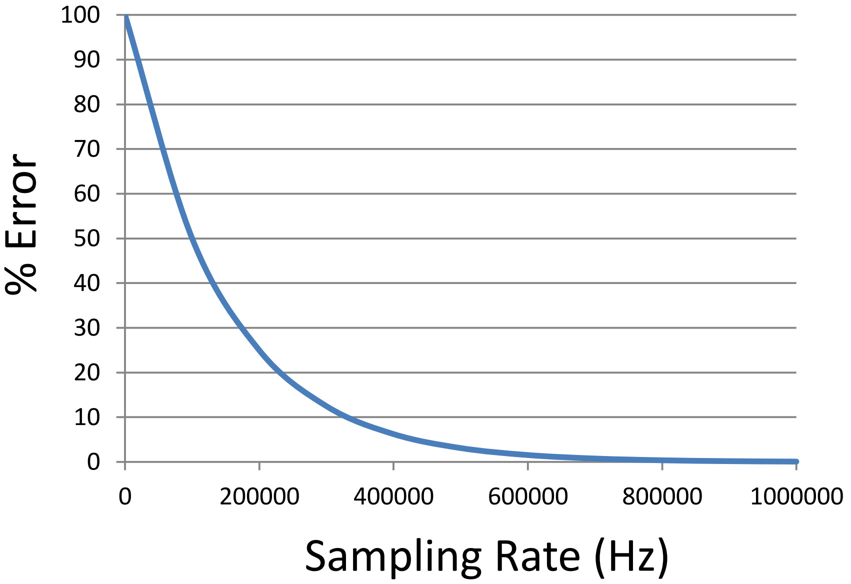
Cross Correlation Method

- Only need two samples per waveform to reconstruct signal
- Nyquist–Shannon sampling theorem
  - If a function contains frequencies of B hertz, it need only be sampled 1/2B times per second to perfectly reconstruct the signal

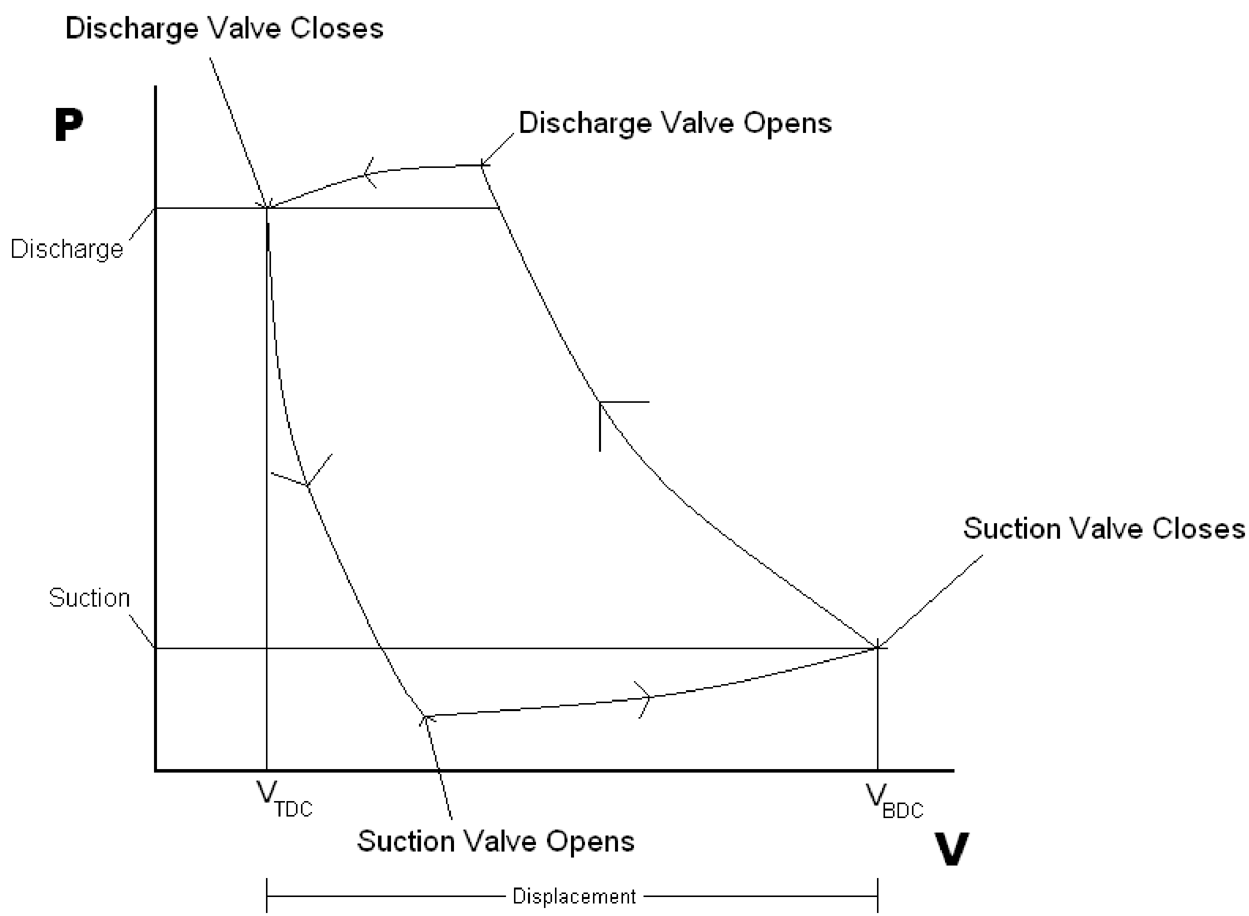
Signal Burst Method

- Bursts of signal can be sent through transducers with the microprocessor waiting for input
- The % Error is inversely proportional to the number of times the microprocessor checks for new information per second.



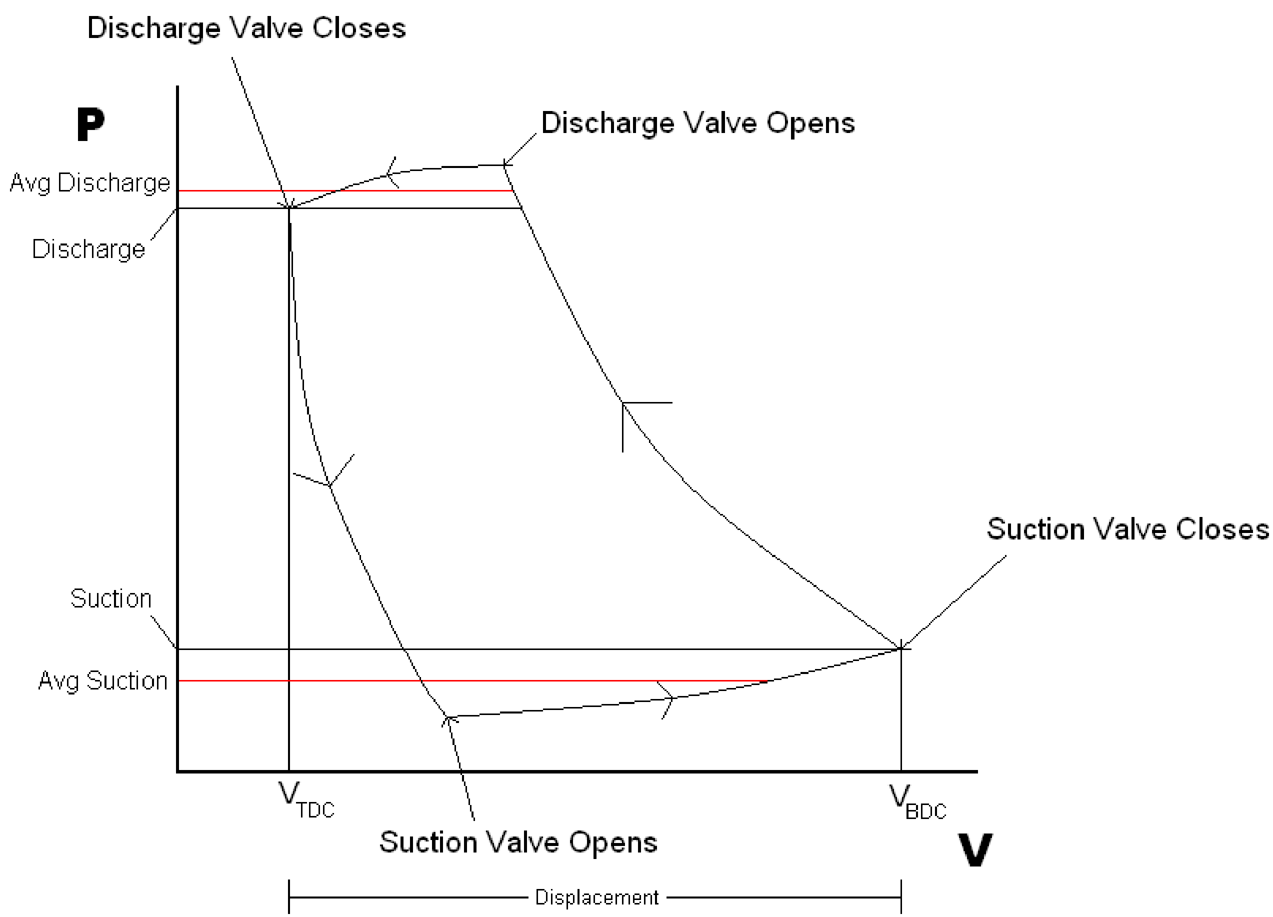


P-V Diagram



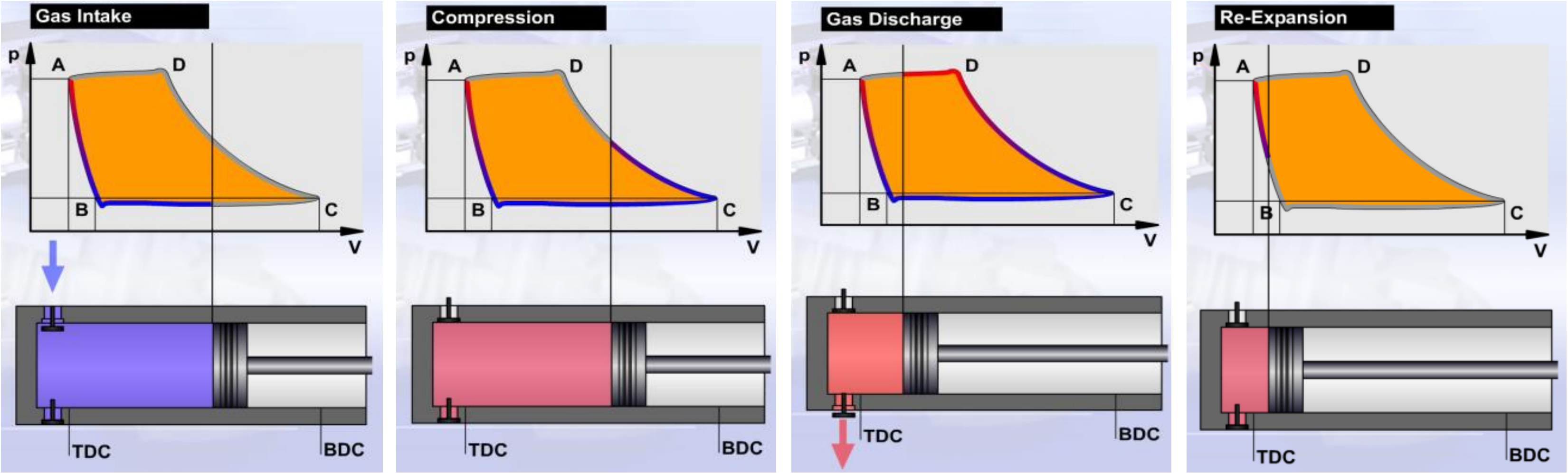
Discharge Valve Closes
P
Discharge Valve Opens
Discharge
Suction Valve Closes
Suction
V_TDC
V_BDC
Suction Valve Opens
V
Displacement

P-V Diagram


Discharge Valve Closes
P
Discharge Valve Opens
Avg Discharge
Discharge
Suction Valve Closes
Suction
Avg Suction
V
TDC
V
BDC
Suction Valve Opens
V
Displacement

P-V Diagram

pv_diagram_eng.exe



Calculating Pressure in Pipe

- Pressure in P-V Diagram is Total Pressure
- Total pressure defined as:

$$P_{total} = P_{static} + P_{dynamic}$$

- However, static pressure cannot be measured

Calculating Static Pressure

- Previously, we had proposed to calculate static pressure based on assumed suction pressure, suction and discharge temperatures, and compression ratio, and model the curve using these static pressures with the measured dynamic pressure
- Discharge Pressure (ideal):

$$P_2 = P_1 \frac{V_1}{V_2} \frac{T_2}{T_1}$$

- Where:
  - V_1/V_2 = compression ratio
  - T_1 and T_2 are measured or assumed
  - P_1 is known or assumed

Static Pressure

- Wholly insufficient and very inaccurate way to model the P-V curve
- Too many assumptions made to calculate static pressure
- Static pressure up to 200x magnitude of dynamic pressure
- As a result, any appreciable change in flow would not be seen on the curve (too far out of scale)

Dynamic Pressure

- P-V curve will be modeled on dynamic pressure only
- So, any difference in our P-V curve from ideal case will be due solely to change in dynamic pressure:

$$P_{dynamic} = \frac{1}{2}\rho V^2$$

- Not a good assumption if real cylinder total pressure measurement is needed, but good enough to graphically represent a flow problem in a compressor

Varying Pressures Along Pipe Length

- Transducers need to be mounted in specific locations, specified distances away from valves, bends or pipe reducers
- Need method of normalizing suction and discharge pressures to comparable values along varying lengths of pipe

Pressure Drop in Pipe

- Pressure drop in pipe between valve and transducers:

$$\Delta p = f * \frac{L}{D} * \frac{1}{2} \rho V^2$$

- Where:

f = Darcy friction factor

L = distance between valve and middle of transducers

D = inner diameter of pipe

ρ = density of the fluid

V = measured velocity of the fluid in the pipe

Pressure Drop in Pipe

- Friction factor dependent on Reynolds Number:

$$Re = \frac{\rho V D}{\mu}$$

- μ = Dynamic viscosity of the fluid

- No need for real pressure drop numbers - just a consistent manner to compare measured values and normalize for values measured at different pipe lengths
- So assume laminar flow:

$$f = \frac{64}{Re}$$

- No need for Moody charts, much simpler for operator and App

Pressure Drop in Pipe

- Pressure Drop in pipe resolves to:

$$\Delta p = \frac{8\mu LV}{3D^2}$$

- Using common units

- L in inches
- D in inches
- V in $\frac{ft}{s}$
- μ in $\frac{lb_f * s}{ft^2}$

Calculating Cylinder Pressure

- Discharge:

$$P_{cyl} = P_{measured} + \Delta p$$

$$P_{cyl} = \frac{\rho {V_{discharge}}^2}{9273.6} + \frac{8\mu L V_{discharge}}{3D^2}$$

- Suction:

$$P_{cyl} = P_{measured} - \Delta p$$

$$P_{cyl} = \frac{\rho {V_{suction}}^2}{9273.6} - \frac{8\mu L V_{suction}}{3D^2}$$

Specifying Flow

- Aside from the P-V curve, main parameter needed is volumetric flow rate
- Each compressor has specified ideal flow rate and efficiency
- This is the bottom line showing the output of natural gas
- Efficiency can be calculated:

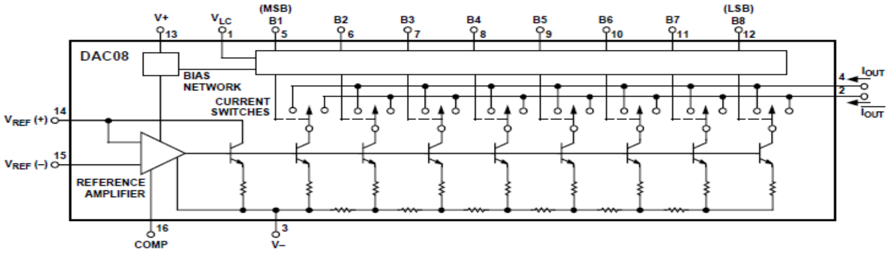
$$\eta = \frac{\upsilon_{measured}}{\frac{\pi}{4} * bore^2 * stroke * rotational\ speed}$$

- Where:

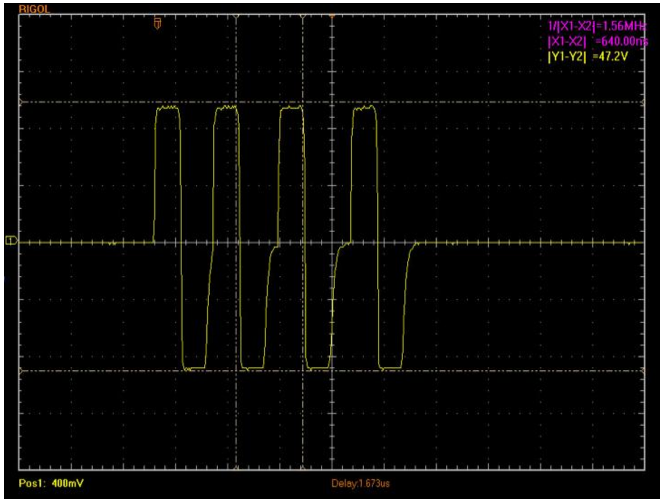
$$\upsilon_{measured} = V_{measured} * A_{pipe}$$

Signal Generation

- In order to generate a clean >100Khz signal, an external DAC may be needed
- Analog Devices Inc. carries a range of DAC's < $20 that are capable of doing this
- Will be amplified to 50Vpp before being sent to transducer.



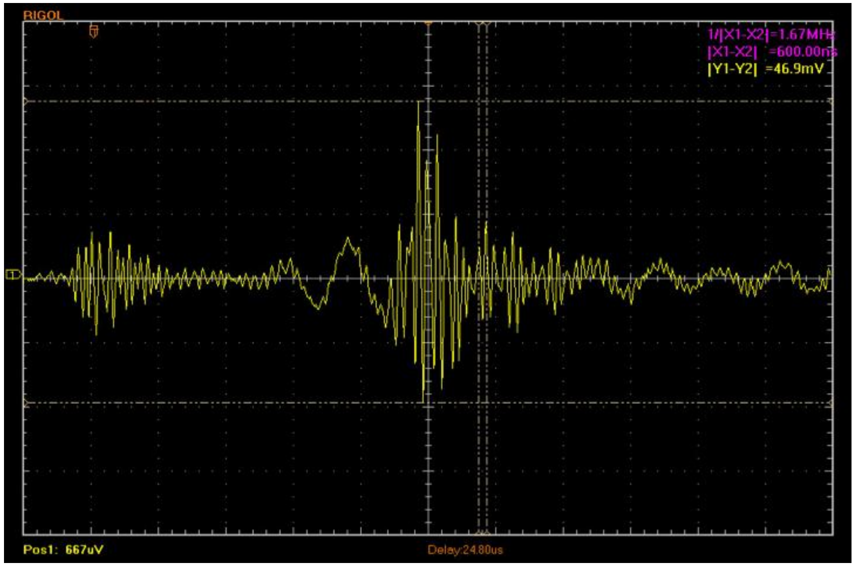
Analog Devices DAC08



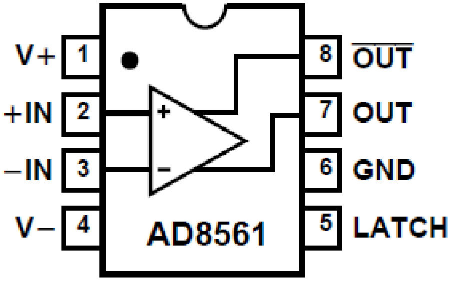
Pulse Sent From FUJI Meter

Processing Using Signal Burst

- Time stamps are used, calculate the time it takes for a single burst to reach the receiver.
- Burst can be detected by two methods:
  - Comparator used, triggers an interrupt to SBC when signal reaches certain voltage level corresponding to center of burst.
  - Sampled with ADC, beginning and end of burst identified.



Signal Seen From Transducer



AD 8561 Comparator

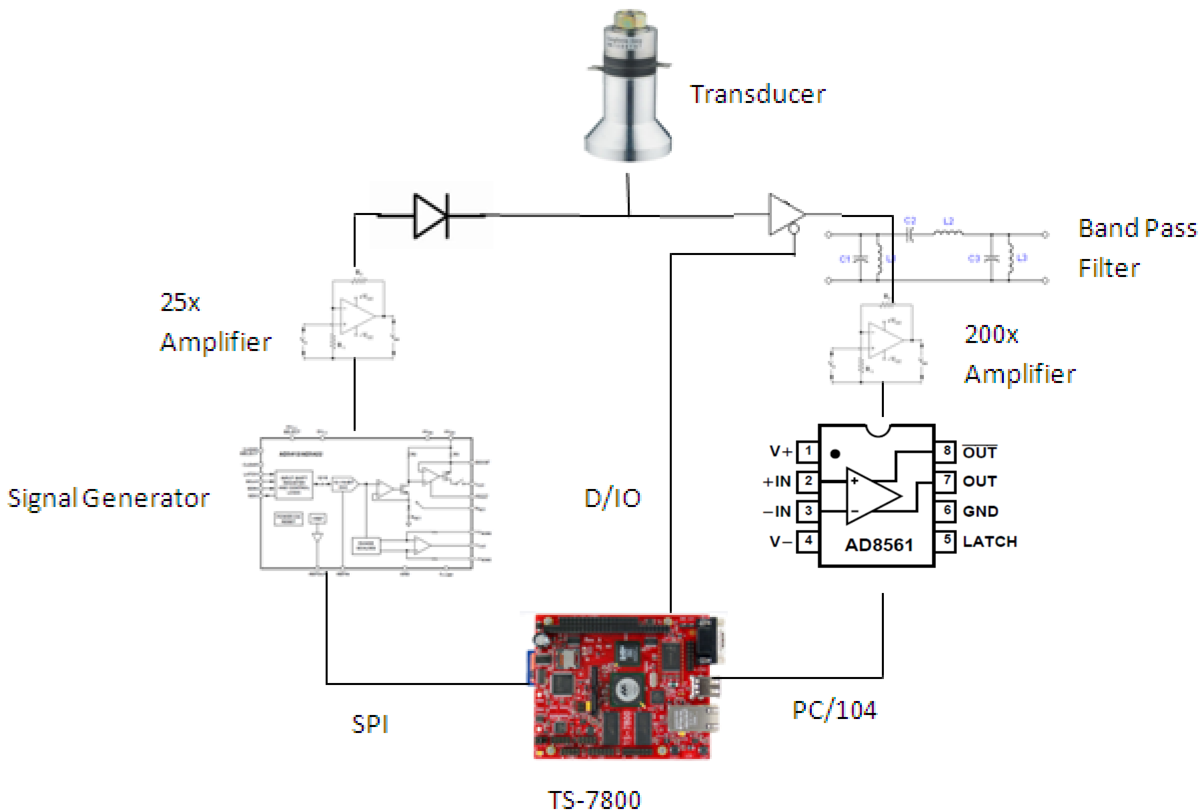
Processing Using Cross Correlation

- 100Khz = Minimum frequency for an ultrasonic signal to properly penetrate a gas medium.
- The cross-correlation method requires us to reconstruct that >100Khz sine wave => our Analog to Digital converter must at least sample at 200Khz as per Nyquist Theorem. Realistically would like to sample much more than 2x.
- Floating point calculations required which a simple 8-bit microcontroller (i.e. Arduino), cannot do fast enough to have proper throughput.

TS-7800 SPC
500Mhz ARM9 CPU
Built-in 2khz ADC

TS-ADC24 Add-on
2Mhz ADC

Signal Processing Circuit



Top-Level Diagram For Signal Processing Circuit On a Single Transducer

Time Stamping

- Crucial for accurately determining transit time when using signal burst method.
- Time between receiving signal burst and stamping time needs to be either:
  - Small as possible to be neglible.
  - Reproducible (Can be accounted for when calculating velocity).
  - Will be determined experimentally.

```
//Thread1
While(1)
{
        Lock_thread();
        Send_Signal_Trans2();
        Double time_sent2=time_stamp();
        While(!Signal_Received_Trans1);
        Double time_received2=time_stamp();
        Send_Signal_Trans1();
        Double time_sent1=time_stamp();
        While(!Signal_Received_Trans2());
        Double time_received2=time_stamp();
        Unlock_thread();
}
```

```
//Thread 2
While(1)
{
        Lock_thread();
        Transtime1=time_received1-time_sent1;
        Transtime2=time_recevied2-time_sent2;
        Velocity=((Transtime2-Transtime1)/(Transtime1*Transtime2))*(L/cos(theta)); //theta and L are known
        Send_to_phone(velocity);
        Unlock_thread();
}
```

Time Stamping

Options For Improving Time Stamp Precision:

Increase Tick Rate in Kernel:

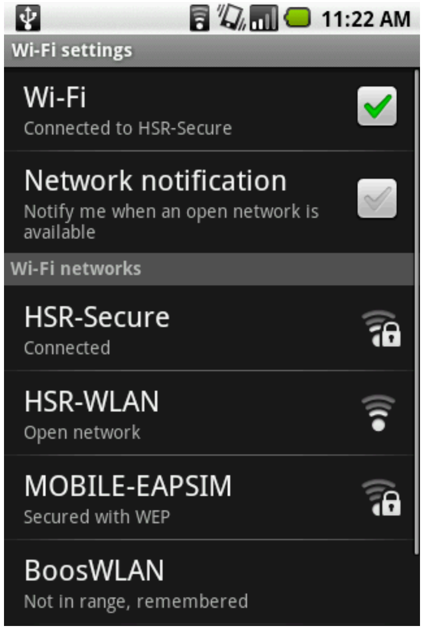
- How often a new instruction is checked for
- May help decrease propagation time

Use Real-Time Kernel Patch:

- Eliminates preemption of tasks
- Jobs that are deemed real-time are processed till finished, can't be interrupted
- Thread used for time-stamping can be set as highest priority and set to be real-time

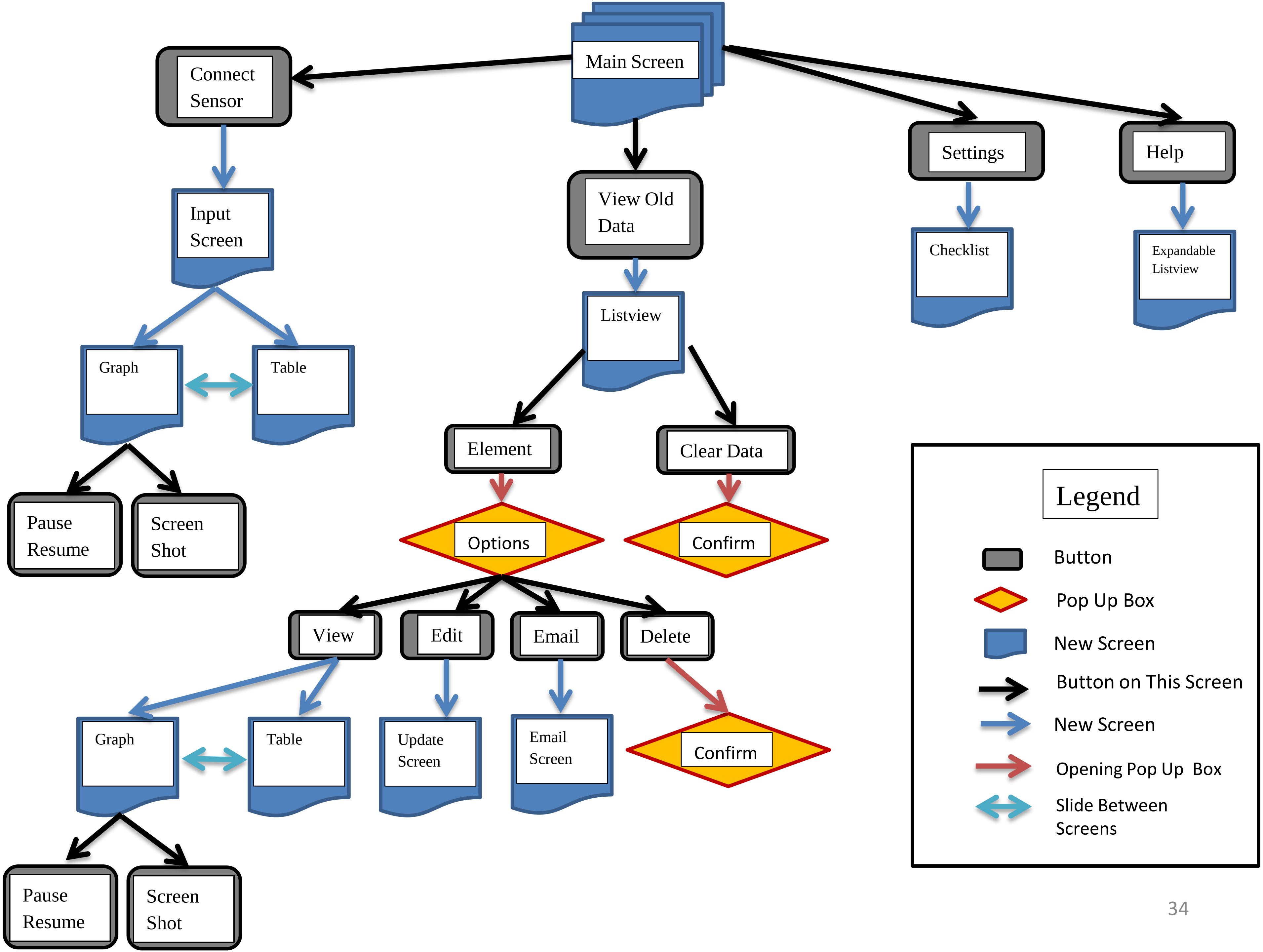
Communication To Phone

- 802.11 Direct Wi-Fi
  - Proper Wi-Fi module would need to be purchased and implemented.
  - Can configure operating system to setup Wi-Fi module as an access point.
  - 11Mbps Bandwidth.
  - Secured by WEP.
- BlueTooth
  - Proper BlueTooth module would need to be purchased and installed.
  - ~10m range.
  - 800-1000Kbps Bandwidth
  - May present some security issues.



Application Design

- Collect Transmitted data from Data Processing Unit
- Store data on phone
- Calculate velocity to pressure conversions
- Graph data on PV curve

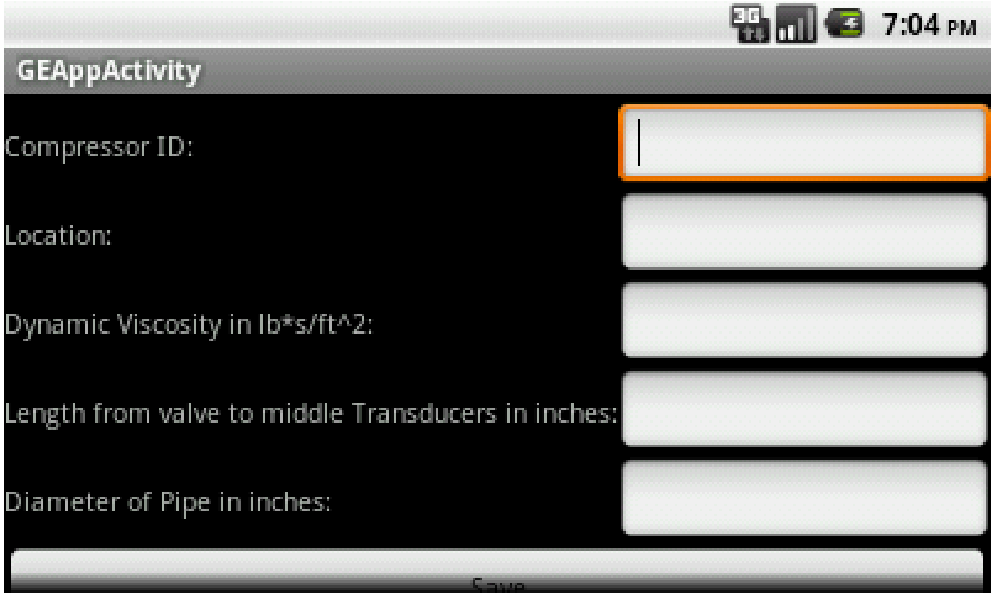

Main Screen
Connect Sensor
Input Screen
Graph
Table
Pause Resume
Screen Shot
View Old Data
Listview
Element
Clear Data
Options
Confirm
View
Edit
Email
Delete
Graph
Table
Update Screen
Email Screen
Confirm
Pause Resume
Screen Shot
Settings
Checklist
Help
Expandable Listview
Legend
Button
Pop Up Box
New Screen
Button on This Screen
New Screen
Opening Pop Up Box
Slide Between Screens

Main Screen

- Connect Sensor: check Wi-Fi connection and move to inputform
- View Old Data: shows list of old data and offers more options
- Preferences: different options for customizations
- Help: list of info explaining all functions of the application

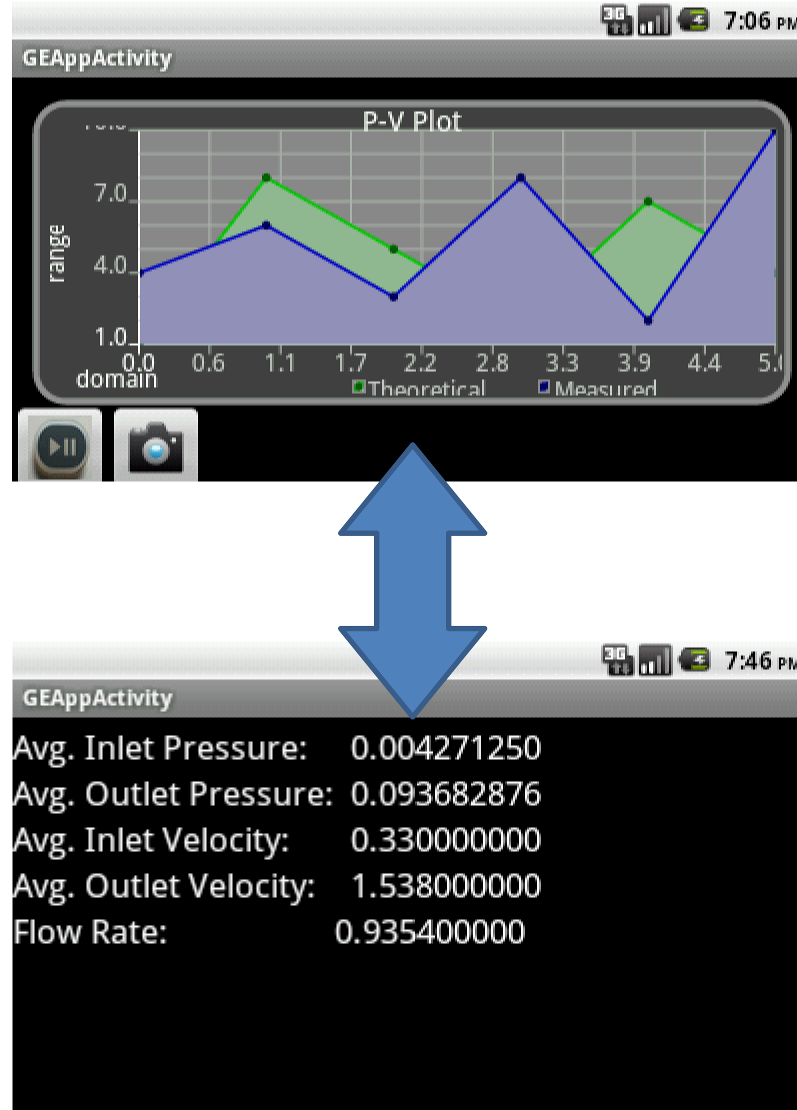
Input Screen

- Creates new entry for database
- Also takes in values from user required for calculations
- Pressing enter will signal to start receiving data from MCU and go to graph

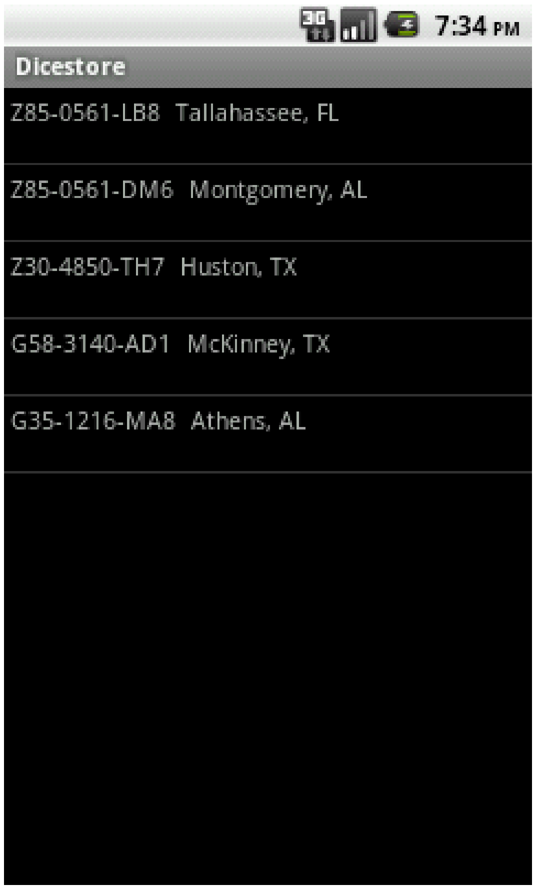


Data Screens

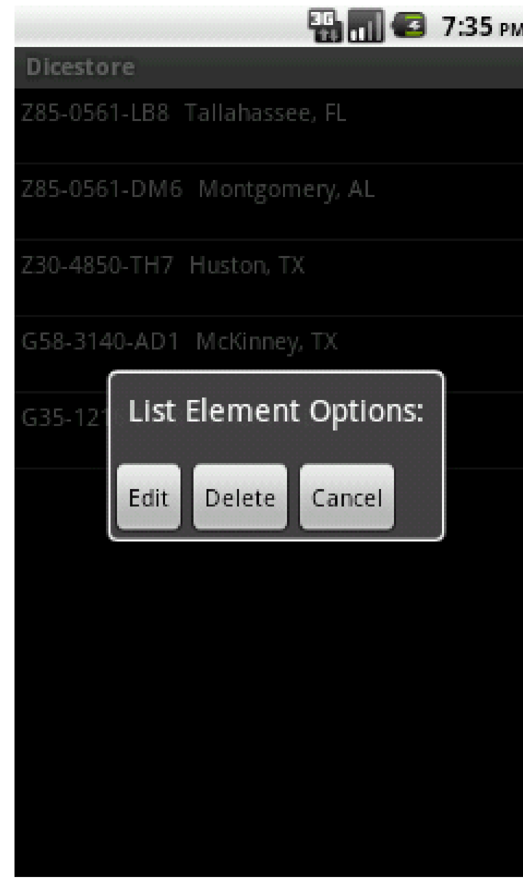
- Display data in PV graph and table
- Allows to Pause/Resume live plotting
- Screenshot the graph
- Table consists of additional info not on graph
- SlideView allows user to go between graph and table by sliding finger on screen



ListView Screen

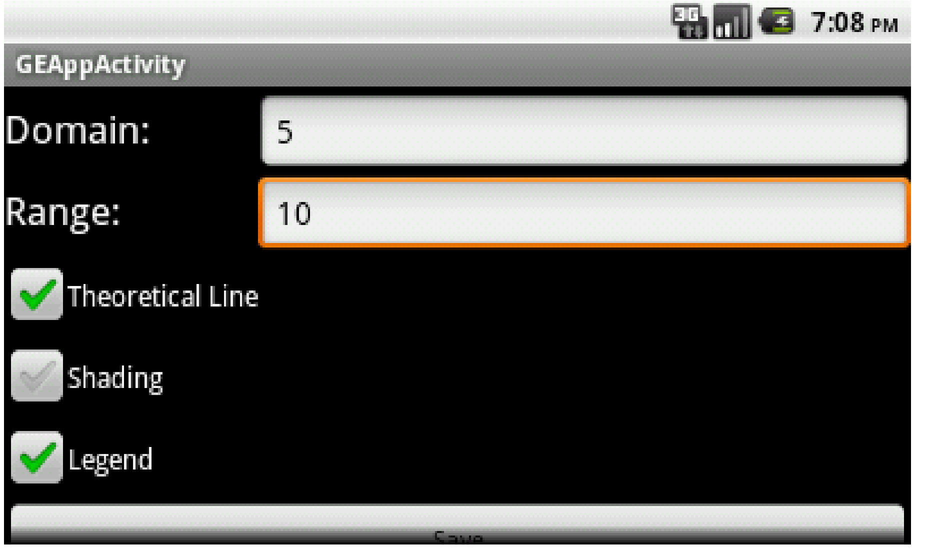


- Shows list of old data
- Sort by compressor or location
- Clicking on element in list opens more options
- Allows for editing of inputted info
- Allows for delete
- Allows for viewing old data in graph and table



Preferences Screen

- Allows for more customization of graph
- Input domain and range
- Check on/off other settings



Mounting System (LMA)

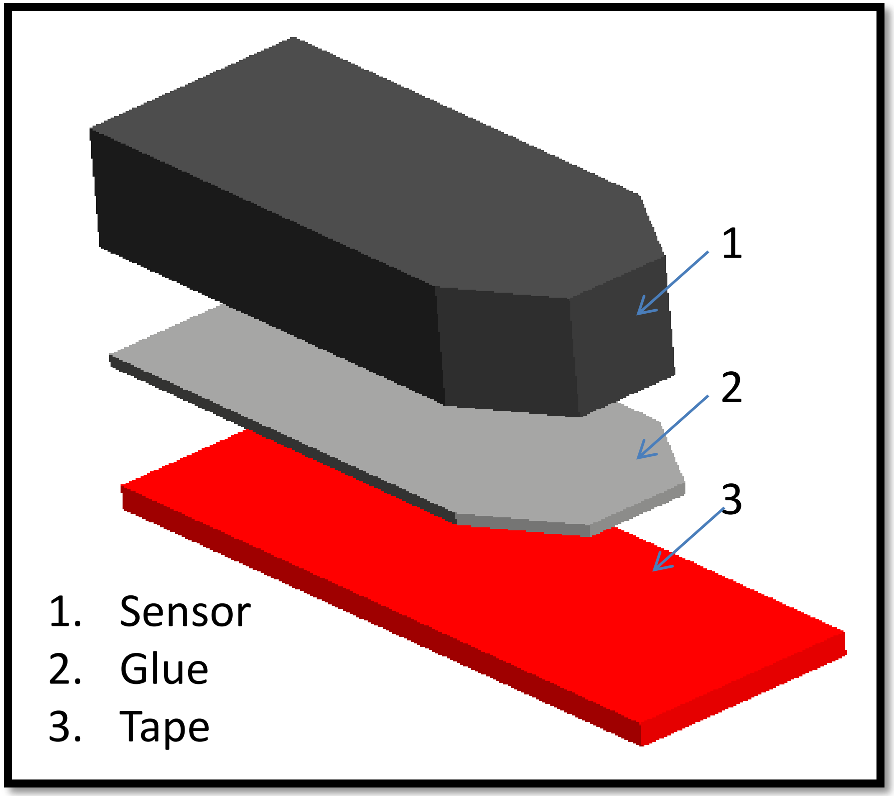
Lubricating

Measuring

Attaching

Pre-lubricated Sensors

Lubrication is used as an acoustic couplet



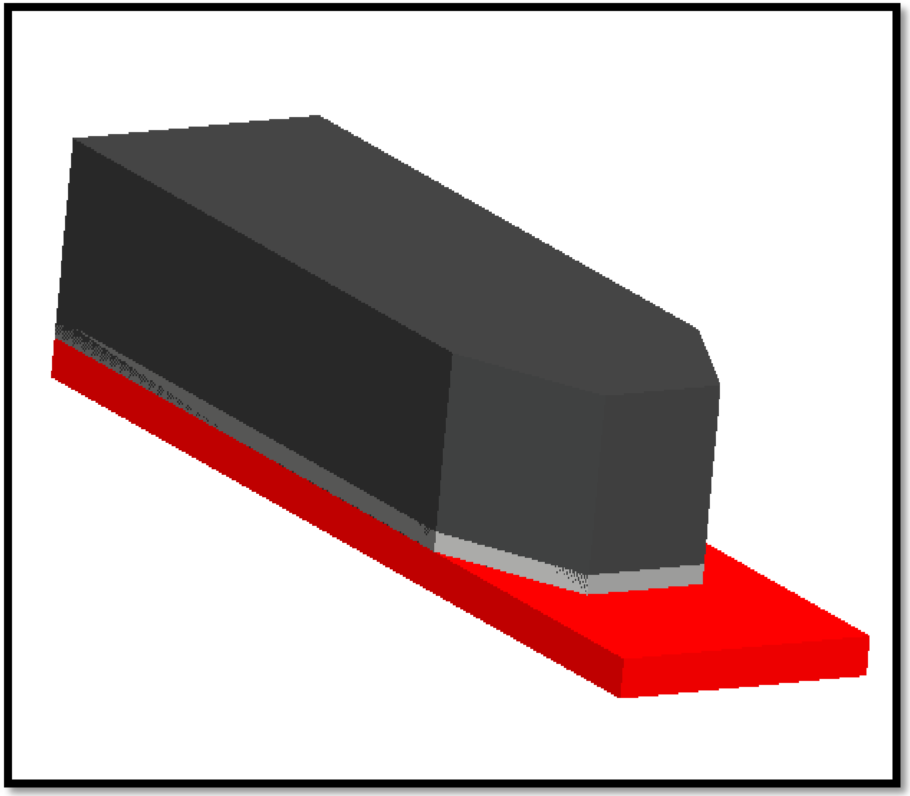


Figure 1: Exploded View

Figure 2: Assembled View

Pre-lubricated Sensors: Tape Analysis

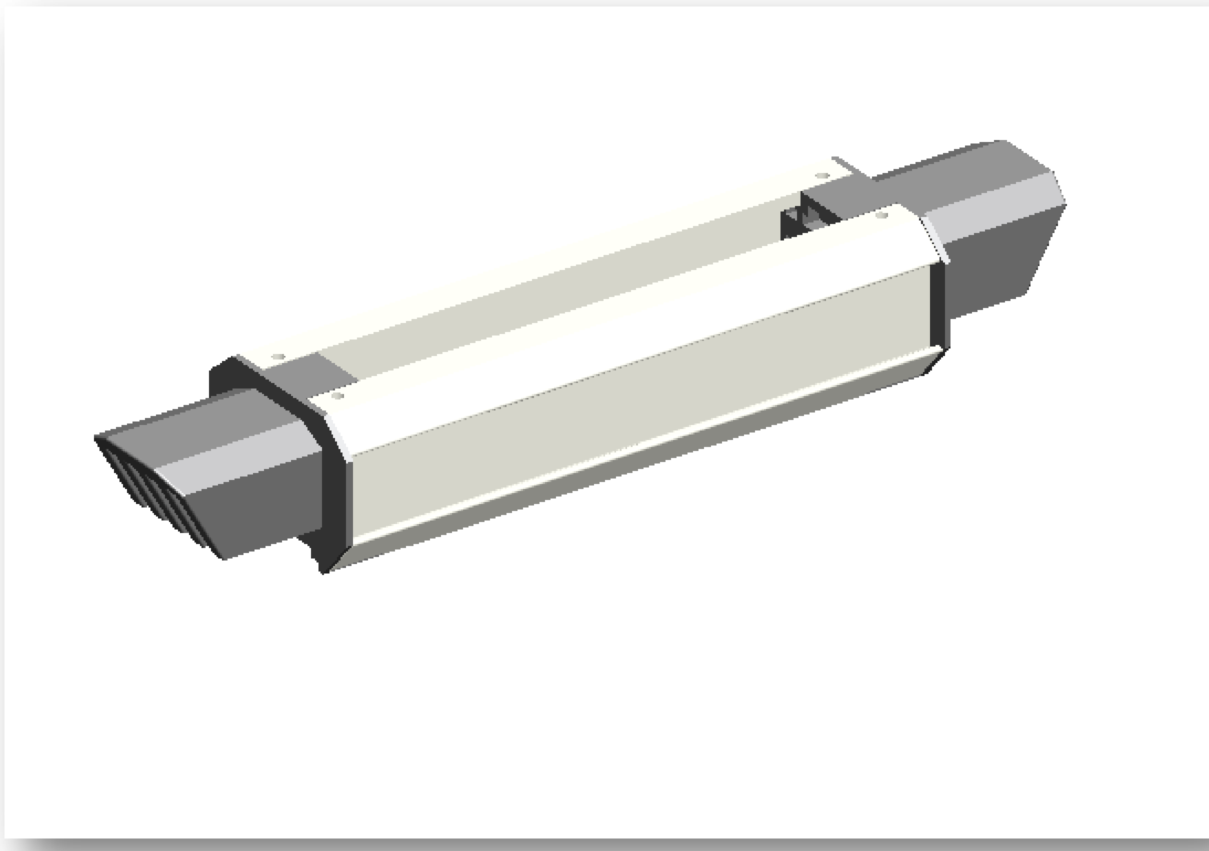
Tapes and Adhesives	Pros	Cons
Polyamide film coated with a high performance silicone adhesive (PFC)	• Thin • Conformable • Resistant to tear /abrasion at high temperatures. • Resistance • Acids • Oils • Solvents	Adhesive will thermo-set to higher values
Low density polyethylene film tape with Acrylic adhesive (LDP)	• Conformable • Great moisture barrier properties. • UV resistant.	Too strong for this application, it will leave a residual
High Quality aluminum foil with Uglu (HQA)	• Non toxic • Waterproof • Weatherproof. • Be cleanly removed • Bonds to most any surface	Needs a foil lining, not a tape.

Pre-lubricated Sensors: Tape Analysis

Push Matrix for Lubrication Tape					
Design Features	Current Methods	PFC	LDP	HQA	Importance Rating
Cost	0	-2	-1	-1	1.00
Removability	0	-2	-2	-1	2.00
Feasibility	0	-1	-1	3	4.00
Functionality	0	2	2	3	3.00
Sum	0	-3	-2	4	
Total	0	-4	-3	18	

Measuring

- Utilizing existing track on the ultrasonic transducers



Attaching

1. Velcro Bands

Provided by Long & McQuade Musical Instruments

2.Interlocking Clamp

Provided by directindustry.com

3. Quick Release Hose Clamps

Provided by kshoseclamp.com

4. Magnetics

Provided by northerntool.com

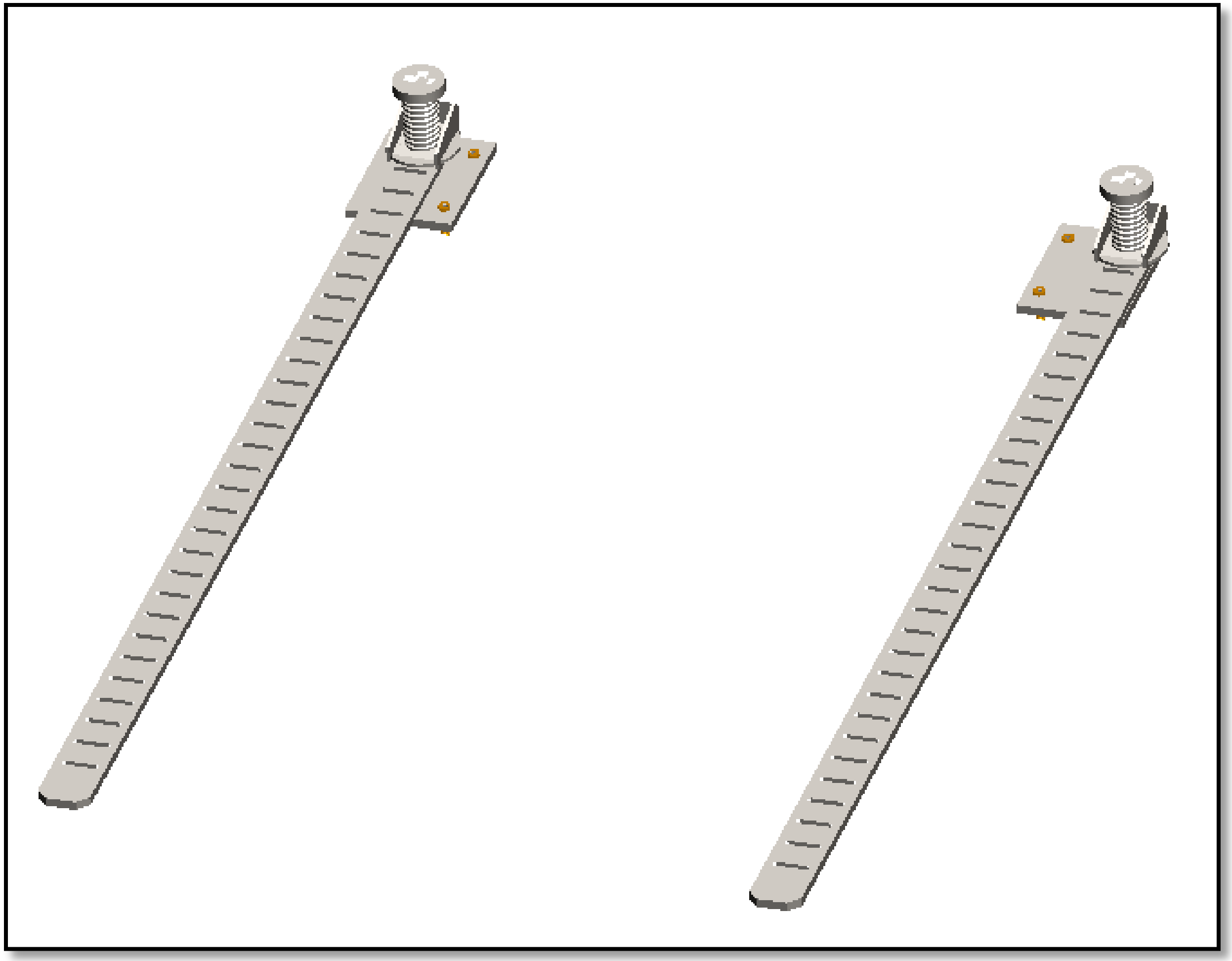
Attaching Analysis

Analytical Hierarchy Process						
	Cost	Lead Time	Installation	Functiona	Usability	Importance Rating
Cost	1	3	1/7	1/9	1/5	4.45
Lead Time	1/3	1	1/9	1/7	1/7	1.73
Installation Time	7	9	1	1	1/3	18.33
Functionality	9	7	1	1	1	19.00
Usability	5	7	3	1	1	17.00

Attaching Analysis

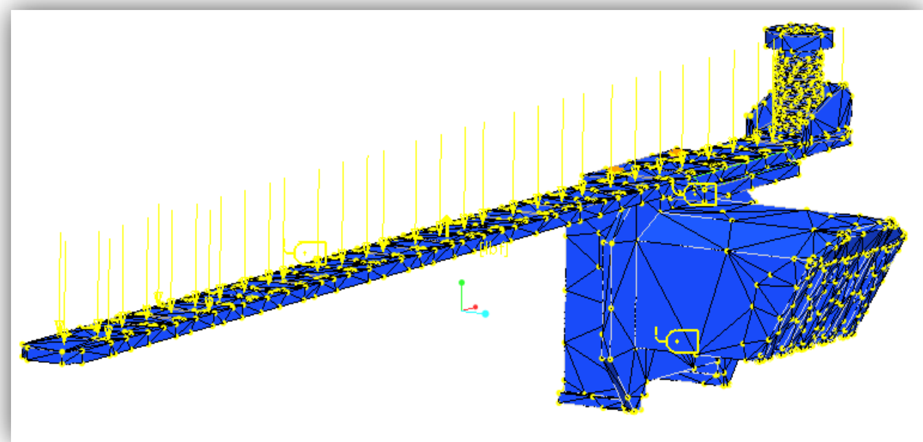
Push Matrix						
Design Freatures	Current Methods	Velcro Bands	Quick Release Clamps	Interlocking Clamps	Magnetics	Importance Rating
Cost	0	-1	-2	-3	-3	4.45
Lead Time	0	1	-1	-2	-1	1.73
Installation Time	0	-1	2	-2	3	18.33
Functionality	0	3	2	-1	-3	19.00
Usability	0	1	1	-1	2	17.00
Sum	0	3	2	-9	-2	
Total	0	52.942857	81.02857143	-89.48888889	16.90794	

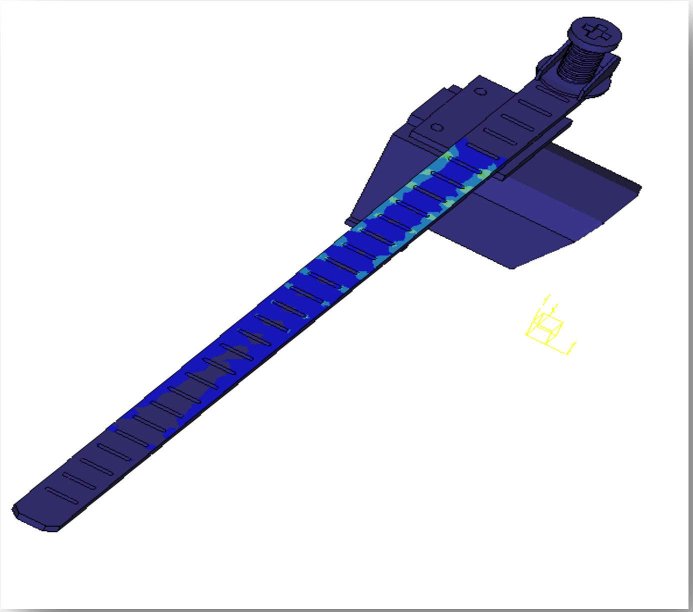
Pro-Engineer Model



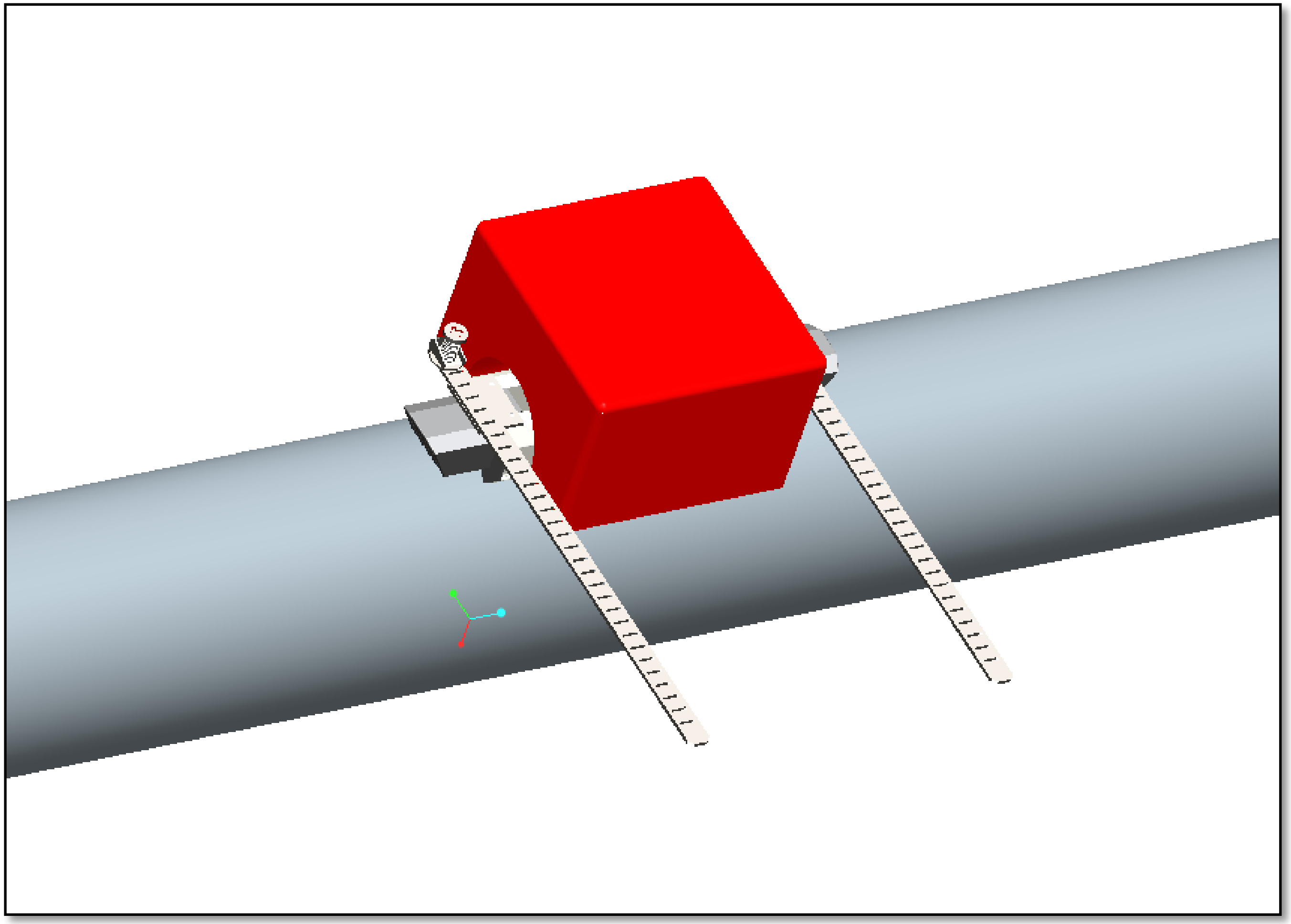
Principle Stress Analysis with FEM Analysis

- Finite Element Analysis (FEA) was done in Pro-Engineer.





Pro-Engineer Model



Environmental and Health Concerns

- Natural Gas compressors have their own concerns
- Our device has no particular concern in and of itself
- Wireless communication specified to take the operator out of the violent compressor environment while measuring and analyzing
- AGA 9 requires electrical equipment to be rated to operate in hazardous environments per NFPA 70

Cost

Sensors	Unit Price	Quantity	Cost
Fuji ultrasonic flow meters*	$950	1	$950
Data Processing Hardware			
Single-Board PC	$269	1	$269
WiFi interface	$35	1	$35
Battery pack	$20	1	$20
A-D Converter	$109	1	$109
DACs	$3	3	$8
Comparators	$5	3	$14
Breadboards	$9	2	$18
Op Amps	$7	3	$21
Switches	$3	3	$8
Data Processing Subtotal			**$502**
Total			**$1,452**

* We have acquired a set to borrow for the duration of this project

References

- "1" Rescue Tape - Self Fusing Silicone Waterproof Tape - Filmtools." *Filmtools: Hollywood's Source for Motion Picture and Digital Video Equipment and Supplies - Filmtools*. Web. 07 Dec. 2011. <http://www.filmtools.com/rescuetape1.html>.
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Questions?

Input v (ft^3/s), T (unitless, magnitude of degrees Fahrenheit), D (in) and ρ (lbm/ft^3).
Flow rates and temperatures taken from a GE HSR Compressor Performance Report.
Densities derived from temperatures and static pressures in report.
Diameter of pipe assumed, and L chosen based on pipe diameter.

$v_s := 9.375 \frac{ft^3}{s}$ $v_d := 19.329 \frac{ft^3}{s}$ $\rho_s := 2.9 \frac{lbm}{ft^3}$ $\rho_d := 6.18 \frac{lbm}{ft^3}$

$T_s := 298.$ $T_d := 225.$

$D := 4in$ $L := 10 \cdot D$

$A_{pipe} := \left(\frac{\pi}{4}\right) \cdot D^2$ $L = 40in$ $V_s := \frac{v_s}{A_{pipe}}$ $V_d := \frac{v_d}{A_{pipe}}$

Dynamic Pressure

$q_s := \left(\frac{1}{2}\right) \cdot \rho_s \cdot V_s^2$ $q_d := \left(\frac{1}{2}\right) \cdot \rho_d \cdot V_d^2$

Pressure Drop in Pipe

$$\mu_s := \left[\left(-6.70244 \cdot 10^{-14}\right) \cdot T_s^2 + \left(5.05027 \cdot 10^{-10}\right) \cdot T_s + \left(3.43615 \cdot 10^{-7}\right)\right] lbf \cdot \frac{s}{ft^2}$$

$$\mu_d := \left[\left(-6.70244 \cdot 10^{-14}\right) \cdot T_d^2 + \left(5.05027 \cdot 10^{-10}\right) \cdot T_d + \left(3.43615 \cdot 10^{-7}\right)\right] lbf \cdot \frac{s}{ft^2}$$

$Re_s := \frac{(\rho_s \cdot V_s \cdot D)}{\mu_s}$ $Re_d := \frac{(\rho_d \cdot V_d \cdot D)}{\mu_d}$

$f_s := \frac{64}{Re_s}$ $f_d := \frac{64}{Re_d}$ $V_s = 107.43 \frac{ft}{s}$

$\Delta p_s := \frac{\left(f_s \cdot L \cdot \rho_s \cdot V_s^2\right)}{2 \cdot D}$ $\Delta p_d := \frac{\left(f_d \cdot L \cdot \rho_d \cdot V_d^2\right)}{2 \cdot D}$ $V_d = 221.494 \frac{ft}{s}$

$P_s := q_s - \Delta p_s$ $P_d := q_d + \Delta p_d$

$\Delta p_s = 3.498 \times 10^{-4} \cdot psi$ $\Delta p_d = 6.705 \times 10^{-4} \cdot psi$

$q_s = 3.612 psi$ $q_d = 32.72 psi$

$P_s = 3.612 psi$ $P_d = 32.721 psi$

Transit Time Calculations

Smallest Δt will occur in case where fluid velocity is closest to zero, thus using largest diameter pipe, lowest flow rate, and highest speed of sound (higher temperature). This combination will never happen, so this is a conservative calculated verification. Also, the length between the transducers is recommended to be same as the outer pipe diameter, so L = D and the incident angle = 45deg/2

$v := .327 \frac{ft^3}{s}$ $D := 6in$

$A_{pipe} = 12.566 in^2$ $V := \frac{v}{A_{pipe}}$

$V = 3.747 \frac{ft}{s}$ $\alpha := 22.5 deg$

$$a := \left[\left(-2.03888 \cdot 10^{-4}\right) T_s^2 + \left(1.00405 \cdot T_s\right) + \left(1.05713 \cdot 10^3\right)\right] \frac{ft}{s}$$

$V_{up} := a \cdot \sin(\alpha) - V$ $V_{down} := a \cdot \sin(\alpha) + V$

$V_{up} = 508.507 \frac{ft}{s}$ $t_{up} := \frac{D}{V_{up}}$

$V_{down} = 516.001 \frac{ft}{s}$ $t_{down} := \frac{D}{V_{down}}$

$t_{up} = 9.833 \times 10^{-4} s$ $t_{down} = 9.69 \times 10^{-4} s$

$\Delta t := t_{up} - t_{down}$ $\Delta t = 1.428 \times 10^{-5} s$

Established Transit Time Velocity Equation

$V_{ax} := \left(\frac{D}{2 \cdot \cos(\alpha)}\right) \cdot \left(\frac{\Delta t}{t_{up} \cdot t_{down}}\right)$ $Error := \left[1 - \left(\frac{V}{V_{ax}}\right)\right]$

$V_{ax} = 4.056 \frac{ft}{s}$ $Error = 7.612\%$

Therefore, correct method was used to calculate Δt

Justification for Laminar Flow

$\rho := .075 \frac{lbm}{ft^3}$

$V_{high} := 3000 \frac{ft}{min}$ $\quad V_{low} := 100 \frac{ft}{min}$ $\quad k := 1.5 \cdot 10^{-3} ft$

$D_{high} := 6in$ $\quad D_{low} := 4in$ $\quad L_{high} := 10 \cdot D_{high}$ $\quad L_{low} := 10 \cdot D_{low}$

$T_{high} := 30($ $\quad T_{low} := 6($ $\quad r_{high} := \frac{k}{D_{high}}$ $\quad r_{low} := \frac{k}{D_{low}}$

$$\mu_{low} := \left[\left(-6.70244 \cdot 10^{-14}\right) \cdot T_{low}^{2} + \left(5.05027 \cdot 10^{-10}\right) \cdot T_{low} + \left(3.43615 \cdot 10^{-7}\right)\right] lbf \cdot \frac{s}{ft^2}$$

$$\mu_{high} := \left[\left(-6.70244 \cdot 10^{-14}\right) \cdot T_{high}^{2} + \left(5.05027 \cdot 10^{-10}\right) \cdot T_{high} + \left(3.43615 \cdot 10^{-7}\right)\right] lbf \cdot \frac{s}{ft^2}$$

$Re_{high} := \frac{(\rho \cdot V_{high} \cdot D_{high})}{\mu_{high}}$ $\quad Re_{low} := \frac{(\rho \cdot V_{low} \cdot D_{low})}{\mu_{low}}$

$f_{high} := \frac{64}{Re_{high}}$ $\quad f_{low} := \frac{64}{Re_{low}}$

$Re_{high} = 1.192 \times 10^{5}$ $\quad Re_{low} = 3.466 \times 10^{3}$

$r_{high} = 3 \times 10^{-3}$ $\quad r_{low} = 4.5 \times 10^{-3}$

$f_{high} = 5.371 \times 10^{-4}$ $\quad f_{low} = 0.018$

$f_{high.Moody} := .02($ $\quad f_{low.Moody} := .04($

$\Delta f_{high} := f_{high.Moody} - f_{high}$ $\quad \Delta f_{low} := f_{low.Moody} - f_{low}$

$\Delta f_{high} = 0.027$ $\quad \Delta f_{low} = 0.031$

$$\Delta p_{high.1} := f_{high} \cdot \left(\frac{L_{high}}{D_{high}}\right) \cdot \frac{\left(\rho \cdot V_{high}^{2}\right)}{2}$$

$$\Delta p_{high.2} := f_{high.Moody} \cdot \left(\frac{L_{high}}{D_{high}}\right) \cdot \frac{\left(\rho \cdot V_{high}^{2}\right)}{2}$$

$$\Delta p_{low.1} := f_{low} \cdot \left(\frac{L_{low}}{D_{low}}\right) \cdot \frac{\left(\rho \cdot V_{low}^{2}\right)}{2}$$

$$\Delta p_{low.2} := f_{low.Moody} \cdot \left(\frac{L_{low}}{D_{low}}\right) \cdot \frac{\left(\rho \cdot V_{low}^{2}\right)}{2}$$

$\Delta p_{high.2} - \Delta p_{high.1} = 5.557 \times 10^{-3} psi$

$\Delta p_{low.2} - \Delta p_{low.1} = 6.865 \times 10^{-6} psi$

$\Delta p_{high.2} = 5.666 \times 10^{-3} psi$ $\quad \Delta p_{low.2} = 1.102 \times 10^{-5} psi$ $\quad$ Moody Diagram

$\Delta p_{high.1} = 1.087 \times 10^{-4} psi$ $\quad \Delta p_{low.1} = 4.152 \times 10^{-6} psi$ $\quad$ Laminar

$q_{high} := \frac{\left(\rho \cdot V_{high}^{2}\right)}{2}$ $\quad q_{low} := \frac{\left(\rho \cdot V_{low}^{2}\right)}{2}$

$q_{high} = 0.02 psi$ $\quad q_{low} = 2.248 \times 10^{-5} psi$

$\frac{(\Delta p_{high.2} - \Delta p_{high.1})}{q_{high}} = 0.275$ $\quad \frac{(\Delta p_{low.2} - \Delta p_{low.1})}{q_{low}} = 0.305$

$$1 - \left[\frac{\left[\frac{(\Delta p_{high.2} - \Delta p_{high.1})}{q_{high}}\right]}{\frac{(\Delta p_{low.2} - \Delta p_{low.1})}{q_{low}}}\right] = 10.056\%$$

Difference in total Δ p is a maximum of 10% when assuming laminar vs. turbulent flow