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Development of a hydraulic component leakage detecting system using pressure decay signal

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DEVELOPMENT OF A HYDRAULIC COMPONENT LEAKAGE DETECTING SYSTEM USING PRESSURE DECAY SIGNAL

An Abstract of a Thesis

Submitted

in Partial Fulfillment

of the Requirements for the Degree

Master of Science

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ABSTRACT

It is preferable to detect leakage at the earliest phase in the manufacturing process, and then further assembly of hydraulic components with leakage problems can be avoided. Integrating a USB based microcontroller and a pressure sensor; this study developed a hydraulic leakage detection system in using air instead of hydraulic oil as medium, through measuring pressure decay signals captured by a real time data acquisition system. Compared with the conventional hydraulic system using oils, this system shows advantages in safety operation and little environmental concerns due to use a lower pressure clean air.

The low-cost hydraulic leakage detection system was developed can record and visualize the system pressure in real time. Experimental tests were conducted to test this system performance. The pressure decay of the hydraulic system inserted in good hydraulic tubes were tested as the system pressure holding performance baseline, and then compared with the pressure decay of the same system when the tube was installed with connection errors. The experiments were repeated when the system was set up at different operating pressure levels to test if the system can consistently fulfill its designed functionality. Through statistical analysis it was found that the developed prototype system can capture and visualize the pressure decay curve in real time, and two signals, the pressure drop from the test start to end point and the pressure drop rate in the testing period, can be used as featured characteristics to quickly detect hydraulic leakage components' status.

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CHAPTER I

INTRODUCTION

Based on the definition of Word Net (2012), the hydraulic system is a mechanism operated by the resistance offered or the pressure transmitted when a liquid is forced through a small opening or tube (WordNet 3.0, 2012). Through technical integration of hydraulic, mechanical and electronic systems, hydraulic technologies have evolved significantly in the past few decades (National Fluid Power Association, 2000). The development of computer and automation controls in hydraulic machinery greatly changes the functionality, efficiency and accuracy of hydraulic system. As the analysis report of worldwide markets for hydraulic components mentioned, the science of hydraulics has witnessed substantial improvements over the decades making "Hydraulics" a key component in the field of applied science and engineering (Global Industry Analysts Inc., 2013). The wide use of hydraulic systems such as the iron and steel industry, mining, agriculture machine, defense, automobile, aircraft, ship industry has made it an important discipline related to industrial and mechanical engineering technology fields.

The characteristics of hydraulic system are the primary reasons why hydraulic system, equipment and components are widely used in industry. First, the hydraulic system can transfer high pressure through liquids, and the pressure can reach up to 3000 to 5000 PSI (Pounds per Square Inch), and even more (SKYbrary, 2014). As shown in Figure 1 (Erjavec, 2004), when the pressure is converted to the force and it can complete specific work for example used in the crane, digger, and lifting jack to lift workload.

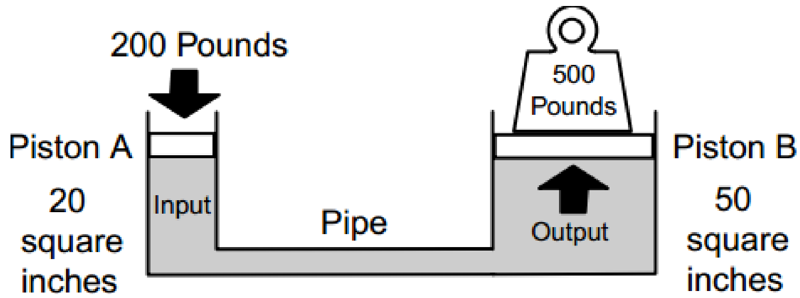


Figure 1: Hydraulic system can increase force (Erjavec, 2004)

Second, power units such as pumps and motors can be connected through hydraulic tubes, which make the assembly of mechanical components more flexible in a constrained space. The typical cases are that the steering unit, driver unit and auto rise up unit can be combined together on the automobile, tractor and spraying machine as shown in Figure 2 (Rosth, 2007). As a result, the connections through hydraulic tubes lead to a hydraulic system with a small size, light weights, and changeable working directions for the mechanical system to conduct workload in flexible means which is another important feature for the hydraulic equipment.

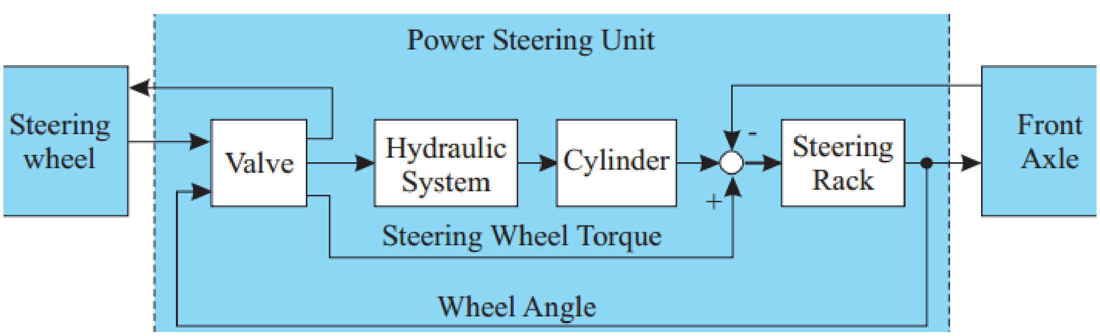


Figure 2: The hydraulic power steering system (Rosth, 2007)

The third very important feature is that the hydraulic system can easily implement control and high degree of automation that means servomechanism or servo. As the definition by Jyotsnaj in his blog (2009), the servomechanism is an automatic device with hydraulic system that uses error-sensing feedback to correct the performance of a mechanism. The process of sending the error signal back for comparison with the input is called feedback. The whole process of the input, output, error signal, and feedback is called a closed loop. The Figure 3 (Jyotsnaj, 2009) shows a typical example of main components of servomechanism. The Figure 4 shows a good example of this application is when an airplane uses the automatic hydraulic servomechanism (Fine Tubes Company, 2006) to adjust the angle and areas of wing through computer control system to automatically balance the flight altitude.

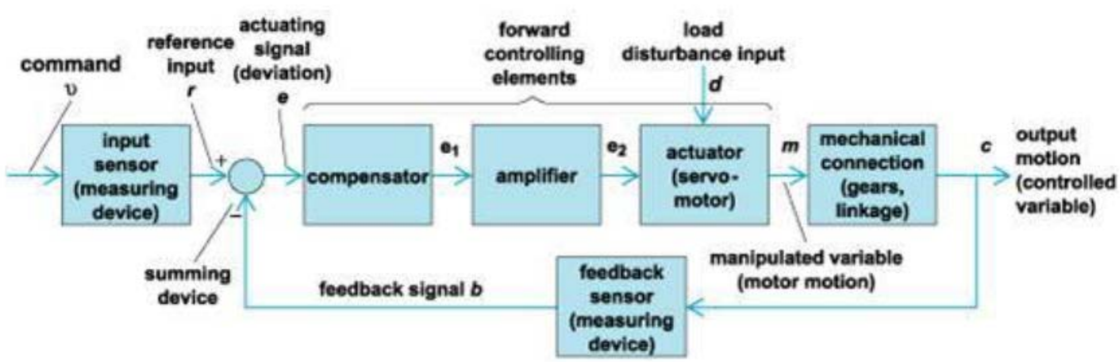


Figure 3: Schematic of servomechanism (Jyotsnaj, 2009)

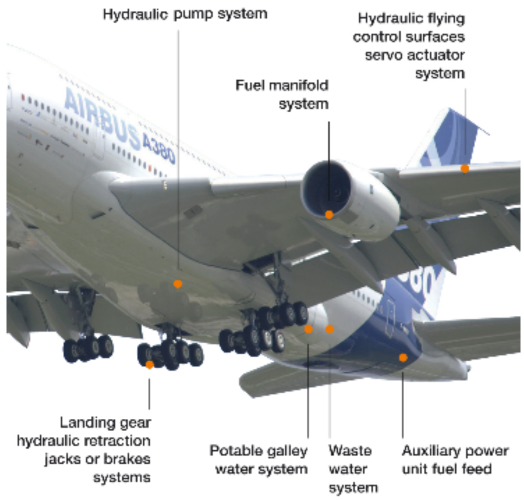


Figure 4: A380 hydraulic flying control servo system (Fine Tubes Company, 2006)

Due to the advantages presented above, the hydraulic products have been extensively used in force conversion, power exchange and other mechanism control system aspects.

Background

The quality of the hydraulic system design and manufacturing plays a key role in the entire machinery system. No leakage is one of the critical quality features that will ensure the hydraulic system quality. Absolute leakage for any hydraulic and pneumatic system is always present. Depending on intended application, a good or faulty system is defined by the certain amount of leakage rate in a period of time.

Hydraulic systems are composed of hydraulic components, including pump, valve, cylinder, tube, hydraulic oil, seal parts, control system and related accessories. Contrary to so many advantages mentioned earlier, there are also some disadvantages. The hydraulic system has higher requirements for maintenance compared with ordinary mechanical systems, such that the hydraulic oil cleanliness must be maintained at a certain level; the working environment temperature must be in certain range; and the cost for components are relatively high. Comparing with common mechanical systems, the complexity, cost, precision and accuracy requirements of manufacturing processes for hydraulic components are higher.

The quality of the components directly influences the functionality of the hydraulic system. From the quality engineering aspect, the hydraulic leakage is one of the main problems in hydraulic systems. It is estimated that contaminated lubricants cause 80% of machine and equipment stoppages and component failures; many times these contaminated fluids are a direct cause of fluid leaks from hydraulic machinery (Leugner, 2010). The leakage will cause unnecessary energy consumption, reduce equipment performance, decrease reliability and increase fluid costs. The direct impact is that the system loses pressure, which results in insufficient power to do the intended work, and even sometimes, the hydraulic system leakage can cause vital accidents. Moore (2012) mentioned an injury that a shop technician who incurs an injection of hydraulic fluid at the base of his finger when investigating a leak in a wheel loader. After few hours when this injury occurred, his hand was severely swollen and inflamed, with dark discoloration in his index and middle fingers. So, effectively and safely detect the leakage status for the hydraulic components and products by hydraulic producers in the manufacturing floor will greatly improve the working efficiency.

Currently, it is still very common to use hydraulic oils to test if there is a leakage in the hydraulic system. Because the medium of the hydraulic system is oil when there is a leak, it may cause pollutions and even risks for fire. Particularly, the petroleum-based hydraulic oils are environmentally more difficult to handle. The cleaning and disposal of hydraulic oils require special physical and chemical treatment techniques by an EPA-authorized hazard waste management agency which would incur additional costs to the manufacturing companies. Sometimes the hydrostatic pressure test can use water as medium, but in some special conditions when the material and system are sensitive for corrosion, this method cannot be used. This study will focus on the detection of leakage for hydraulic systems in using clean air as a testing medium, as a result to filter individual hydraulic components with leakage flaw in the first place, and also help assure the quality of hydraulic subassemblies and final assemblies for manufacturing companies.

Statement of Research Problem

A lot of hydraulic components in hydraulic system could be leakage resources, such as pump, valve, cylinder, tube, seal parts and related connecting accessories. The leakage reasons could be: bad or damaged threads in the connecting hoses, the product dimensions are out of tolerance, and/or faulty actions such as wrong mating occurred in the assembly process. Sometimes the leakage may even be caused when the components are conforming parts without any quality issue. For example, hydraulic connecting tubes in good quality could have leakages caused by the contaminations of the connectors or any above mentioned issues.

Developing a prototype system to quickly and easily detect the leakage risk before the hydraulic component leaving the factory is the main objective of this research.

Statement of Purpose

It is very important to detect leakage of hydraulic components or systems at the earliest phase in the manufacturing process to avoid leakage problems in further assembly. In this research, integrating a microcontroller and a pressure sensor, a hydraulic leakage testing system will be developed by using compressed air instead of hydraulic oil, so that this system can be easily implemented in the manufacturing floor to detect hydraulic components' leakage status, meanwhile the pressure change of the testing component can be visualized in the real time fashion.

Need and Justification

Leakage detection is an important procedure in the manufacturing process for hydraulic parts to ensure the manufacturing quality. It is still common to use liquids to test hydraulic leakage in many applications where the liquids sealed in the hydraulic circuit must be compressed to a very high pressure level. This may not be an easy, safe operation for some small manufacturing shops. This research proposes a novel leakage test method by using compressed air as a test medium at a relatively low pressure range to assure the quality of hydraulic individual parts and assembled systems with less safety and environment concerns. The proposed testing system will provide the following characteristics:

1. Low operation risks and high safety assurances in the operation process compared to the leakage test system employing high pressure hydraulic oil. The general air pressure in the test system is about 100 psi while the oil pressure could be up to 3000 psi and runs the risk of causing accidents and hurt operators.

2. Environment-friendly. Air is a clean and no pollution medium. The high pressure hydraulic oil leakage may influence the working environment; and it will also incur additional costs to clean the pollution if any oil leakage happens in the testing process. In addition, the oil needs containers and places for storage around the manufacturing floor. Even when the hydraulic parts are produced with no leakage problems, disposal and draining of the testing hydraulic oils require resources.
3. Ensure that the hydraulic products freshly produced will comply with visual/appearance quality requirements. Manufactured hydraulic products are required to be clean before they are moved forwarded for the assembly process. With no cleaning process needed, the air based leakage test system could meet the appearance requirements before products are delivered out of the manufacturing facility.
4. Low-cost and high efficiency. The cost for the testing medium (air) could be ignored compared to the hydraulic oil. The proposed leakage test system integrates computer and real time data acquisition technology. Once the testing parameters are set up, it doesn’t need people to be around and it can monitor, record, and visualize the pressure changes automatically. Meanwhile, the pressure change and the pressure change curve and trend visualization can be calculated and displayed by a VBA (Visual Basic for Applications). Given the specific designs and definitions of the hydraulic products, leakage status can be determined.

5. The air has much lower density and viscosity than oil, so it is easier for air to penetrate the tiny gap between the assembled hydraulic components. Therefore the air testing system renders a tight quality standard. The low viscosities indicate less resistance to flow or a higher probability of leaking and flowing at a higher rate.

Leakage rate is a function of fluid viscosity. As the Formula Book for Hydraulics and Pneumatics of Linkoping University (2008), the formula of the leakage flow (q_l) relative to the fix wall is as follows:

$$q_l = \frac{vbh}{2} + \frac{bh^3 \Delta p}{12\eta l}$$

The formula indicates the relationship of gaps, pressure and viscosity. The leakage volume will be directly proportion upon the viscosity and pressure change. The gap height "h" has much more influence on the leakage than the length.

v: relative velocity [m/s]

b: gap width perpendicular to flow direction [m]

h: gap height [m]

Δp: pressure difference through [Pa]

η: dynamic viscosity [Ns/m^2]

ℓ: length [m]

The viscosity of air is 0.018 centipoises at 70 ° F; the viscosity of SAE 10 hydraulic oil is 65 centipoises at 70 ° F. (Cincinnati Test System, 2009). According to above analysis, when the viscosity and pressure values of air and oil are used in the formula respectively, the values of air uses 33 psi and 0.018 centipoises, oil uses 3000 psi and 65 centipoises, the calculated result shows that air can more easily leak at same temperature and same gap than oil. The theoretical derivation shows if the hydraulic component can successfully pass the air-based leakage test system, it may pass the hydraulic oil based leakage test system.

Based on the justifications above, the research proposes to develop an air based leakage detection system that can be easily adapted by the manufacturing companies that produce or apply hydraulic components in the final assembly.

Statement of Research Questions

The research proposes to develop the air based leakage testing system that integrates composition of hardware components and development of a software program. After the system coupling hardware and software components were completed through experimental study, the following research question will be answered:

- If the proposed system can capture the difference of pressure changes for the faulty and good hydraulic components?
- If the proposed system can perform consistently at different air pressure levels?
- If the regular pressure decay pattern for further comparison study could be find out?

Assumptions

In this research, the following are assumptions:

1. The test instruments (sensor, data acquisition board, pressure gauge) are in good shape and can perform the designed function.

2. The testing samples (tubes) can perform consistently and their tiny variations in performance can be ignored.
3. The testing air supplied in the production lab is clean and its impurity will not impact the testing instruments.
4. The air pressure supplied in the production lab may have minor variations, but the air pressure fluctuation will not impact the performance of the developed hydraulic test system
5. The testing accessories in the system such as seals and connectors are normal and no additional leakages influence the testing system.

Limitation

The objective of the research is to develop a low-cost prototype system that can display pressure decay in real time through a low-cost USB-based microcontroller so that it can be easily used in the manufacturing floor. The research bears the following limitations:

1. The research plans to measure the pressure drop for faulty hydraulic components against the performance base line of pressure drop for non-faulty hydraulic components. Conclusions will be made based on qualitative information with leakage or non-leakage. The leakage detection system does not intend to measure the quantitative leakage rate, but it can be calculated by data analysis.
2. This research does not perform the comparison study between hydraulic leakage tests in using air or oil as testing medium. With more data collection in the future, a mathematic equation may be formed to correlate leakage flow rates in pressured

air or in hydraulic oil.

3. Because the air pressure is supplied by the production lab air compressor and the researcher cannot adjust the incoming air pressure level and also because of safety concerns, the leakage detection test will be only conducted at less than 100 psi pressure range. Therefore, the testing results to be concluded only will be applied in a lower pressure range.
4. To construct the hydraulic detection system and make the system function properly, all the components must be connected tightly to make sure the system does not have leakage. As digital wrench tools that can provide numerical torques are unavailable to be used in this research, the regular soap bubble leakage test is applied to establish the hydraulic detection system without system leakage.

Statement of Research Procedure

The procedure of this study is as following:

1. Review the past literature about the leakage detection such as leakage detection theories and methods
2. Design and layout the system schematic before purchasing the components.
3. Build the pneumatic equipment, including the necessary components. The equipment includes pressurized air resource, cylinder, valve, tube, pressure control system, and related accessories.
4. Write and test the data acquisition computer program in using VBA that is embedded in Microsoft Excel.

5. Integrate the proposed pneumatic system by interfacing the data acquisition code with hardware.
6. Conduct test activities including collection and analysis of data, and making conclusions.

Definition of Terms

The terms of definition are clarified as following:

1. PSI: means pounds per square inch. It is a unit of pressure or of stress based on avoirdupois units, and one psi approximately equal 6894.757 Pa.
2. The Pascal (Pa): is the SI derived unit of pressure, internal pressure, stress, Young's modulus and ultimate tensile strength, defined as one newton per square meter. It is named after the French polymath Blaise Pascal.
3. VBA: Visual Basic for Applications (VBA) is a macro language of Basic. It was developed to perform common Microsoft automation in the desktop application task programming language. The main functions can be used to extend the application of Windows program features, especially the Microsoft Office software. It is a Basic version to keep the program application visualization.
4. GPM: Gallon per Minute.
5. Servomechanism: sometimes it was shortened to servo; it is an automatic device that uses error-sensing negative feedback to correct the performance of a mechanism and is defined by its function.

CHAPTER II

LITERATURE REVIEW

The hydraulic leakage generally includes two kinds of status: the external leakage and internal leakage.

The external leakage often happens on the connection and seal position, such as the connecting position between cylinder and tube, or the valve and tube. Faulty installation and poor maintenance are the primary causes of external leakage. The excessive pressures or contamination can cause seals to blow or be damaged. The leakage could be caused by a gash, rust or other corrosion hole, a very tiny pinhole leak, crack or micro crack, or inadequate sealing between components or parts joined together. For example, the seal issue or the tiny pinholes can cause the leakage coming from hydraulic cylinder and hydraulic rod. External leakage can be hazardous, expensive, and unsightly. According to the study by Parker Hannifin Corp (2013), three drops of oil leaking per minute from one place in hydraulic system will lead to 9.3 gallons in a year, which costs $168 a year just in replacement oil.

The internal leakage often happens on hydraulic system interior. It can occur in the pump, valves, and other moving parts such as the leakage between valve spool and valve housing, leakage between two gears in gear pump, leakage between cylinder rod and sleeve. Internal leakage almost can't be avoided and it is more difficult to detect and isolate. Partial internal leakage can act as a self-lubricate function, but too much internal leakage will slow down actuators. The power loss is accompanied by the heat generated at a leakage path. The clearance between two components is the key factor causing internal leakage. It includes the fitting clearance and assembly clearance. The fitting clearance indicates the manufacturing precision of single parts. The assembly clearance indicates the process stability of assembly process. The minimum fitting and assembly clearances are key parameters to ensure the internal leakage. The oil film thickness takes effect to seal two parts instead of the specific seal components. When the clearance of two matching parts is bigger than the oil film thickness, the leakage will happen. Based on the calculation result from "Leakage Calculation through Clearances" (Huang, 1994); the formula of mass flow rate ($\dot{m}$) indicates the relationship between clearance, viscosity and geometry with fixed pressure ratio. The clearance height "δ" has much more influence than other factors.

$$\dot{m} = \frac{\rho\delta^3}{12} G \text{ where:}$$

G = Geometry

δ = clearance height (flank clearance)

ρ = viscosity

The following gives a brief overview of various leakage detection methods that have been used in practice and reported in academic research

Observation and Bubble Detection Method

The simplest external leakage testing method is through observation. The oil leakage area has an obvious oil mark. Sometimes, the leakage is not easy to be observed directly, and the test can be performed by applying a soap solution to potential outer leak sources and observing for bubbles. This is so-called soap bubble method.

The aerostatic pressure test that defined by ASTM 380 - 94 (2012) also belongs to the bubble test. It puts the test hose with pressured air under the water, and once can observe if there are bubbles coming out from hose surface in two minutes. If a steady stream of bubbles out from any location it shall be considered failure to meet the test.

It is the maintenance team's responsibility to decide if the external leakage position should be repaired, SAE Sub 4 (1977) provides a leakage classification as listed in Table 1 to define leakage levels. Table 1 can be used to level leaks based on qualitative leakage information.

The bubble detection method will be used as the initial checking method to determine the equipment is on normal status in this research.

Table 1

SAE J1176 Leakage classification

SAE Class	Leakage Term	Leakage Description
0	Dry	No indications of moisture
1	Weep	Any nonrecurring fluid
2	Seep	Recurring fluid not forming a droplet
3	Droplet	Recurring nonfalling droplet
4	Drip	Recurring falling droplet
5	Flow	Recurring stream forming volume
Per SAE J1176 Recommended Practice (Under Dust-Free Conditions)		

Temperature Change for Leakage Detection

In many complex hydraulic systems, especially for the heavy industry, the high pressure and large rate of flow circuits system are fit to measure the components temperature to justify the internal leakage. Such as the steel mill production line, there are many pumps, valves and cylinders which are served by one hydraulic station, some of valves or cylinders on the function parts; the internal leakage of them is not fit the measurement by flow meter. The basic theory of using heat to detect leakage is that the internal leakage caused the power loss. The flow energy is not transmitted as mechanical power but transformed to the heat. So the lost power gives raise of the temperature. In the research conducted by Mollo (2001), the leakage on the high pressure gears pump increase 1 gpm (gallon per minute), and then the temperature rise would be more than 20 °F at 2250 psi and 80 °F at 4500 psi. The infrared heat gun can be used to measure temperature. Generally, the heat distribution data of a new hydraulic system is treated as the base line, and then it is compared with the operational pressure change and temperature change to justify the internal leakage status. If the temperature change is larger than a certain cutoff value, it can be concluded that the pump or valve needs to maintain or repair. This method cannot quantify pressure lost. But it can only estimate the leakage level base on temperature change status.

Acoustic Emission Technology for Leakage

For the internal leakage, the acoustic emission method has been employed by many researchers. Acoustic emission technology is an effective method to determining high pressure or high speed leaks in different locations of valve and cylinder leakage

(Kaewwaewnoi, Prateepasen & Kaewtrakulpong, 2005).

Acoustic emission was defined as the transient elastic waves generated by the rapid release of energy from localized sources. It has been found that acoustic emission signals can be produced by fluid leakage (Nivesrangsan, Steel, & Reuben, 2007). When turbulent flow conditions existed in the leakage hole in a pressure boundary, the time dependence of the flow was caused by the instability of the fluid flow. The acoustic emission Root-Mean-Square (RMS) value was often used to calculate the average energy contained in the raw (Sharif & Grosvenor, 1998):

$$AE^2_{RMS} = C_1 \frac{1}{\alpha^5 \rho^3 D^{14}} \left(\frac{Q}{c_v}\right)^8 \left(\frac{p_1 S}{\Delta p}\right)^4$$

C_1: the function of fluid variables with some factors neglected to simplify the relationship

Δp: pressure drop across valve

Q: volume flow rate

Ps: the sound power

α: the sound velocity in the fluid (m/s)

ρ: the fluid density (kg/m^3)

v: the average turbulence jet velocity (m/s)

D: the valve size (m)

S: specific gravity (kg/m^3)

c_v: the valve flow coefficient (dimensionless)

This equation is the basis for a quantitative approach. The variants of volume flow rate and the pressure drop across valve are very sensitive to influence the test result. This method is able to fix the position of the leakage and detection of acoustic emission signals produced by liquid and gas. The leakage through valves can be related directly to the qualitative leakage rate. The effect of the influenced factors of leakage rates, inlet pressure levels, valve sizes and valve types are the variants to influence the quantifiable result and its precision.

Flow Meter for Leakage Detection

If it is desirable to measure the flow or quantity of fluid loss in a given time frame, we need to use a flow meter or other related test equipment needs to be used (Slater, 2001). Detection of unknown internal leakage in most cases would depend on specific tools to detect the location and leakage volume. Leakage issues or a unstable hydraulic circuit to perform its designed function need to install flow meters in various locations to detect excessive leakage; that caused by the components over tolerance clearances of mating inner surfaces. The installation flow meters on pumps and motors help to determine when overhaul of these components are needed before performance is severely affected. For example, when the internal leakage happens, the pump has to increase flow rate to keep the system maintain a constant pressure. When the flow rate is out of defined range, it can be deduced that the internal leakage is unacceptable. In critical hydraulic systems, both the control valves and the hydraulic cylinders need timely testing or real time monitoring to ensure leakage rate is in an acceptable range.

Pressure Gauge for Leakage Detection

Another leakage detection method is to use pressure gauge to measure the pressure change. According to ASTM A1047M – 05 (2014) testing standard, leakage can be tested equivalently through three kinds of approaches.

Procedure A is through pressure differential to measure the drop in pressure over time. This method uses one set standard part to be the base line, and against another tube at an identical pressure or volume, the instruments to measure the pressure at the end of test period, if the final test pressure has not cross the threshold pressure, it could be determined the test is passed. Otherwise, it will be failed.

Procedure B is through pressure gauge to measure the pressure decay. Measuring the drop in pressure over time in a specific range could determine if the test is passed or not.

Procedure C is through vacuum decay. This method involves evacuating the tubing to a suitable low pressure and measures the increase in pressure. If the pressure has not crossed the threshold pressure, the test should be passed.

Under the conditions prescribed by the above procedure with a pressure measurement instrument, an operator needs to be around all the time so that the operator can read the pressure change immediately. If the pressure gauge is not connected in an automatic data acquisition system, it is hard to record and remember the pressure change.

The research of Zhang (2011) investigates effects of leakages on a multi-actuator (cylinders) PLC control pneumatic system. It monitored pneumatic systems and implemented predictive maintenance through the on-line monitoring solution based on fast detection and diagnosis of leakage conditions. The Festo (US) system company developed PLC-based real-time control and data acquisition system. It includes hardware, software, and human machine interface control panel to make up this mechatronic system. The research was to diagnose the leakage fault of pneumatic system by comparing the flow rate and pressure change. The leakage classification curve can show the multiple-actuator pressure change result. It gets feature extraction through the wavelet transform. Its localized properties are in time and frequency domains. Its fast algorithms are ready for an on-line implementation. And its efficient data compression is for feature extraction. Figure 5 (Zhang, 2011) displays the threshold range in details. In coming cycle, each sampled value will be compared with the three-sigma rang.

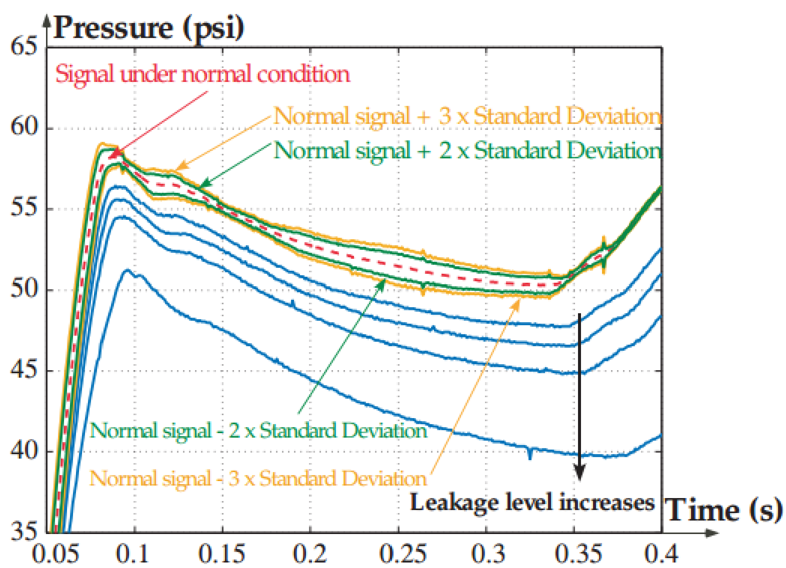


Figure 5: A detailed view of pressure change on every cycle (Zhang, 2011)

The research of Zhang (2011) and the equipment of Festo system company PLC-based real-time control and data acquisition system have practical and theoretical meaning, it inspired the proposed research approach to combine the pressure gauge and monitor system together through a microprocessor data acquisition system, so that the pressure drop due to leakage can be captured and displayed in a computer in real time. This approach for leak detection is called on-line system monitoring and performance analysis (Grace, Datta & Tassou, 2005).

CHAPTER III

METHODOLOGY

This chapter will describe the methodology of the study, including categories: (1) pneumatic system schematic and layout, (2) hardware set up, (3) data collection system development, (4) data analysis software development, (5) data collection, (6) data analysis.

Pneumatic System Schematic and Layout

The schematic of pneumatic system in Figure 6 is the key document to illustrate the study, test and analysis for hydraulic leakage detection. Based on the schematic, the components' functions, models, assembly methods, quantities can be identified.

The testing procedure is as follows:

1. The dry and pressurized air from the production lab is pumped through the filter to clear the impurities and then is pumped into the testing system.
2. The regulator and flow valve controls the pressure and rate of flow for the test needs.
3. The first bidirectional valve is used to control the air into to test unit or not, while the second bidirectional valve is used to control the air release from the test unit. They all accept the signal from the computer control board.
4. The pressure transducer monitors the pressure change on line, and sends the changed signal to the data acquisition module. The data will then be recorded and calculated by the computer.
5. The gauge on line could be the pressure monitor and read directly by the tester.

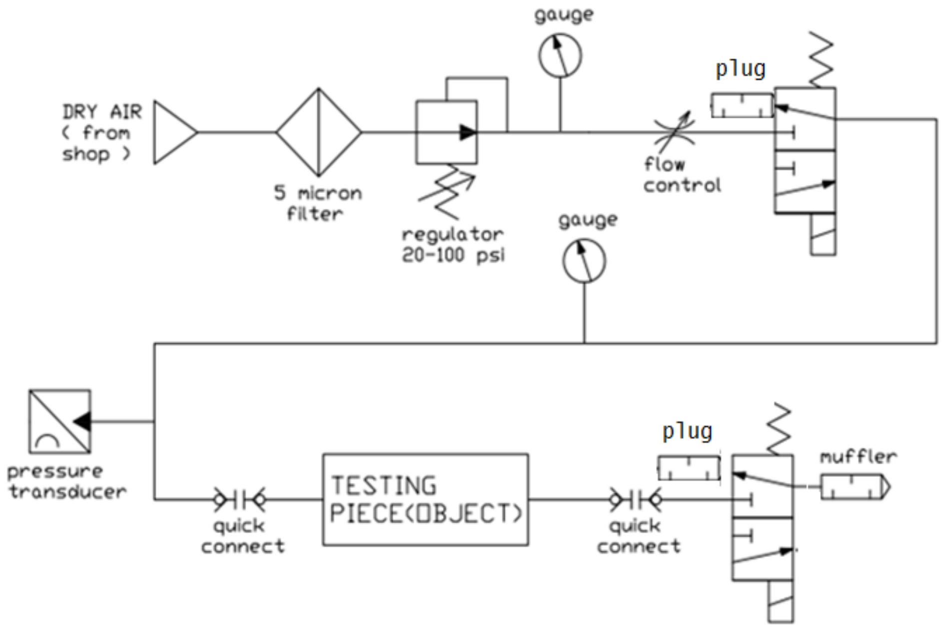


Figure 6: The schematic of pneumatic system

Hardware Setup

The test system includes:

1. A regulator that combines with 5 micrometer filter and a 100 psi gauge, it was used to adjust the air pressure of test system.
2. A flow controller and two bidirectional valves, they were used to control the air in and out from test unite.
3. A 200 psi pressure gauge, it can observe the pressure of test unite.
4. A pressure transducer to monitor the pressure change and create the voltage signal.
5. Power supplies of transducer and multifunction USB data acquisition device.
6. Two sets of quick connector to connect the test unite.

7. Test unit (Hydraulic tube)

8. Hose, plug, muffle and connector

9. Two muffles assembled on bidirectional valve to reduce the noisy of air release.

All the test components were mounted on the testing platform that is a sheet metal board shown in Figure 7, the components part list is Table 2.

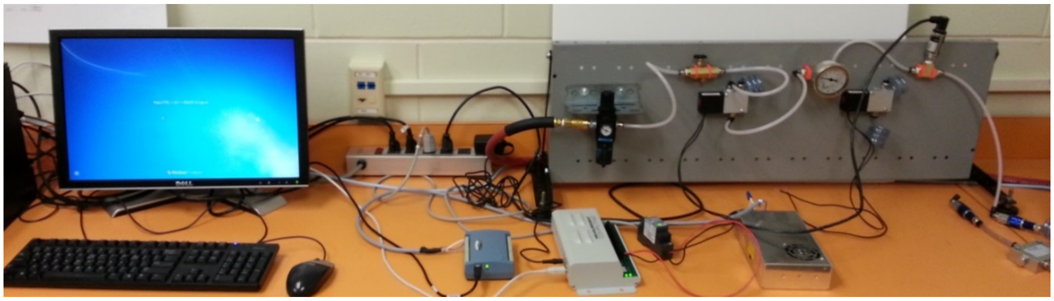


Figure 7: Pneumatic equipment

Table 2

Pressure detection system part list

Components Name	Mode Number	Manufacturer	Major Parameter
Regulator & filter	B08-FK-02G0	Wilkerson	5 micron filter, 100psi with 1/4 NPT famale
Pressure Transducer	2001001522	Noshok	30v, 100psi, 1/4 NPT
Bidirectional valve	32012VDC	Humphrey	8W, 12v, 3way 125PSIG, 1/4 NPT
Inline flow control	F20B	Deltrol	Famale to Famale 1/4 NPT, Max 2000psi
Male adapter	727	Surpluscenter	1/4 NPT
Famale adapter	728	Surpluscenter	1/4 NPT
Air quick coupler	711	Surpluscenter	1/4 NPT
Pressure transducer Power supply	S-320-15	Meanwell	AC/DC single output 320w/15v
Solenoid power supply	PSC-12-015	Rhino PSC	input 100-240v output 15w
Multifunction USB Data Acquisition Device	USB-1608G	Measurement Computing	16-Bit, 400 kS/s, 8 signal-ended
Electromechanical Relay Interface Device	USB-ERB08	Measurement Computing	8-channel 6 amps at 240 VAC / 28 VDC

Data Collection System Development

The basic working theory of the data collection system is: the pressure transducer detects the pressure change when the test unite has leakage, and the pressure change is transformed to the voltage change signal and then captured by DAQ Board (USB-1608G). The DAQ board connected with the computer by a USB port, the voltage signal was collected and recorded by the software that was developed in using VBA (Visual Basic Application). The pressure and voltage ratio through the pressure transducer was:

1.0 psi equal to 0.03 volts, the related coefficient was defined in the software and directly reflects on the pressure degradation curve that was created by the software.

As the Figure 8 shows, the USB-ERB08 EM relay module is used to automatically control the system operations. The bidirectional valves will take action through the commands from the VBA software in Excel so it will release the air in and out of the test unit.

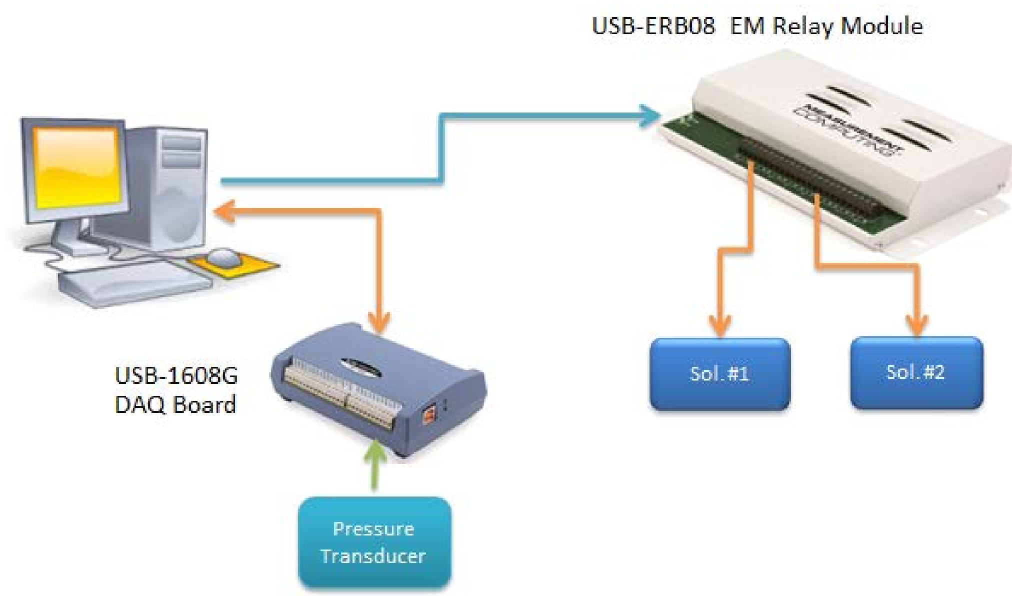


Figure 8: Data collection system

Data Analysis Software Development

The data acquisition software was customized and developed. It uses Microsoft VBA functions in an Excel file to control the electrical –mechanical equipment to realize the electrical signal collection and test system control function. The data acquisition interface is showed in Figure 9.

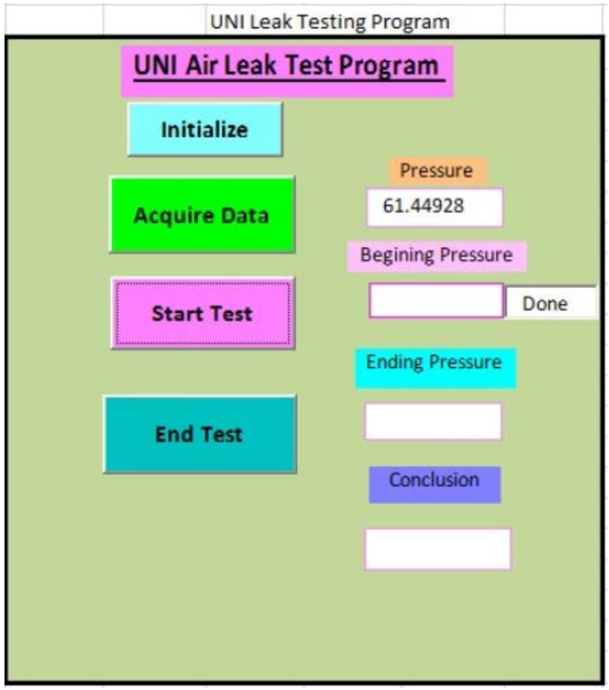


Figure 9: Data acquisition interface

The software operation process is as following:

1. When starting a new test, it needs to initialize the data to clean out the old recording from the last test.
2. The acquire icon can show the real time pressure point.
3. Click the start test icon, the software starts recording the real time pressure.
4. At the end of test, the final pressure and the real time data of pressure changes will be recorded by the software in a test cycle (50 seconds) on the data sheet page.

5. The pressure change curve will be created and shown on the main interface. Figure 10 was a pressure change curve under non-leakage status that was obtained from a pilot test. Figure 11 was a pressure change curve under leakage status.
6. Copy or move the test data to another data sheet for reference and calculation.

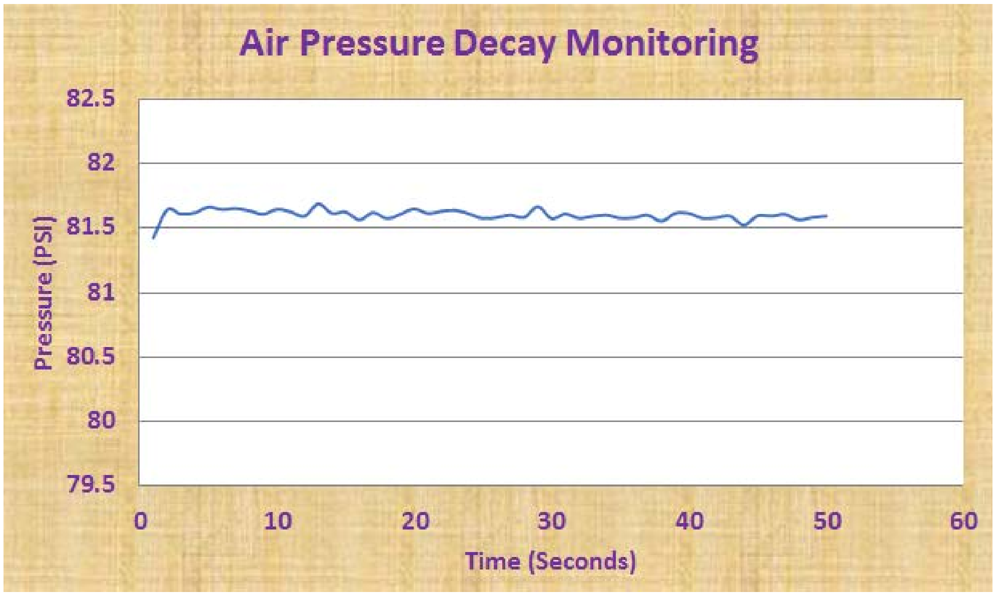


Figure 10: Pressure decay curve under non-leakage status

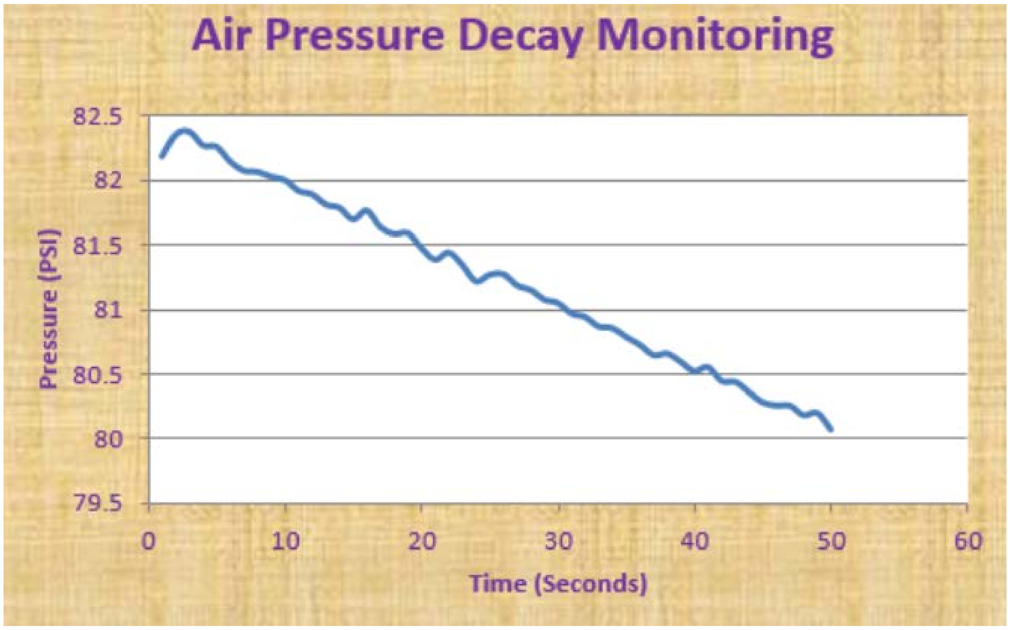


Figure 11: Pressure decay curve under leakage status

Data Collection

The experiment was conducted in two steps. In step one, the system performance baseline on the pressure drop was established. To do this, the first treatment was the normal system setting, which was generated by tightly inserting a good thread tube. In Step two, the system was set up on purpose to have leakage by loosely inserting the hydraulic tube.

The pressure holding time was set at 50 seconds. A testing time is given in ASTM 1047 / A 1047M – 05 that quantifies the leakage detection time for pressure decay. For a -inch OD by 0.050 inch wall by 60 feet long tube with a 0.003 inch diameter hole, the leakage detection time is 1.7 seconds. Therefore the testing period of 50 seconds would be sufficient for measuring pressure decay in this leakage detection system.

To answer the second research question, the purpose of this step was to check whether the system can consistently perform the designed function. The pressure decay was measured 10 times when the hydraulic system inserted in a good tube was set to different pressure levels less than 100 PSI (82 PSI and 50 PSI respectively);

Two groups of data were acquired at two kinds of artificial conditions. The first condition was under non-leakage status. The bubble checking method was used to confirm there was no leakage happening. There were ten sub groups of data recorded under the pressure 50 psi condition, and every sub group includes 50 pressure values (recorded in appendix). The same method was used on the second condition under leakage status, which means the bubble checking method was used to confirm that there was leakage happening.

Data Analysis

To identify the pressure decay at the setup pressure levels, the leakage and non-leakage status were recorded. The statistics analysis software Minitab was used as the primary tool for data analysis. The pressure change value ΔP of every sub group was calculated in the database from start to end test points.

When the system was set at 50 psi, the changed pressure values of every sub group at non-leakage (ΔP_1) and leakage (ΔP_2) status were listed in Table 3.

Table 3

The changed pressure value at 50 psi

ΔP_1	0.4610	0.3987	0.3914	0.3781	0.3941	0.1895	0.4285	0.2477	0.3712	0.2811
ΔP_2	8.4164	8.1931	8.3363	8.4489	8.3798	8.2841	8.3318	8.3130	8.1999	8.2603

Based on the statistical analysis, the two samples of T-Test results are as following.

Two-Sample T-Test and CI: ΔP_1, ΔP_2

Two-sample T for ΔP_1 vs ΔP_2

	N	Mean	StDev	SE Mean
ΔP_1	10	0.3541	0.0860	0.027
ΔP_2	10	8.3164	0.0851	0.027

Difference = μ (ΔP_1) - μ (ΔP_2)
Estimate for difference: -7.9622
95% CI for difference: (-8.0430, -7.8815)
T-Test of difference = 0 (vs $\neq$): T-Value = -208.09 P-Value = 0.000 DF = 17

From the above T-Test result, the P-value equals zero so it can be concluded that the second group of data was statistically different from the first group of data. The leakage status was confirmed by the analysis result.

For the object to verify the test system will be able to perform consistently at different air pressure levels, the higher pressure with the 82 psi test condition was conducted. The changed pressure values at non-leakage (ΔP_3) and leakage (ΔP_4) status are shown in Table 4.

Table 4

The changed pressure values at 82 psi

ΔP_3	0.2092	0.1689	0.2129	0.2637	0.2367	0.2719	0.2435	0.1648	0.2065	0.2628
ΔP_4	2.336	2.2929	2.3016	2.1844	2.2911	2.1423	2.2092	2.0805	2.1524	2.1762

The two samples of T-Test results are as follows.

Two-Sample T-Test and CI: ΔP_3, ΔP_4

Two-sample T for ΔP_3 vs ΔP_4

	N	Mean	StDev	SE Mean
ΔP_3	10	0.2241	0.0382	0.012
ΔP_4	10	2.2167	0.0841	0.027

Difference = μ (ΔP_3) - μ (ΔP_4)
Estimate for difference: -1.9926
95% CI for difference: (-2.0563, -1.9289)
T-Test of difference = 0 (vs $\neq$): T-Value = -68.20 P-Value = 0.000 DF = 12

The results demonstrated that the data at leakage status was statistically different from the data at non-leakage status. The leakage status was identified. The system can work consistently at different pressure level.

To further analyze the trend of system pressure change and conclude the pressure decay model in testing period, Microsoft Excel software was used as the data analysis tool.

Firstly, the linear pressure decay curve of every sub group data was created as shown Figures 12 to 15. The curves can intuitively and clearly reveal the pressure decay status for every test. When the linear trend lines were added on the selected chart series in Excel, the specific pressure change equations and the coefficient of time are listed on the charts. The intercepts and slopes (coefficients) showed that the air pressure of test was not perfectly consistent; the inconsistency is due to the fact that the initial pressure was obtained from the shop had a little variations. But all the pressure decay curve trends are not impacted by the inconsistency.

The random selected equation of sub group data of every figure is as following:

The equation of sub group data linear 5 at 50 psi under non-leakage status in Figure 12 is:

$$y=-0.0012x + 50.315$$

The equation of sub group data linear 1 at 50 psi under leakage status in Figure 13 is:

$$y = -0.1716x + 51.368$$

The equation of sub group data linear 7 at 80 psi under non-leakage status in Figure 14 is:

$$y = -0.001x + 83.123$$

The equation of sub group data linear 6 at 80 psi under leakage status in Figure 15 is:

$$y = -0.0456x + 82.99$$

The equation of linear 5 in Figure 12 indicated the slope for pressure change is very small accompanied with time change. The slope for pressure change of linear 1 in Figure 13 is approximate 143 times comparing to the corresponding proportion in Figure 12.

The pressure change curves and slopes at 82psi pressure status are as Figure 14 and Figure 15. The slope proportion of leakage lines is 45 times of non-leakage lines.

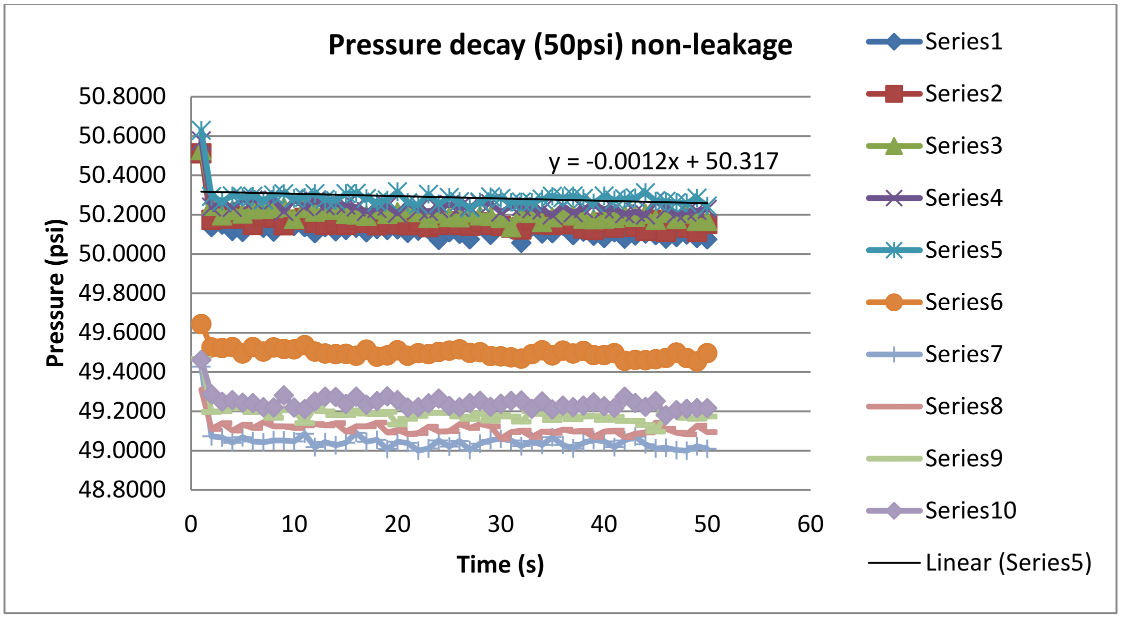


Figure 12: Pressure decay curve at 50 psi under non-leakage status

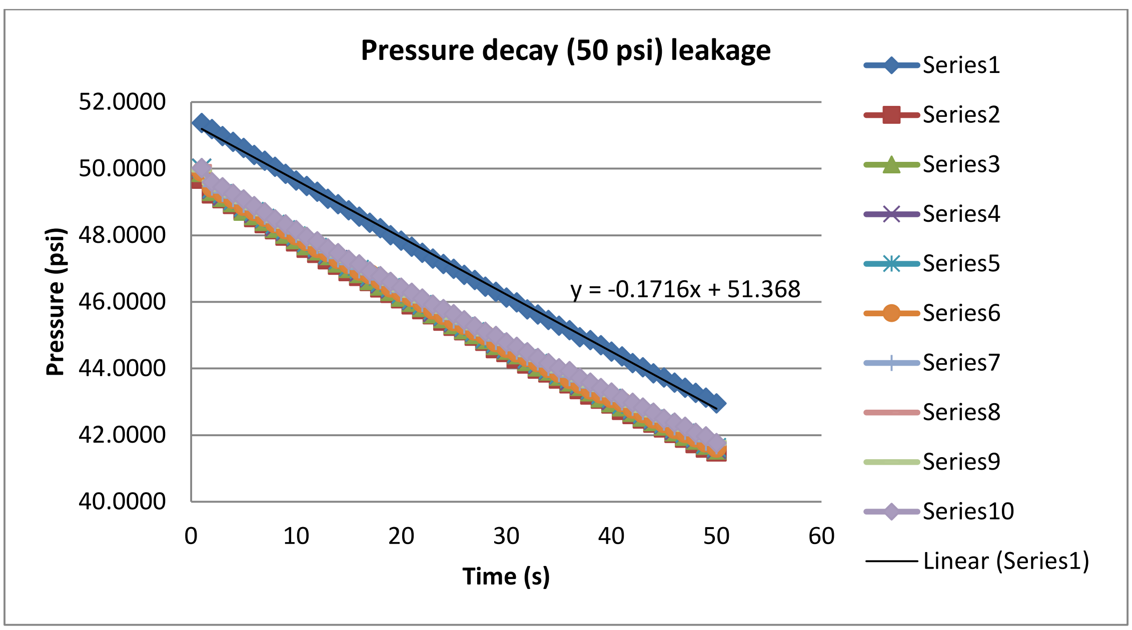


Figure 13: Pressure decay curve at 50 psi under leakage status

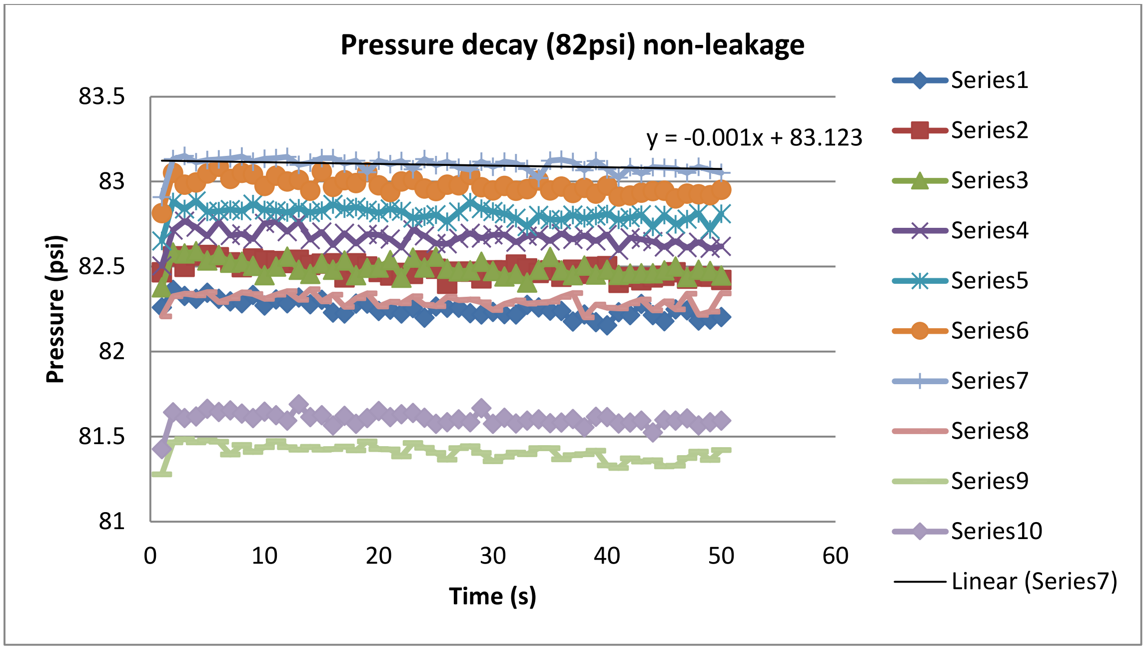


Figure 14: Pressure decay curve at 82 psi under non-leakage status

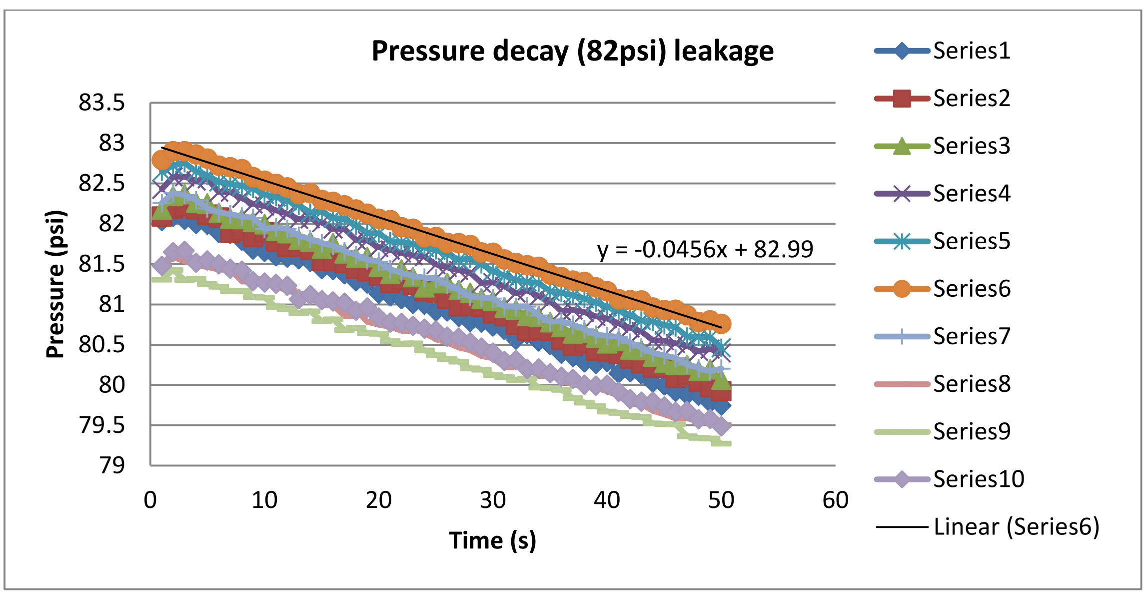
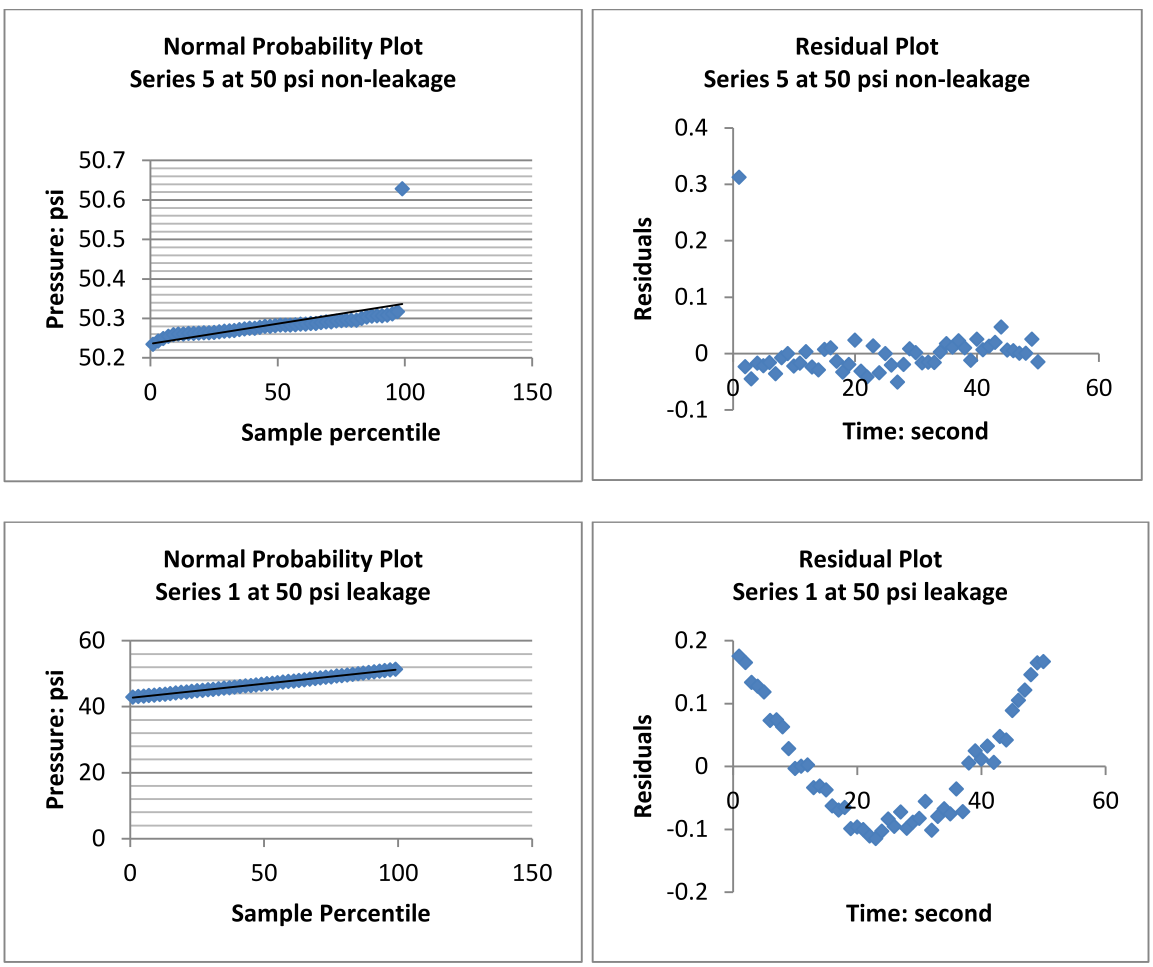


Figure 15: Pressure decay curve at 82 psi under leakage status

According to the observation of pressure change curves at 50 psi and 82 psi, the pressure decay curves appear to fit well in a linear line. One linear regression model was generated out of the four data collection treatments and was marked in Figure 12, 13, 14, and 15, respectively. To confirm that the experimental data meet the assumptions of multiple regressions, the normal probability plot of pressure data was created to check normality and residual plot was created in Figure 16 to make sure that regression models include all the explainable items.



(Figure continues)

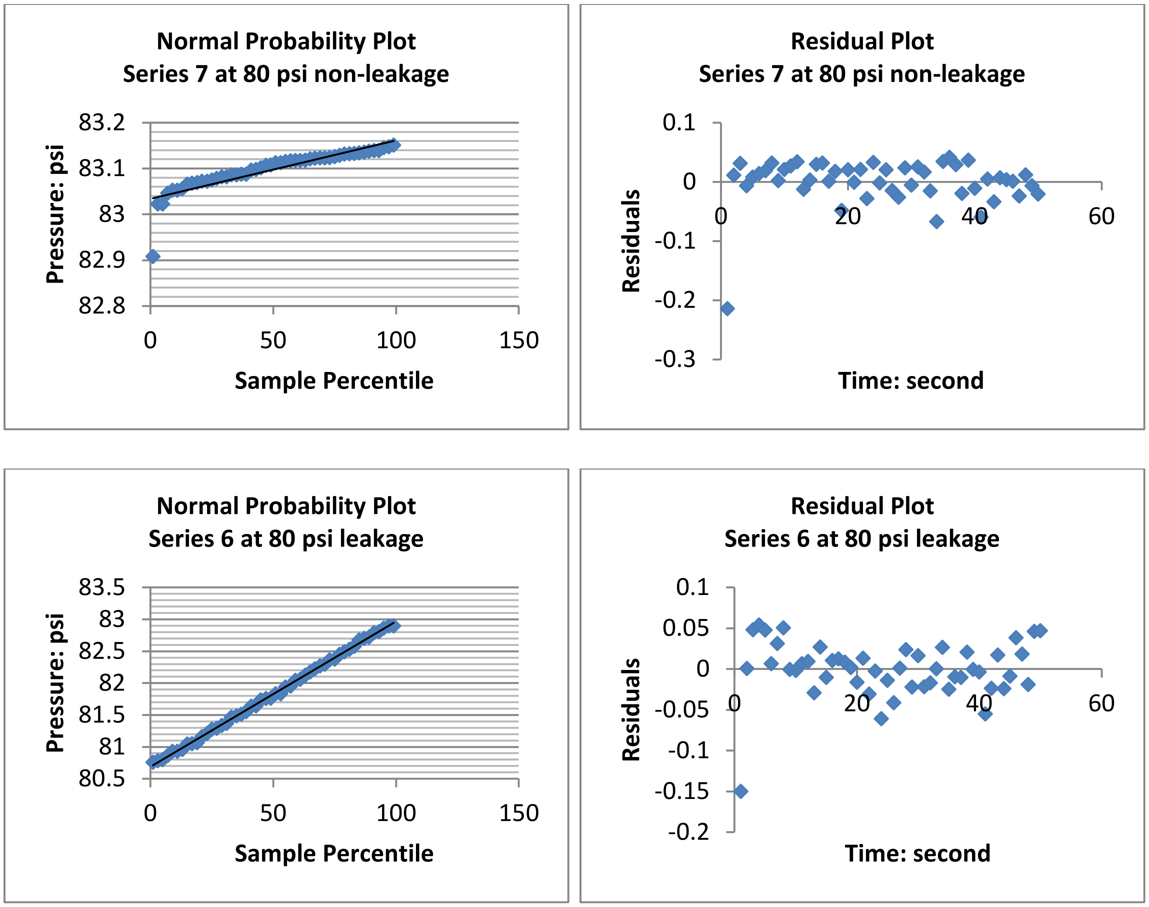


Figure 16: Normal probability and residual plots

Above four normal probability plots indicated an approximately normal distribution of the pressure data. The residual plots for non-leakage at 50 psi and non-leakage at 82 psi indicated the residuals were approximately constant magnitude and randomly spread, which means the linear regression line includes all the explainable items; the residuals for leakage at 50psi leakage condition, there was an obvious quadratic pattern, which indicated a second order term should be included in the regression model; the residuals for leakage at 82 psi are in between of the random pattern and quadratic pattern. So, the polynomial equation and R-Square were generated regarding the pressure data for leakage status at 50psi in Figure 17 and intended to verify whether there are other to be included in the regression model.

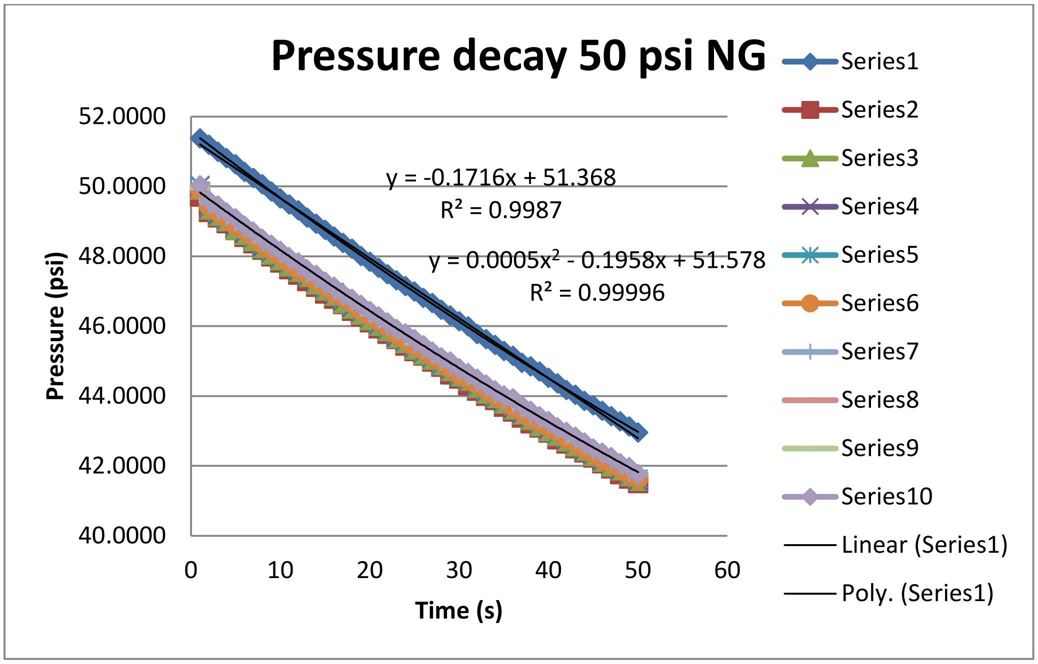


Figure 17: Pressure decay curve and equations at 50 psi under leakage condition

The linear equation and R-Square are as follows:

$$y = -0.1716x + 51.368$$

$$R^2 = 0.9987$$

The polynomial equation and R-Square are as follows:

$$y = 0.0005x^2 - 0.1958x + 51.578$$

$$R^2 = 0.9996$$

The R-Square value of polynomial model equals 0.9996(99.96%); it indicates that the model explains all the variabilities of the response data are around its mean, so the model fits the test data almost perfectly. The R-Square value of linear model equals 0.9987 (99.87%); it also indicates that the linear model fits the test data very well. Meantime, the coefficient for the second term in polynomial model is 0.0005; the value is very small and only contributes a very little portion to the result, so it could be ignored on the influence to leakage.

According to above analyses, the linear model can be used as leakage model to evaluate whether the air leakage status is acceptable.

CHAPTER IV

CONCLUSION AND RECOMMENDATION

The air based hydraulic leakage detection system was developed by pressure decay signal acquisition technology in this research. Based on above experiment and analysis result, the test theory and equipment were verified, the leakage model was concluded. This study proved following conclusions:

1. The proposed system can capture the difference of pressure changes for the faulty and good hydraulic components.
2. The proposed system can perform consistently at different air pressure levels.
3. The linear pressure regression model was created and analyzed.

These linear equation analysis methods are very easy to be put into practice in factory with Excel software by quality control or engineering teams. When the specific slope value is defined, the benchmark curve of non-leakage is fixed, it can very easily justify the leakage is happening or not. The proposed system can fulfill its designed function properly. Although the research does not perform the comparison study between hydraulic leakage tests in using air or oil as testing medium, but the fundamental pressure decay equation for further comparison with real hydraulic system has concluded.

For further study, the leakage relationship with mathematic equation could be formed to correlate with leakage flow rates in pressured air or in hydraulic oil.

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APPENDIX

TEST DATA

Table 5

Test data at 50 psi under non-leakage condition

	1	2	3	4	5	6	7	8	9	10
1	50.5179	50.5115	50.5270	50.5751	50.6282	49.6431	49.4270	49.3094	49.4678	49.4609
2	50.1361	50.1727	50.2441	50.2377	50.2913	49.5250	49.0723	49.1098	49.1954	49.2847
3	50.1489	50.2020	50.1956	50.2606	50.2684	49.5209	49.0654	49.1391	49.1995	49.2485
4	50.1160	50.1805	50.2217	50.2364	50.2954	49.5255	49.0393	49.1011	49.2439	49.2567
5	50.1109	50.1906	50.2052	50.2744	50.2895	49.4943	49.0672	49.1313	49.2133	49.2426
6	50.1457	50.1471	50.2263	50.2734	50.2940	49.5268	49.0457	49.1148	49.1945	49.2412
7	50.1329	50.1910	50.2309	50.2762	50.2730	49.5030	49.0411	49.1441	49.2078	49.2206
8	50.1128	50.1846	50.2327	50.2744	50.3000	49.5245	49.0517	49.1235	49.1666	49.2192
9	50.1636	50.1457	50.2377	50.2158	50.3064	49.5163	49.0517	49.1235	49.2123	49.2810
10	50.1416	50.1741	50.1778	50.2757	50.2831	49.5140	49.0457	49.1148	49.2041	49.2188
11	50.1352	50.1833	50.2341	50.2405	50.2872	49.5355	49.0860	49.1277	49.1386	49.2101
12	50.1054	50.1572	50.2158	50.2679	50.3059	49.5030	49.0164	49.1336	49.2201	49.2490
13	50.1366	50.1476	50.2249	50.2451	50.2776	49.4934	49.0425	49.1281	49.1995	49.2741
14	50.1155	50.1590	50.2249	50.2547	50.2716	49.4902	49.0274	49.1386	49.1794	49.2728
15	50.1205	50.1471	50.2034	50.2483	50.3064	49.4916	49.0407	49.0974	49.1794	49.2371
16	50.1324	50.1750	50.2016	50.2377	50.3082	49.4820	49.0901	49.1222	49.2041	49.2741
17	50.1100	50.1576	50.1938	50.2158	50.2831	49.5131	49.0453	49.1231	49.1872	49.2339
18	50.1270	50.1453	50.2277	50.2304	50.2629	49.4778	49.0549	49.1418	49.1844	49.2517
19	50.1210	50.1659	50.2048	50.2428	50.2748	49.4843	49.0082	49.0924	49.1982	49.2760
20	50.1247	50.1498	50.2126	50.2066	50.3169	49.5094	49.0443	49.1048	49.1327	49.2558
21	50.1073	50.1453	50.2350	50.2579	50.2606	49.4820	49.0375	49.0837	49.1615	49.2192
22	50.1187	50.1636	50.2116	50.2267	50.2492	49.4948	48.9986	49.0883	49.1766	49.2210
23	50.1242	50.1361	50.1828	50.2148	50.3032	49.4897	49.0105	49.1208	49.1908	49.2393
24	50.0711	50.1471	50.2061	50.2304	50.2542	49.5012	49.0508	49.0965	49.1922	49.2645
25	50.1096	50.1654	50.1883	50.2510	50.2872	49.5090	49.0201	49.0979	49.1908	49.2270
26	50.1013	50.1471	50.1855	50.2364	50.2657	49.5149	49.0480	49.1336	49.1739	49.2201
27	50.0743	50.1439	50.2112	50.2396	50.2341	49.4971	49.0027	49.1139	49.1602	49.2412
28	50.1439	50.1627	50.1961	50.2597	50.2643	49.5007	49.0356	49.1341	49.1895	49.2526
29	50.0967	50.1476	50.1933	50.2556	50.2908	49.4801	49.0530	49.1231	49.1524	49.2215
30	50.1416	50.1421	50.1823	50.2126	50.2831	49.4783	49.0590	49.0617	49.1803	49.2380
31	50.1260	50.1343	50.1357	50.2423	50.2634	49.4733	49.0512	49.0942	49.1730	49.2535
32	50.0569	50.1242	50.2107	50.2405	50.2638	49.4682	49.0219	49.1020	49.1464	49.2540
33	50.1384	50.1718	50.2094	50.2304	50.2620	49.4902	49.0485	49.0691	49.2009	49.2119
34	50.1036	50.1512	50.1617	50.2240	50.2794	49.5094	49.0283	49.0961	49.1858	49.2494
35	50.1054	50.1471	50.1869	50.1984	50.2931	49.4838	49.0668	49.0906	49.1533	49.2087
36	50.1434	50.1535	50.2071	50.2441	50.2853	49.5085	49.0279	49.1071	49.1830	49.2293
37	50.0958	50.1503	50.1961	50.2084	50.2954	49.4939	49.0100	49.0965	49.1579	49.2197
38	50.1128	50.1292	50.1791	50.2299	50.2817	49.5062	49.0384	49.1002	49.1730	49.2288
39	50.0922	50.1210	50.1768	50.2469	50.2588	49.4847	49.0540	49.0700	49.1753	49.2444
40	50.0803	50.1590	50.1796	50.2286	50.2950	49.4856	49.0462	49.0965	49.1551	49.2256
41	50.1100	50.1338	50.1837	50.2290	50.2748	49.4957	49.0178	49.1011	49.1698	49.2165
42	50.0766	50.1714	50.1993	50.2048	50.2798	49.4563	49.0508	49.0681	49.1505	49.2737
43	50.0935	50.1375	50.1892	50.2126	50.2858	49.4618	49.0704	49.0860	49.1510	49.2412
44	50.1031	50.1160	50.2048	50.1970	50.3114	49.4591	49.0324	49.0915	49.1290	49.2220
45	50.0954	50.1736	50.1736	50.2702	50.2693	49.4646	49.0109	49.1418	49.0965	49.2513
46	50.0780	50.1132	50.2098	50.2281	50.2675	49.4710	49.0146	49.1103	49.1840	49.1798
47	50.0858	50.1672	50.1787	50.2043	50.2615	49.4984	49.0022	49.0897	49.1936	49.2055
48	50.0981	50.1338	50.2061	50.2121	50.2602	49.4701	48.9995	49.0828	49.1670	49.2128
49	50.0803	50.1128	50.1677	50.2213	50.2840	49.4536	49.0224	49.1263	49.1620	49.2151
50	50.0739	50.1517	50.1686	50.2277	50.2428	49.4952	49.0091	49.0938	49.1739	49.2155

Table 6

Test data at 50 psi under leakage condition

	1	2	3	4	5	6	7	8	9	10
1	51.3721	49.7063	49.9068	50.0249	50.0125	49.9196	50.0418	50.0656	49.9718	50.0258
2	51.1903	49.2691	49.3387	49.3813	49.4055	49.4403	49.4801	49.5282	49.5891	49.5959
3	50.9871	49.1176	49.1629	49.1812	49.2513	49.2741	49.2847	49.3675	49.3991	49.4485
4	50.8095	48.9445	49.0054	49.0421	49.0544	49.1002	49.1341	49.1556	49.2293	49.2549
5	50.6287	48.7610	48.7445	48.8452	48.8516	48.8919	48.9565	48.9903	49.0320	49.0828
6	50.4117	48.5568	48.6072	48.6562	48.7184	48.7386	48.7711	48.8022	48.8521	48.8782
7	50.2409	48.3737	48.4355	48.5088	48.5138	48.5646	48.6026	48.6415	48.6607	48.6951
8	50.0583	48.1906	48.2309	48.2588	48.3307	48.3673	48.3888	48.4369	48.4630	48.4904
9	49.8523	47.9947	48.0560	48.1256	48.1659	48.1851	48.2231	48.2753	48.2863	48.3293
10	49.6490	47.8262	47.8912	47.9539	47.9851	48.0043	48.0542	48.1233	48.1627	48.1563
11	49.4810	47.6353	47.7127	47.7869	47.7896	47.8377	47.8656	47.8958	47.9352	47.9590
12	49.3117	47.4797	47.5584	47.5781	47.6422	47.6358	47.7159	47.7187	47.7667	47.8244
13	49.1039	47.2902	47.4129	47.3996	47.4408	47.4948	47.4916	47.5713	47.6152	47.6102
14	48.9345	47.1272	47.1877	47.2742	47.2540	47.2934	47.3167	47.4138	47.4234	47.4646
15	48.7569	46.9331	47.0274	47.0554	47.0677	47.1405	47.1378	47.2224	47.2559	47.2701
16	48.5600	46.7871	46.8700	46.9029	46.9757	46.9473	46.9849	47.0425	47.1053	47.1286
17	48.3820	46.6379	46.6640	46.7290	46.7693	46.8343	46.8237	46.8951	46.9107	46.9221
18	48.2144	46.4447	46.5028	46.5463	46.5898	46.6631	46.6699	46.7001	46.7798	46.7766
19	48.0093	46.2804	46.3316	46.3934	46.4301	46.4438	46.5079	46.5225	46.5720	46.6026
20	47.8400	46.1119	46.1668	46.2410	46.2415	46.2936	46.2996	46.3788	46.3820	46.4337
21	47.6646	45.9375	46.0103	46.0428	46.0670	46.1536	46.1755	46.1961	46.2099	46.2808
22	47.4825	45.7860	45.8546	45.9050	45.9242	45.9837	45.9796	46.0057	46.0469	46.1064
23	47.3071	45.6335	45.6624	45.6844	45.7498	45.7828	45.8620	45.8601	45.9192	45.9210
24	47.1469	45.4422	45.5154	45.5722	45.5901	45.6203	45.6720	45.6610	45.7320	45.7896
25	46.9949	45.2911	45.3378	45.3809	45.4124	45.4381	45.4852	45.5370	45.5548	45.6313
26	46.8118	45.1561	45.1881	45.2380	45.2655	45.3232	45.3246	45.3868	45.4257	45.4491
27	46.6631	44.9886	45.0439	45.0870	45.1044	45.1437	45.1698	45.2060	45.2440	45.2747
28	46.4653	44.8398	44.8842	44.8874	44.9084	45.0037	44.9876	45.0792	45.0549	45.1053
29	46.3033	44.6169	44.7185	44.7391	44.7670	44.8027	44.8398	44.8828	44.9428	44.9854
30	46.1380	44.4992	44.5674	44.5747	44.6040	44.6320	44.7070	44.7382	44.7835	44.7926
31	45.9933	44.3060	44.4333	44.4328	44.4644	44.4960	44.5464	44.5738	44.6475	44.6530
32	45.7759	44.1536	44.2332	44.2763	44.2969	44.3536	44.3710	44.4196	44.4484	44.4919
33	45.6262	44.0076	44.0712	44.1142	44.1536	44.1925	44.2213	44.2676	44.2923	44.3248
34	45.4669	43.8922	43.9462	43.9444	43.9769	44.0268	44.0598	44.1174	44.1628	44.1669
35	45.2870	43.7009	43.7924	43.8144	43.8167	43.8753	43.8744	43.9673	43.9590	44.0163
36	45.1552	43.5612	43.6176	43.6299	43.7100	43.6967	43.7581	43.7549	43.8611	43.9297
37	44.9478	43.3887	43.4811	43.4912	43.5471	43.5553	43.6075	43.6102	43.6986	43.7260
38	44.8535	43.2211	43.3200	43.3539	43.3653	43.3818	43.4317	43.5118	43.5095	43.5773
39	44.7011	43.0984	43.1424	43.2147	43.2280	43.2541	43.3237	43.3438	43.3919	43.4198
40	44.5166	42.9533	42.9945	43.0449	43.1090	43.1158	43.1868	43.1561	43.2211	43.2838
41	44.3655	42.7647	42.8682	42.9291	42.9327	42.9959	43.0220	43.0673	43.0939	43.1039
42	44.1682	42.6443	42.7048	42.7487	42.7876	42.7991	42.8613	42.9080	42.9089	42.9767
43	44.0378	42.5084	42.5597	42.6260	42.6476	42.6727	42.7396	42.7263	42.7583	42.8334
44	43.8606	42.3834	42.4306	42.4457	42.4883	42.5020	42.5812	42.6260	42.6224	42.6750
45	43.7357	42.2383	42.2914	42.3253	42.3555	42.3701	42.4223	42.4493	42.4704	42.4965
46	43.5805	42.0758	42.1188	42.1431	42.2003	42.1994	42.2768	42.3102	42.3523	42.3807
47	43.4253	41.9316	41.9884	42.0589	42.0648	42.0703	42.1449	42.1495	42.1875	42.2530
48	43.2779	41.7659	41.8730	41.8881	41.9339	41.9371	42.0003	42.0433	42.0795	42.0735
49	43.1255	41.6336	41.7151	41.7238	41.7384	41.7833	41.8117	41.8616	41.9078	41.9669
50	42.9556	41.5132	41.5704	41.5759	41.6327	41.6354	41.7101	41.7526	41.7719	41.7654

Table 7

Test data at 82 psi under non-leakage condition

	1	2	3	4	5	6	7	8	9	10
1	82.2592	82.4666	82.3773	82.5046	82.6501	82.8154	82.9079	82.2079	81.2778	81.4261
2	82.3636	82.56	82.5829	82.7142	82.8799	83.0521	83.1326	82.3247	81.4659	81.6422
3	82.3274	82.4977	82.5774	82.7682	82.8383	82.9811	83.1514	82.3398	81.4842	81.6096
4	82.3114	82.565	82.5902	82.7321	82.8868	82.9944	83.1129	82.332	81.4659	81.6188
5	82.3462	82.5687	82.5357	82.6785	82.8227	83.0484	83.1262	82.3508	81.4778	81.6637
6	82.3105	82.5549	82.5673	82.7641	82.8259	83.0873	83.1313	82.2917	81.4691	81.644
7	82.2958	82.5256	82.5229	82.6822	82.8351	83.0164	83.1354	82.3146	81.3945	81.6531
8	82.2839	82.4963	82.5284	82.6932	82.8268	83.0516	83.1473	82.3489	81.4513	81.6348
9	82.3325	82.5476	82.5046	82.663	82.8671	83.0424	83.1166	82.3393	81.4101	81.6087
10	82.2716	82.5357	82.4492	82.7536	82.8328	82.9752	83.134	82.3105	81.4384	81.6467
11	82.3068	82.533	82.5005	82.7646	82.8273	83.0342	83.139	82.3352	81.4742	81.6266
12	82.2835	82.5215	82.5581	82.706	82.8186	83.0003	83.1454	82.3558	81.4371	81.5932
13	82.3174	82.5398	82.4808	82.7655	82.8429	83.0099	83.0978	82.3055	81.422	81.6888
14	82.2784	82.5096	82.4579	82.6588	82.8191	82.9468	83.1125	82.3663	81.4394	81.6151
15	82.305	82.5165	82.5197	82.7032	82.83	83.0594	83.1377	82.2949	81.4233	81.6252
16	82.229	82.5201	82.4808	82.6263	82.8662	82.9692	83.139	82.3347	81.427	81.5652
17	82.2235	82.4373	82.5371	82.6968	82.8406	83.0081	83.107	82.2638	81.4407	81.6211
18	82.283	82.5201	82.4501	82.635	82.8511	82.9921	83.123	82.3151	81.4183	81.5753
19	82.283	82.5014	82.4922	82.6895	82.831	83.0553	83.0562	82.343	81.4723	81.6087
20	82.2391	82.4684	82.4954	82.6859	82.8172	82.9784	83.1239	82.2661	81.427	81.6495
21	82.2459	82.4483	82.5385	82.663	82.8392	82.9385	83.1015	82.2926	81.4243	81.6147
22	82.2244	82.4629	82.4345	82.6122	82.8264	83.0003	83.1221	82.2849	81.3831	81.6321
23	82.2556	82.4565	82.5536	82.717	82.7866	83.0095	83.0722	82.326	81.4618	81.6385
24	82.2002	82.5357	82.494	82.6813	82.7934	82.9596	83.1322	82.2748	81.4348	81.6115
25	82.2652	82.4872	82.5586	82.6355	82.8049	82.9449	83.0965	82.2679	81.4037	81.5753
26	82.2569	82.3997	82.4881	82.6341	82.7637	82.9825	83.1175	82.3219	81.3647	81.5836
27	82.2569	82.4707	82.4725	82.6653	82.8214	82.9779	83.0818	82.3022	81.4325	81.6019
28	82.2263	82.4702	82.4771	82.6968	82.8777	83.0392	83.0695	82.3059	81.443	81.5845
29	82.218	82.4313	82.5293	82.6685	82.8415	82.9678	83.118	82.2894	81.4032	81.6673
30	82.234	82.4776	82.4748	82.6872	82.8241	82.9486	83.0878	82.2446	81.3556	81.5753
31	82.2194	82.4785	82.4419	82.6891	82.8113	82.9752	83.1175	82.2798	81.3821	81.611
32	82.2176	82.5114	82.4565	82.6437	82.7847	82.9468	83.1079	82.3009	81.4059	81.5776
33	82.2752	82.4886	82.4057	82.6785	82.7357	82.9555	83.075	82.2821	81.3968	81.5936
34	82.2606	82.4625	82.4808	82.6868	82.8017	83.0063	83.0223	82.2885	81.4316	81.6019
35	82.2409	82.4785	82.5568	82.6506	82.7765	82.9472	83.123	82.2935	81.4325	81.5785
36	82.2386	82.4396	82.478	82.6936	82.7756	82.971	83.129	82.3215	81.367	81.5822
37	82.1773	82.4821	82.4496	82.6598	82.8026	82.9326	83.1152	82.3434	81.3913	81.6023
38	82.2185	82.4579	82.5064	82.6831	82.7847	82.9633	83.0658	82.2015	81.3968	81.5538
39	82.1722	82.4991	82.4529	82.6501	82.798	82.9285	83.1212	82.2771	81.4169	81.6156
40	82.1544	82.5027	82.4817	82.6886	82.8081	82.9756	83.0722	82.2583	81.33	81.6151
41	82.2313	82.4043	82.451	82.597	82.7751	82.912	83.0228	82.2537	81.3153	81.5776
42	82.2139	82.4377	82.4583	82.6703	82.7888	82.9189	83.0859	82.2844	81.3721	81.5817
43	82.2812	82.4199	82.4615	82.6598	82.8044	82.9358	83.0466	82.3068	81.3528	81.5945
44	82.2139	82.4373	82.4611	82.6479	82.7335	82.9449	83.0859	82.2437	81.3602	81.524
45	82.1786	82.4451	82.4771	82.6144	82.803	82.9454	83.0818	82.2963	81.3249	81.5968
46	82.2491	82.4657	82.5	82.6483	82.749	82.9019	83.0782	82.2491	81.329	81.5941
47	82.2423	82.4286	82.4391	82.6108	82.7797	82.9285	83.0525	82.3402	81.3739	81.6074
48	82.1823	82.4419	82.4817	82.6442	82.8127	82.9257	83.0873	82.2162	81.4114	81.5657
49	82.1887	82.4396	82.4744	82.6071	82.7179	82.9207	83.0676	82.2359	81.3629	81.5845
50	82.2025	82.4213	82.4474	82.619	82.8099	82.9514	83.0525	82.343	81.4206	81.5941

Table 8

Test data at 82 psi under leakage condition

	1	2	3	4	5	6	7	8	9	10
1	82.03537	82.09076	82.17865	82.42905	82.64557	82.79526	82.25922	81.47095	81.30936	81.47964
2	82.08527	82.19009	82.34894	82.58102	82.72202	82.90009	82.37961	81.58493	81.42792	81.64902
3	82.05276	82.21893	82.37	82.58423	82.75452	82.90192	82.35672	81.53595	81.30295	81.66504
4	81.99875	82.18185	82.26379	82.53067	82.64923	82.86255	82.29309	81.48285	81.31943	81.51947
5	81.9928	82.11594	82.25418	82.55814	82.59705	82.81036	82.18872	81.46317	81.25168	81.54694
6	81.8866	82.07886	82.13791	82.39105	82.52014	82.72385	82.14294	81.43295	81.22192	81.50024
7	81.87561	81.88889	82.06787	82.39059	82.49634	82.70279	82.11685	81.4357	81.1647	81.44302
8	81.7923	81.91635	82.05872	82.31873	82.4675	82.6767	82.08893	81.28372	81.16928	81.41968
9	81.68152	81.83487	82.02255	82.24594	82.43774	82.58011	82.07382	81.31668	81.09192	81.28693
10	81.65314	81.89758	81.99417	82.22351	82.3645	82.53342	81.93512	81.28281	81.08597	81.27319
11	81.59729	81.7749	81.91132	82.16537	82.33246	82.49588	81.9548	81.2265	80.96832	81.25488
12	81.58173	81.71814	81.88431	82.12692	82.28577	82.45331	81.93649	81.16882	80.94177	81.23245
13	81.56067	81.71814	81.80649	82.05414	82.22992	82.36908	81.85272	81.12946	80.89279	81.0672
14	81.53137	81.67648	81.78131	82.06238	82.13928	82.37961	81.81335	81.08185	80.91568	81.1171
15	81.43799	81.54785	81.69067	82.01614	82.14981	82.29675	81.76071	80.99121	80.79117	81.05438
16	81.42654	81.53687	81.7598	81.9342	82.07062	82.27203	81.72913	80.99167	80.81406	81.03882
17	81.37436	81.51352	81.63254	81.93512	82.06238	82.22855	81.66229	80.8548	80.68405	81.02371
18	81.28738	81.4476	81.57898	81.80099	81.97952	82.17911	81.61377	80.9317	80.70923	80.923
19	81.26129	81.41235	81.5863	81.79138	81.88568	82.12692	81.5506	80.78247	80.64514	80.96283
20	81.13495	81.36154	81.47003	81.70898	81.87927	82.06329	81.53183	80.74814	80.6369	80.83969
21	81.10107	81.27045	81.38123	81.67465	81.7836	82.04727	81.43616	80.72205	80.54718	80.77606
22	81.0672	81.30615	81.43661	81.63895	81.77216	81.95755	81.38992	80.67398	80.51193	80.77057
23	81.01181	81.24115	81.34048	81.60599	81.75064	81.94016	81.35284	80.69092	80.5188	80.73486
24	80.99762	81.16562	81.21323	81.59546	81.70624	81.83624	81.33087	80.64651	80.43182	80.70053
25	80.91339	81.15051	81.26495	81.49521	81.67191	81.83762	81.32401	80.56686	80.37048	80.67719
26	80.91614	81.07224	81.26907	81.46042	81.62796	81.76483	81.24619	80.52704	80.32242	80.60257
27	80.84885	80.97794	81.18164	81.42288	81.5538	81.76163	81.18073	80.4657	80.29037	80.59067
28	80.78339	80.98526	81.14639	81.39679	81.56479	81.73874	81.09879	80.42999	80.20935	80.53024
29	80.7756	80.97336	81.07224	81.26358	81.49979	81.64719	81.08597	80.36041	80.19058	80.46661
30	80.72937	80.89142	81.04568	81.27411	81.41327	81.64032	81.07361	80.3334	80.12558	80.40115
31	80.68634	80.85571	80.9642	81.22559	81.35651	81.55655	80.97977	80.22583	80.09949	80.29999
32	80.56549	80.75134	80.93674	81.14319	81.30615	81.51581	80.96741	80.24551	80.06699	80.31097
33	80.63416	80.67535	80.86304	81.17294	81.28098	81.48743	80.97473	80.20981	80.08072	80.20157
34	80.54169	80.6868	80.85022	81.10062	81.26495	81.4682	80.86166	80.11276	79.97131	80.20752
35	80.49774	80.67398	80.78064	81.04111	81.16013	81.37115	80.78613	80.13336	79.96124	80.15076
36	80.38971	80.56183	80.72067	80.9166	81.1441	81.34094	80.79254	80.0592	79.94247	80.10452
37	80.35309	80.48538	80.64102	80.93124	81.11389	81.29471	80.74997	80.00427	79.83765	80.07797
38	80.28534	80.52246	80.65338	80.90286	81.07132	81.28006	80.69092	79.9942	79.785	80.00748
39	80.26428	80.43228	80.58929	80.85297	81.02829	81.21323	80.62408	79.96582	79.74106	79.99374
40	80.28854	80.41534	80.51697	80.82367	80.97015	81.1647	80.60989	79.9205	79.67239	80.00656
41	80.15076	80.38742	80.55038	80.76508	80.9198	81.06766	80.59662	79.86511	79.65637	79.91684
42	80.16266	80.3302	80.44144	80.70923	80.8667	81.05347	80.52475	79.76807	79.61517	79.82529
43	80.13519	80.27069	80.43457	80.66666	80.80078	81.04889	80.46616	79.76349	79.60373	79.79691
44	80.03448	80.21576	80.354	80.55496	80.78979	80.96191	80.39886	79.67972	79.52545	79.79462
45	79.99786	80.21622	80.27664	80.55038	80.74356	80.9317	80.36728	79.63852	79.51721	79.73511
46	79.91776	80.09491	80.25284	80.51834	80.71564	80.93307	80.33386	79.5845	79.51218	79.66873
47	79.88068	80.12833	80.25238	80.48584	80.59982	80.86761	80.25604	79.59	79.36569	79.68201
48	79.86923	80.04639	80.17822	80.41946	80.59845	80.78476	80.21118	79.54788	79.34647	79.57581
49	79.7818	79.97498	80.19699	80.44785	80.59204	80.80444	80.17044	79.53415	79.33731	79.5813
50	79.7493	79.92599	80.06836	80.39978	80.46341	80.75958	80.20477	79.50439	79.27551	79.48883