A LabVIEW Based Respiratory Sounds Reconstruction Tool

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KEYWORDS

Respiratory Sounds, Cough Sounds, Sound Reconstruction, Signal Processing, LabVIEW Application

ABSTRACT

The purpose of this project was to develop an auscultatory system capable of training health care workers to identify components of respiratory sounds associated with lung disease. A LabVIEW based playback system accurately recreates respiratory sounds obtained using a previously described recording system [1]. Under ordinary conditions, the original sound is distorted by the amplifier, speaker and surroundings. The reconstruction tool modifies the signal delivered to the speaker in such a way as to reproduce the signal as it was originally generated by the patient. A graphical user interface displays the recorded time signal and time-frequency distribution. Complete respiratory sounds or selected components, such as a single wheeze, can then be played back accurately. Components of the signals are extracted by a time-varying filter, based on user graphical selections. This tool can serve as a user-friendly graphical program which accurately reproduces respiratory sounds for teaching purposes.

INTRODUCTION

Many investigators have shown that alterations in lung structure resulting from a respiratory disease will alter sounds produced within the lung. Over centuries, respiratory sounds have been interpreted and used as a valuable aid in the diagnosis of lung function. Physicians are trained in auscultatory techniques to detect abnormalities of the respiratory system. Current teaching tools which utilize respiratory sounds suffer from the disadvantage that playback environments may affect the sound fidelity. Sound reconstruction techniques can minimize this problem by accounting for environmental conditions. The respiratory sound reconstruction tool reproduces sounds obtained using a previously described recording system [1] which was designed to record voluntary cough and breath sounds at the mouth. The recording system minimizes measurement error resulting from sound reflections yielding a high signal to noise ratio. When the recorded sounds are played back, however, considerable distortion may occur from the speaker and the environment. The ability to produce respiratory sounds as they were originally recorded is important when training health care workers to recognize characteristic sounds associated with lung disease. The goal of this project was to precisely reproduce the recorded respiratory sounds and to aid the training of health care workers in identifying lung sounds associated with respiratory complications.

SYSTEM HARDWARE

A basic diagram of the system hardware is given in Figure 1. The previously recorded respiratory sounds were digitally stored on a computer (Dell Dimension XPS 400) and could be selected for play back using the system software (see software section). A National Instruments Dynamic Signal Acquisition and Generation PCI-4451 (NI DAQ) card was used to record and generate analog signals. A digital to analog converter on the NI DAQ card converted the recorded signal to an analog voltage. The analog signal was then amplified and delivered to the speaker using a Yamaha RX-596 amplifier. The speaker (Atlas Sound PD-5VH) was coupled to a 1" metal tube which had a stethoscope and a 1/4" microphone both mounted tangent to the tube. The sound traveled down the tube where it could be monitored via a stethoscope. A Bruel & Kjaer type 4136 microphone was mounted on the tube 1.5" from the stethoscope port. The close proximity of the microphone and stethoscope enabled approximately the same sound pressure wave to be obtained by both. The NI DAQ card acquired the microphone signal which was then stored on the computer. The sound signal was produced and recorded at a rate of 12800 Hz with 16-bits of resolution. In the following sections of this paper, a previously recorded respiratory sound will be referred to as PRS (previously recorded signal) and the sounds recorded during the playback of a PRS will be referred to as RRS (re-recorded signal).

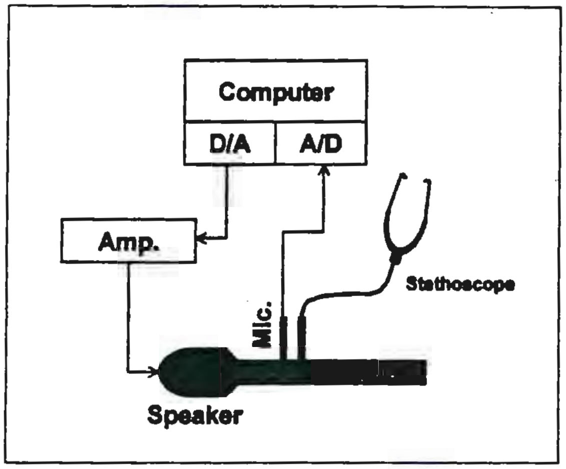

Figure 1 System diagram

ACOUSTICAL RECONSTRUCTION

Ideally, the sound produced in the tube (RRS) and the PRS should be identical. When the respiratory sounds are played, the signal is distorted by the playback system including: the speaker, amplifier and surroundings. Figure 2 illustrates actual system data showing the PRS and the distorted RRS. It can be seen that the sound generated in the tube has been significantly modified by the system components. Acoustical reconstruction techniques were used to predict how the input to the amplifier should be modified to accurately reproduce the original sounds. A stable version of the inverse system model was used to reconstruct the signal. As shown in Figure 3, the inverse model, 1/H(z), was used to cancel the modifications made to the signal by the playback system, H(z).

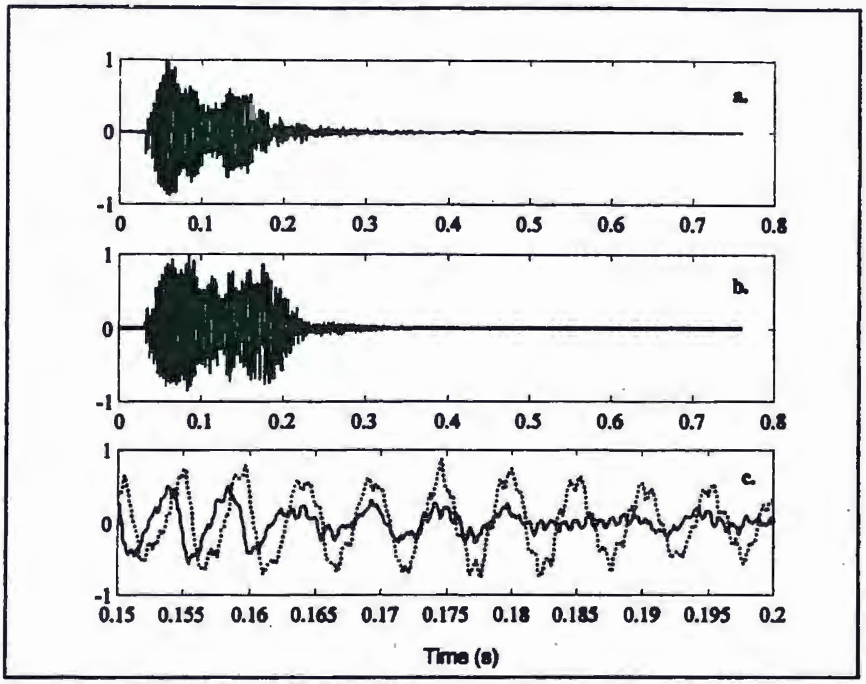

Figure 2 Signal Played Without Reconstruction (a) Plot of PRS (b) Plot of RRS (c) Enlarged portion of the signals, solid = PRS, dotted = RRS

Since the input to the system (PRS) is known and the output of the system (RRS) can be found, the system inverse model can be estimated in the form of a 100th order digital IIR filter. An order of 100 was chosen because it accurately models the system with acceptable computer processing time. Equation 1 shows the general form of the inverse filter. The main LabVIEW program contained Matlab script nodes, which used a batch least squares method to solve for the inverse filter coefficients. It is possible that the solution, however, may have poles outside the unit circle making the inverse filter unstable. To achieve a stable solution the method of adding a delay to the output signal was used [2].

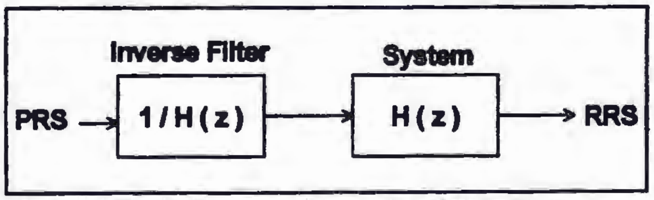

Figure 3 Block diagram of reconstruction technique used to cancel the effects of system distortion.

$$1 / H(z) = \frac{1 + a_1 z^{-1} + a_2 z^{-2} + \ldots a_{100} z^{-100}}{b_0 + b_1 z^{-1} + b_2 z^{-2} + \ldots b_{100} z^{-100}} \tag{1}$$

By employing the inverse model it is possible to reconstruct the PRS and accurately play it back as originally produced. Figure 4 illustrates the same cough as in Figure 2 played with the acoustical reconstruction method described in this section. By comparing Figure 2 and Figure 4 one can see a major improvement made to the accuracy of the systems ability to reproduce respiratory sounds.

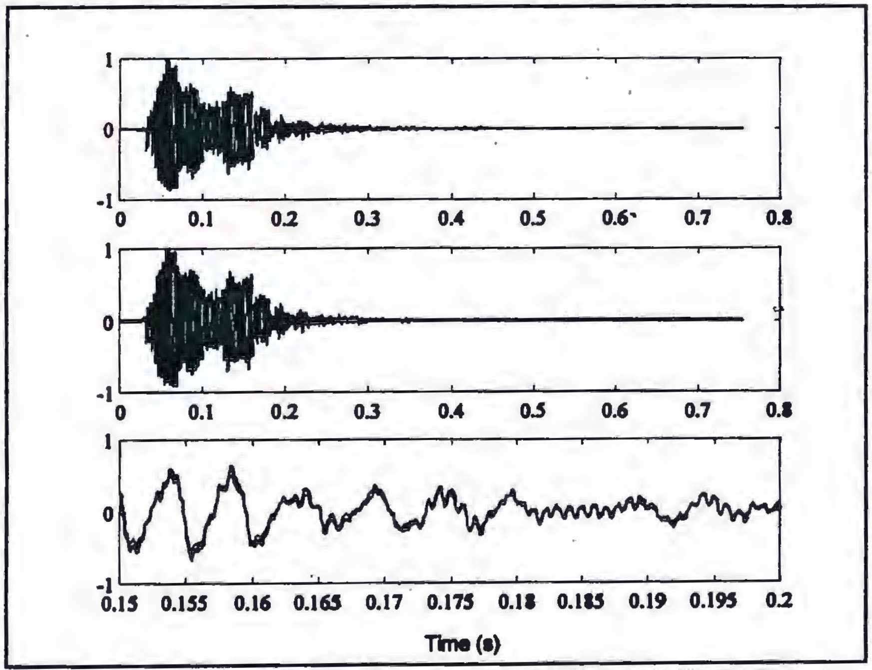

Figure 4 Signal Played With Reconstruction (a) Plot of PRS (b) Plot of RRS (c) Enlarged portion of the signals, solid = PRS, dotted = RRS.

SYSTEM SOFTWARE

The system software was developed in the LabVIEW programming environment. The main user screen can be seen in Figure 5. The time signal display located on the top half of the screen shows both the PRS and the RRS in different colors. The peak magnitudes of the signals are normalized to 1.0 compensating for amplitude differences which occur from the amplifier gain. The average amplitude error between these two signals can be seen on the main user screen. This value can be used to determine how accurately the signal was reconstructed. The panel on the lower right hand side of the screen displays the currently loaded respiratory sound file and the reconstruction module currently being used. The buttons on this panel are used to load and play sound files with or without the reconstruction algorithm. Before a sound file can be played using the reconstruction technique, a system inverse model is needed. A previously calculated model can be loaded or a new model can be generated. After clicking on the "generate model" button the LabVIEW program will automatically play the currently loaded signal and use it to calculate a stable inverse filter.

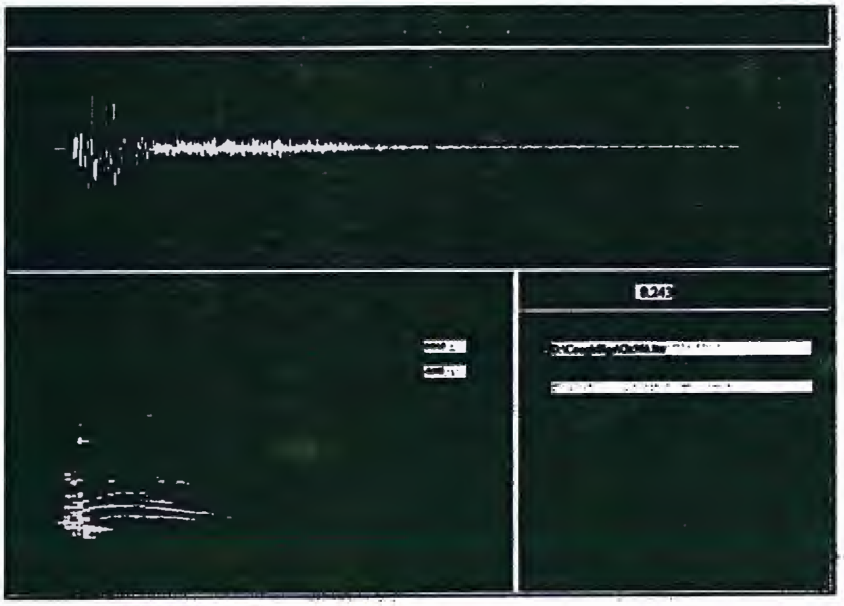

Figure 5 Main User Screen

The spectrogram of the PRS is displayed on the lower left portion of the user screen. The spectrogram represents the time and frequency energy distribution of the signal. The x-axis is time, the y-axis is frequency and energy intensity is indicated by a color scale, with white representing high intensity and black representing low intensity. The software allows the user to graphically select a specific region of the spectrogram for playback. Selections are made, using the mouse, by drawing a line around the sound component to single out or eliminate. The unwanted portion of the signal is eliminated using a 2nd order time-varying Butterworth filter. The filter cut-off frequencies are changed every 20 ms based on the user selection. When the "Play Selected Portion" or the "Play Without Selected Portion" button is pressed, a new window will open as shown in Figure 6. This window displays the results of the filtering and gives the option to play the signal. The "Play Selected Portion" button was pressed in this example. An example of the sound component selection capability can be seen by examining Figures 5 and 6. In Figure 5 a cough was loaded and a narrow band of high intensity energy centered around 3200 Hz was selected. This band represents a continuous high-pitched lung sound which can occur during a respiratory maneuver and is referred to as a wheeze. Notice from the spectrogram in Figure 6 that the selected wheeze still remains while most other sound components have been removed by the filter.

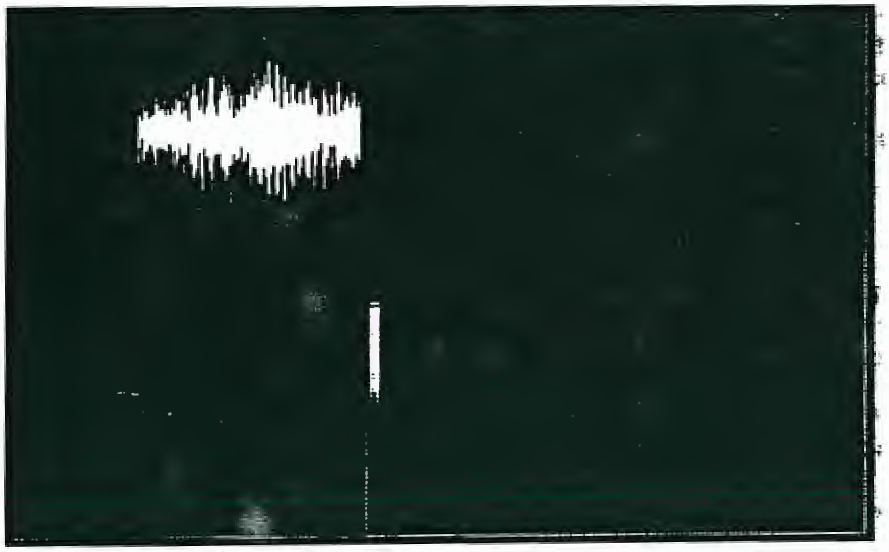

Figure 6 Filtered signal window

AND CONCLUSION

ly reproduce respiratory sounds. The user interface
l using the LabVIEW programing language. A stable
nstruction technique to be utilized. Previously saved
ırse models. Using a respiratory signal to generate
sed to accurately reconstruct that signal. However,
ı on a different respiratory signal the accuracy of the
to frequencies in the second signal which were not
ɜs may excite a portion of the system which is not
first signal. A new model can be generated for each
ıtaining all frequencies can be used to generate a
l signals. It should also be noted that the signal is
s of the listener. The stethoscope may filter portions

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n be used to identify sounds associated with lung
sound with or without a selected component can be
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l being developed and other methods of audio

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Observed Thermal Hysteresis on 5-Wire Pressu

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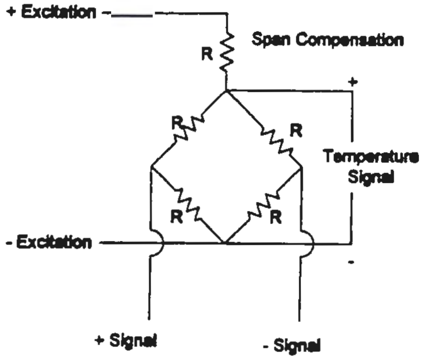

Figure 1. 5-Wire Pressure Transducer Bridge Configuration

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Observed Thermal Hysteresis on 5-Wire Pressure Transducers

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Abstract

In the course of calibrating 5-wire pressure transducers a higher than expected Root Mean Square Error of a response surface model has been observed and documented. Further investigation indicates that this error is driven by a systematic offset in the intercept of the first and last ambient temperature calibrations. The use of a first order linear regression on the calibration data provides a way of viewing systematic uncertainties that show up as patterns in residuals. It is these patterns in the residuals that lead to the assertion that the observed uncertainties are manifestations of thermal hysteresis.

Introduction

Over the last decade Pratt & Whitney Instrumentation Laboratory in West Palm Beach Florida has been supporting engine test measurements with a unique type of pressure transducer. This pressure-measuring device is called a 5-wire pressure transducer as introduced by Carlson [1]. The 5-wire pressure transducer is manufactured by the Kulite Semiconductor Products Inc. and differs from conventional transducers by providing two output voltages one proportional to pressure and the other to temperature. It derives its name '5-wire' because in addition to the classical 4 leads of the Wheatstone bridge there is a fifth lead, which provides the temperature output voltage.

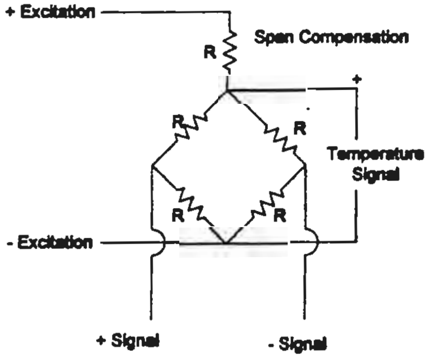

Figure 1. 5-Wire Pressure Transducer Bridge Configuration

The calibration of the 5-wire pressure transducers is done by applying a full-scale load to the transducer in 20% increments through a predetermined temperature cycle. The pressure and temperature data gathered from the calibration are put through a mathematical model that is described by Carlson [1]. Regression analysis is used to quantify the coefficients for the general form of the equation that describes the theoretical behavior of these transducers. The Root Mean Square Error obtained from the regression is multiplied by a t95 statistic. The result is called the 5-wire uncertainty. The acceptance criterion of a calibration is determined by this value which should be no greater than 0.3% of full-scale output.

First and Last Ambient Temperature Anomaly

Typically, a calibration temperature cycle consists of eight set points starting at ambient, 30, 150, 250, 350, 450, 550°F and then ambient again. Over the course of time it was noticed that a number of 5-wire pressure transducers were not passing our acceptance criteria of 0.3% 5-wire uncertainty. The common characteristic of these nonconforming transducers was a marked difference between the first and last ambient temperature calibration data. Most noticeably, differences in the "no load" pressure output voltage which, under the assumption that the transducer behaves linearly, shows up as a non-repeatable intercept value. The calibration failures were sporadic and few in terms of the total population of transducers. The failures were also indiscriminate, not limited to a specific model or range of 5-wire transducers. As the number of nonconforming transducers grew, there was a need to find a resolution to this problem. What was driving difference in intercept values for the first and last ambient temperature data? Were there calibration procedural errors? Was it the calibration system hardware?

The 5-wire calibration process is fully automated, eliminating the possibility of human procedural errors. Furthermore, there were sufficient legacy data to show consistent performance of our calibration system hardware over time.

The established 0.3% 5-wire uncertainty acceptance criterion is a stricter acceptance condition than the vendor specifications for this device. The manufacturer specifies maximum non-repeatability values at only one temperature. Pratt & Whitney's 5-wire uncertainty considers a broad temperature cycle in order to quantify non-repeatability. The idea of raising Pratt & Whitney's acceptance criterion uncertainty to fall within the manufacturer's specifications is certainly an option but it would have significant consequences in the uncertainty of engine test parameters. Also raising the acceptance criterion would not answer the observed discrepancy between the first and last ambient temperature calibrations.

The transducers could not be returned to the manufacturer since they met manufacturer's specifications. Even though they had a high 5-wire uncertainty that exceeded our acceptance criterion, the difference in intercept value consistently fell within the full-scale output vendor specified tolerance for intercept thermal sensitivity. This was the quandary; a slowly growing population of non-conforming transducers whose established acceptance criterion did not meet Pratt & Whitney's standards, yet no actual failures by the manufacturer's performance specifications had occurred.

Hypothesis: Thermal Hysteresis

Out of all the plausible explanations of the first and last ambient temperature anomaly, the most promising turned out to be Thermal Hyteresis.

Thermal Hyteresis is defined as non-repeatability of a parameter at reference temperature. [4] In the case of 5-wire pressure transducers, this parameter was the intercept value at ambient temperature. Thermal Hysteresis can vary with time and manifest itself as:[4]

- Cold Cycle Hysteresis- In this condition a measured parameter changes due to a temperature excursion below the reference temperature.

- Hot Cycle Hysteresis- A measured parameter changes due to a temperature excursion above the reference temperature.
- Full Cycle Hysteresis- A measured parameter changes due to temperature excursions above and below the reference temperature.

Theoretical Source of Thermal Hysteresis

Stability of a sensor is characterized by how repeatable its performance is over a period of time. Thermal Hysteresis, if present in a measurement, can alter pressure sensor stability. In general, the sources of sensor instability can be subdivided in two categories; mechanical and electrical instabilities as noted by Bryzek[2]. Mechanical instabilities can come from the actual manufacture and packaging of semiconductor devices where stress is built up in the packed layers of a semiconductor sensing element. This stress can affect the offset, pressure sensitivity and temperature coefficient of the sensor. Electrical instabilities can be caused by the mobility of ions within the crystal lattice of the sensing element. As the device is heated and subjected to pressure these ions move about randomly, changing the resistance of the semiconductor, thereby changing the output voltage [3]. Temperature and pressure facilitate the manifestation of these instabilities in the form of Thermal Hyteresis. According to Lycoudes[3] these instabilities depending on their severity are bake-reversible. The continuous applications of temperature and pressure can reduced or remove instabilities in semiconductor sensors. Therefore, in theory, if Thermal Hysteresis was the cause of the first and last ambient temperature anomaly, it could be eliminated by a subjecting the nonconforming 5-wire transducers to extended periods of temperature and pressure as suggested by Lycoudes[3].

The Experiment

To test the Thermal Hysteresis Hypothesis, a group of transducers was selected. The selection was based on those with the highest reported 5-wire uncertainty by which they had been rejected. The experiment consisted of exposing these transducers to a series of consecutive calibrations through a full cycle of temperature and full-scale pressure to see if there was an improvement in the calculated 5-wire uncertainty. However, looking at the 5-wire uncertainty would not be sufficient to attribute the transducer failures to Thermal Hysteresis. A first order linear regression of the pressure output data would give another perspective to the experiment. Assuming the transducer to be linear throughout its entire range, regression analysis residuals give a glimpse of the change in slope and intercept values for each calibration. As mentioned earlier it was believed that the differences in intercept values between the first and last ambient temperature data was driving the high 5-wire uncertainty for these transducers.

Results

Figures 2, 3 and 4 show the results of three of the 5-wire pressure transducers used in the experiment. By means of a first order linear regression one straight line is fit through the first and last ambient temperature calibration data. This straight line fit is a useful diagnostic tool because the residuals, defined as Actual minus Predicted response, if not zero, should be bounded about zero as mentioned by Carlson [1]. The residuals are plotted as a function of the set pressure. If the transducers were truly ideal, the residual plot for the first ambient calibration should overlap with the last ambient temperature residuals effectively yielding zero error.

First Order Linear Regression on First and Last Ambient Temperatures for Three Separate Calibrations on XCEL-82 450A S/N J41-2

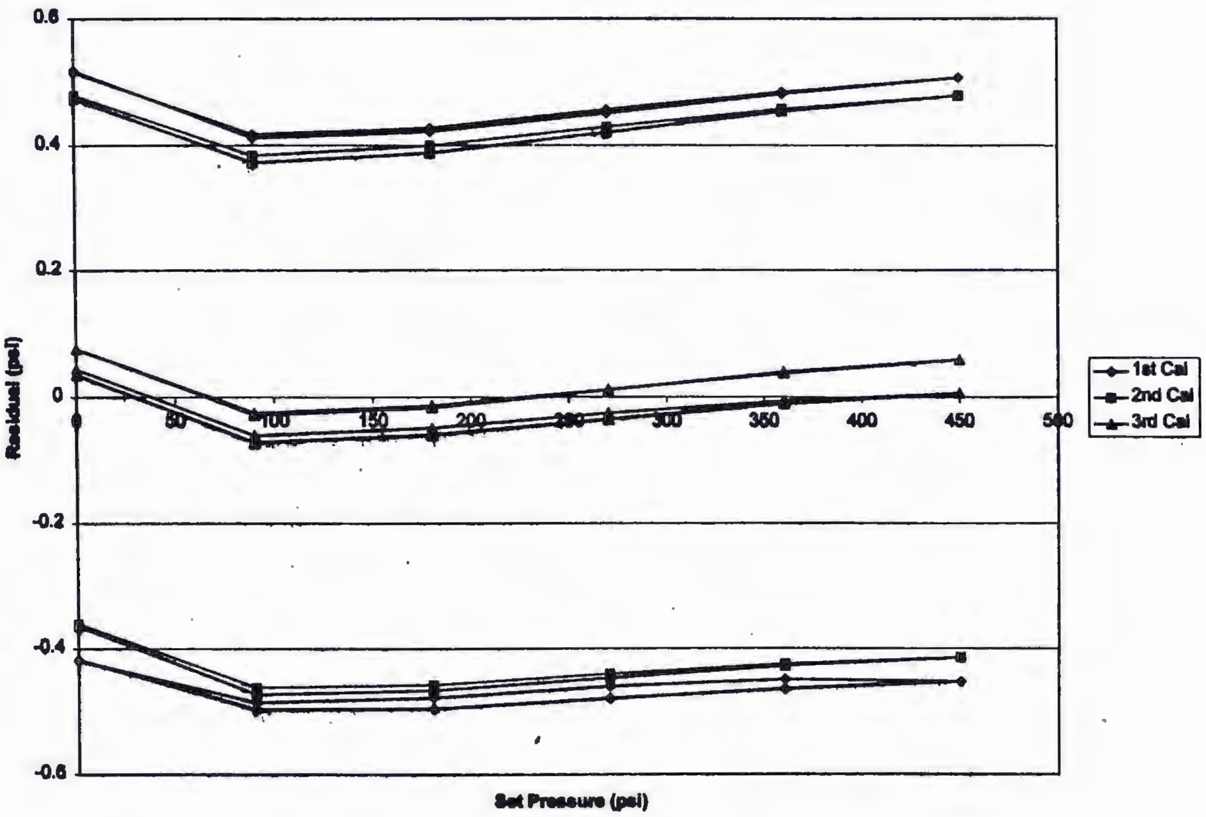

Figure 2

First Order Linear Regression on First and Last Ambient Temperatures for Three Separate Calibrations

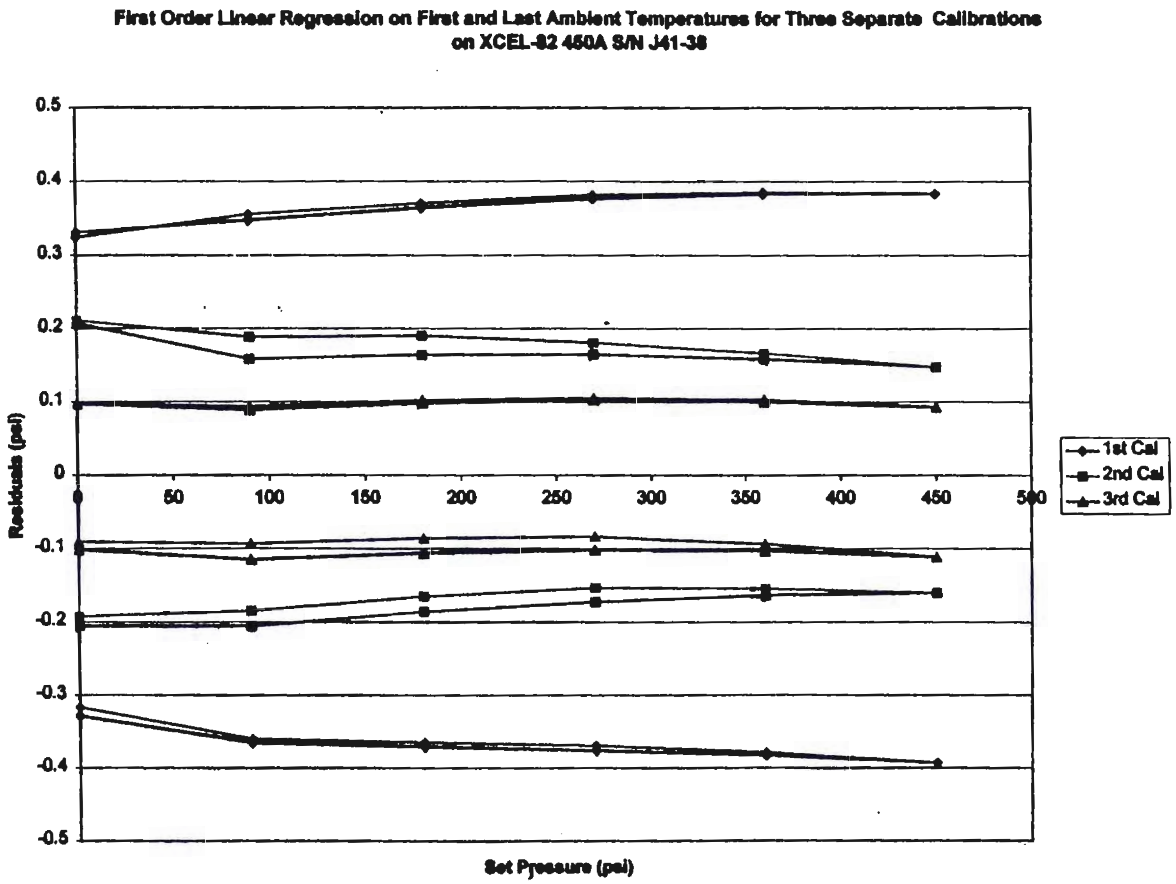
First Order Linear Regression on First and Last Ambient Temperatures for Three Separate Calibrations on XCEL-82 450A S/N J41-38
Residuals (psi)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
50
100
150
200
250
300
350
400
450
500
Set Pressure (psi)
1st Cal
2nd Cal
3rd Cal

Figure 3

First Order Regresion for First and Last Ambient Temperature for Three Seperate Calibrations on XCEL-82 450A S/N J41-39

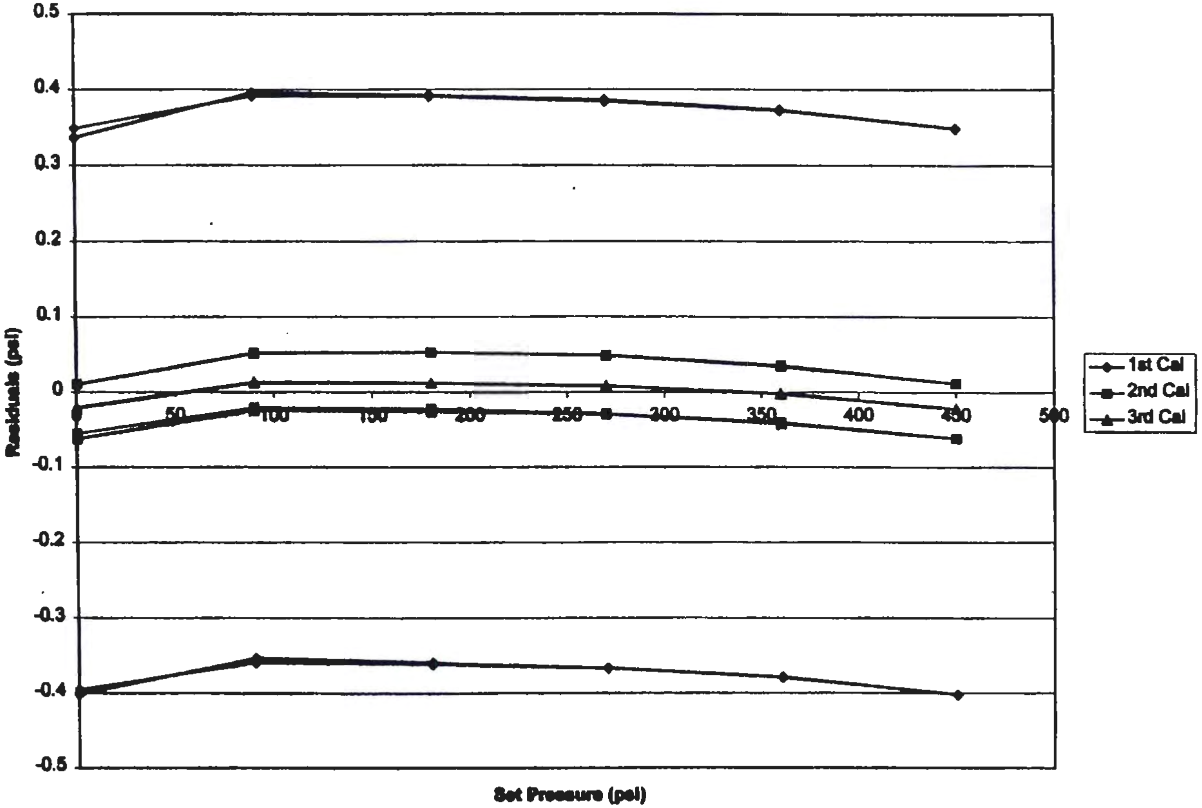

Figure 4

Conclusion

At the conclusion of this experiment the data gathered showed a reduction in the 5-wire uncertainty. Three consecutive calibration cycles brought these transducers within Pratt & Whitney's uncertainty acceptance criteria of 0.3%.

Transducer XCEL-82	5-wire uncertainty before	5-wire uncertainty after
J41-2	0.93%	0.15%
J41-38	0.65%	0.17%
J41-39	0.78%	0.17%

Table 1. 5-wire uncertainty values before and after calibration temperature cycles.

The transducers all had reductions in the intercept difference for the first and last ambient data. In all cases the movement of the intercept values was toward closing the error "gap" in the residual plots. In essence these transducers were improving their "repeatability" and by definition removing Thermal Hysteresis. Can the data conclusively say that there were mechanical or electrical instabilities in these transducers? No, further testing and analyses could only confirm or deny this point. But what can be concluded from this experiment is that the first and last ambient temperature anomaly was able to be rectified by the application of a technique specifically tailored to address temperature related instabilities manifested as Thermal Hysteresis.

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