University of Southern Queensland
Faculty of Engineering & Surveying

Fast-Response Piezoresistive Pressure Transducers For
Thermofluids Experiments

A dissertation submitted by

Peter Hockings

in fulfilment of the requirements of

ENG4112 Research Project

towards the degree of

Bachelor of (Mechanical Engineering)

Submitted: October, 2004
Abstract

Thermo-fluids experiments often require the use of fast-response pressure transducers that maintain their accuracy over a wide range of operating temperatures. Existing pressure sensing technologies are available which suit these demanding applications, however these transducers are usually relatively expensive. This project investigates the use of inexpensive piezoresistive pressure transducers in the measurement of transient fluid pressures.

A temperature compensation routine was developed which improved the accuracy of the piezoresistive pressure transducers over a substantial range of operating temperatures. A dynamic response analysis indicated that the diaphragm resonant frequency of these sensors was 246.7 kHz (without the addition of latex or grease) and that the response times could be improved from approximately 12.5 $\mu s$ to 0.38 $\mu s$ with simple case modifications. These results demonstrated the suitability of piezoresistive pressure transducers for use in fast-response thermo-fluids experiments.

A piezoresistive pressure transducer produced very similar results to a piezoelectric sensor when both devices were tested simultaneously in the USQ Gun Tunnel. This indicated that the piezoresistive sensor was capable of accurately recording rapid fluctuations in pressure levels. The cylinder pressures of an internal combustion engine recorded by a piezoresistive and piezoelectric sensor also compared well. The high operational temperatures of the engine verified the success of the piezoresistive sensor temperature compensation routine.
Limitations of Use

The Council of the University of Southern Queensland, its Faculty of Engineering and Surveying, and the staff of the University of Southern Queensland, do not accept any responsibility for the truth, accuracy or completeness of material contained within or associated with this dissertation.

Persons using all or any part of this material do so at their own risk, and not at the risk of the Council of the University of Southern Queensland, its Faculty of Engineering and Surveying or the staff of the University of Southern Queensland.

This dissertation reports an educational exercise and has no purpose or validity beyond this exercise. The sole purpose of the course pair entitled “Research Project” is to contribute to the overall education within the student’s chosen degree program. This document, the associated hardware, software, drawings, and other material set out in the associated appendices should not be used for any other purpose: if they are so used, it is entirely at the risk of the user.

Prof G Baker
Dean
Faculty of Engineering and Surveying
Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

PETER HOCKINGS

Q11219289

________________________
Signature

________________________
Date
Acknowledgments

I would like to sincerely thank the following individuals for their assistance in my work. Without the support of these people this project could not have reached completion.

Dr. David Buttsworth for his guidance and patience. Even with such a large number of project students, David was still able to find the time to lend assistance when it was needed.

Dr. Ahmad Sharifian for his assistance in the last few weeks of semester 2, once David had left for England.

The staff from the mechanical and electrical workshops for their vital contributions of supplying and manufacturing various components.

Finally, a special thankyou to my family, college friends and my girlfriend Emily. The understanding and support of these people was invaluable to the successful completion of this dissertation.

Peter Hockings

University of Southern Queensland
October 2004
# Contents

Abstract i  

Acknowledgments iv  

List of Figures xi  

List of Tables xv  

## Chapter 1 Introduction  

1.0.1 Project Aims and Objectives 1  

1.1 Overview of the Dissertation 2  

## Chapter 2 Background, Literature Review and Assessment of Consequential Effects 4  

2.1 Project Background 4  

2.2 Literature Review 5  

2.2.1 Background - Piezoresistive Pressure Transducers 5  

2.2.2 Temperature Compensation 7
2.2.3 Dynamic Response Calibration ......................................... 10

2.3 Assessment of Consequential Effects .................................. 12
  2.3.1 Substantiality ........................................................ 12
  2.3.2 Ethical Responsibility ............................................. 13

2.4 Chapter Summary .......................................................... 15

Chapter 3 Design Methodology ................................................. 16
  3.1 Static Calibrations and Temperature Compensation for Pressure Sensors 16
  3.2 Testing of Dynamic Response Characteristics ............................ 20
  3.3 Pressure Testing with the USQ Gun Tunnel ............................... 21
  3.4 Pressure Testing with an IC Engine and Theoretical Analysis ........... 22
  3.5 Chapter Summary .......................................................... 24

Chapter 4 Static Calibration and Temperature Compensation ............... 25
  4.1 Chapter Overview .......................................................... 25
  4.2 Initial Static Calibrations ............................................... 25
    4.2.1 Detailed Experimental Design ..................................... 27
    4.2.2 Static Calibration of Unmodified SX150AHO ....................... 28
    4.2.3 Static Calibration of 13U3000 ....................................... 30
    4.2.4 Static Calibration of 13U0500 ....................................... 31
  4.3 Temperature Compensation Calibrations .................................. 32
CONTENTS

4.3.1 Detailed Experimental Design . . . . . . . . . . . . . . . . . . . 32
4.3.2 Analysis of Temperature Effects . . . . . . . . . . . . . . . . . . 34
4.3.3 Application of Temperature Calibrations . . . . . . . . . . . . . 38
4.3.4 Temperature Compensation Effectiveness . . . . . . . . . . . . . 39
4.4 Chapter Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 42

Chapter 5 Dynamic Response Characteristics

5.1 Chapter Overview . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 43
5.2 Shock Tube Testing . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 43
5.2.1 Detailed Experimental Design . . . . . . . . . . . . . . . . . . . . 44
5.2.2 Modification of Pressure Sensors . . . . . . . . . . . . . . . . . . . 46
5.3 Analysis of Results . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 47
5.3.1 Reflected Shock Pressures . . . . . . . . . . . . . . . . . . . . . . . 48
5.3.2 Identification of Resonant Frequencies . . . . . . . . . . . . . . . . 54
5.3.3 Errors Related to Frequency of Measured Pressures . . . . . . . . 59
5.3.4 Sensor Response Time . . . . . . . . . . . . . . . . . . . . . . . . . 61
5.4 Chapter Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 65

Chapter 6 Pressure Measurement in the USQ Gun Tunnel

6.1 Chapter Overview . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 66
6.2 Gun Tunnel Testing . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 66
Appendix B  Specification and Data Sheets  94

B.1  Specifications for 13U0500 and 13U3000 Piezoresistive Sensors  . . . . . . 95

B.2  Specifications for SX150AHO Piezoresistive Sensor  . . . . . . . . . . . . 101

B.3  Specifications for INA114 Instrumental Amplifier  . . . . . . . . . . . . 105

B.4  Specifications for PCB 112B11 Piezoelectric Sensor  . . . . . . . . . . . . 117

B.5  Specifications for Encoder Optical Sensor  . . . . . . . . . . . . . . . . 118

Appendix C  MATLAB Scripts and Functions  119

C.1  MATLAB Scripts and Functions  . . . . . . . . . . . . . . . . . . . . . . . 120

Appendix D  Detail and Assembly Drawings  145

D.1  Detail Drawings for SX150AHO Pressure Attachment  . . . . . . . . . . . 146

D.2  Detail Drawings for Oven Insulating Tube  . . . . . . . . . . . . . . . . . 147

D.3  Detail Drawings for Shock Tube Sensor Mountings  . . . . . . . . . . . . 158

D.4  Detail Drawings for Gun Tunnel Sensor Mountings  . . . . . . . . . . . . 160

D.5  Detail Drawings for Engine Shaft Encoder  . . . . . . . . . . . . . . . . . 162

Appendix E  Shock Tube Experimental Data  166

E.1  Shock Tube Experimental Data  . . . . . . . . . . . . . . . . . . . . . . . 167

E.1.1  Shock Tube Test 1  . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 168

E.1.2  Shock Tube Test 2  . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 170

E.1.3  Shock Tube Test 3  . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 172
E.1.4  Shock Tube Test 4 ........................................... 174
E.1.5  Shock Tube Test 5 ........................................... 176
E.1.6  Shock Tube Test 6 ........................................... 178
E.1.7  Shock Tube Test 7 ........................................... 180
E.1.8  Shock Tube Test 8 ........................................... 182
E.1.9  Shock Tube Test 9 ........................................... 184
E.1.10 Shock Tube Test 10 ......................................... 186
E.1.11 Shock Tube Test 11 ......................................... 188
E.1.12 Shock Tube Test 12 ......................................... 190
E.1.13 Shock Tube Test 13 ......................................... 192
E.1.14 Shock Tube Test 14 ......................................... 194
E.1.15 Shock Tube Test 15 ......................................... 196
E.1.16 Shock Tube Test 16 ......................................... 198
E.1.17 Shock Tube Test 17 ......................................... 200
List of Figures

2.1 The Sensym 13U Stainless Steel Pressure Transducer (Honeywell/Sensym) 5
2.2 Basic Structure of Piezoresistive Pressure Transducer (MAXIM 2001) 6
2.3 Wheatstone Circuit of the Pressure Transducer (Honeywell) 7
2.4 The comparison of outputs between an uncompensated pressure sensor (a) and a sensor compensated for temperature changes (b) (Ainsworth et al. 2000) 8
2.5 Basic circuit to determine $V_{sense}$ (Ainsworth et al. 2000) 9
2.6 Output of a piezoresistive pressure transducer after a step input pressure signal (Ainsworth et al. 2000) 10
2.7 The power spectrum from a typical step response, showing the resonant frequency at the dominant peak on the graph (Ainsworth et al. 2000) 11
3.1 The ‘Dead Weight’ tester used for the static calibrations 17
3.2 Conditioning Circuit to determine $V_{sense}$ 18
3.3 Oven used for temperature calibrations 19
3.4 Basic Shock Tube design, similar to the apparatus used for this project 20
LIST OF FIGURES

3.5 The USQ Gun Tunnel used for experimental testing ... 21

4.1 A block diagram, showing the approached used for the static calibrations 27

4.2 A photograph of the electrical circuit used to produce the sensor outputs,
$V_{out}$ and $V_{sense}$ ........................................ 28

4.3 Static calibration of Sensym SX150AHO sensor .............. 29

4.4 Static calibration of Sensym 13U3000 sensor ................. 30

4.5 Static calibration of Sensym 13U0500 sensor ............... 31

4.6 The modified oven (right) and the Dead Weight tester (left) used for
temperature calibrations ...................................... 33

4.7 The Positive Linear Relationship between $V_{sense}$ and Sensor Temperature 35

4.8 The Positive Linear Relationship between Span and Sensor Temperature 36

4.9 The Relationship between Offset and Sensor Temperature ....... 37

4.10 Error from an uncompensated piezoelectric sensor ............ 40

4.11 Error from a compensated piezoelectric sensor ............ 41

5.1 Photograph of the shock tube used to test the sensor dynamic characteristics ....................................... 44

5.2 Schematic diagram of Shock Tube showing positions of pressure sensors 45

5.3 A block diagram, showing the method of pressure measurement for shock
tube tests .................................................. 45

5.4 Modification of SX150AHO sensors .......................... 46
5.5 A typical sensor response and a comparison between measured and predicted reflected shock pressures. ................................. 50

5.6 A typical long time scale sensor response and a comparison between measured and predicted reflected shock pressures. .............. 51

5.7 Comparison of sensor response and theoretical internal pressure over time for shock test 2 ...................................................... 53

5.8 Comparison of sensor response and a possible theoretical model of internal pressure over time for shock test 2, given that the shock wave increases the internal pressure of the sensor to 250kPa .................. 54

5.9 Sensor output from Shock Tube test 4, demonstrating multiple modes of vibration ................................................................. 55

5.10 The power spectrum density of Shock Tube test 4, showing the resonant frequency of the silicon diaphragm ............................ 57

5.11 The amplitude ratio and phase shift for relative frequency ratios (Ainsworth et al. 2000) ............................................................. 60

5.12 The 10 and 90% lines used to measure the response time of the sensor . 62

6.1 A schematic diagram of the USQ Gun Tunnel in the format used for this project (Top View) ...................................................... 67

6.2 Mountings of piezoresistive and piezoelectric sensors in the Gun Tunnel barrel (note: the end of the barrel is unsealed at this stage) ........ 68

6.3 A block diagram, showing the method of pressure measurement for the USQ Gun Tunnel ..................................................... 69

6.4 A comparison between the piezoresistive and piezoelectric pressure sensors 70
6.5  A comparison between the piezoresistive and piezoelectric pressure sensors after the peak Gun Tunnel pressure ........................... 71

6.6  A comparison between the smoothed piezoresistive data and the piezoelectric sensor output ......................................................... 72

6.7  A comparison between the smoothed piezoresistive and piezoelectric pressure sensors after the peak Gun Tunnel pressure .................. 72

7.1  A photograph showing the mounting of the piezoelectric (right) and piezoresistive (left) sensors on the engine ................................. 75

7.2  The Shaft Encoder attached to the engine ................................. 76

7.3  A block diagram, showing the method of pressure measurement for the internal combustion engine ................................. 77

7.4  The layout of the engine testing apparatus ......................... 77

7.5  Engine pressures determined from the piezoresistive and piezoelectric pressure transducers - motored, closed throttle ................. 78

7.6  Engine pressures determined from the piezoresistive and piezoelectric pressure transducers - fired, closed throttle, no load ............ 79

7.7  Engine pressures determined from the piezoresistive and piezoelectric pressure transducers - fired, closed throttle, loaded .......... 79

7.8  Engine pressures determined from the piezoresistive and piezoelectric pressure transducers - fired, open throttle, loaded ............. 80

7.9  A comparison between the theoretical and measured cylinder pressures - motored ................................................................. 82

7.10 A comparison between the theoretical and measured cylinder pressures - fired, open throttle, loaded ........................................... 83
**List of Tables**

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Engine Specifications for the Kubota GS200 Petrol Engine</td>
<td>23</td>
</tr>
<tr>
<td>4.1</td>
<td>Sensor Characteristics for Sensym 13U0500 Piezoresistive Pressure Transducer - Experimental Values and Manufacturer’s Specifications (Experimental Offset coefficient for 27 to 97°C, Manufacturer’s Spec. Offset coefficient for 0 to 82°C)</td>
<td>37</td>
</tr>
<tr>
<td>5.1</td>
<td>Summary of sensor modifications used for shock tube tests</td>
<td>47</td>
</tr>
<tr>
<td>5.2</td>
<td>Shock Tube tests and corresponding sensors used</td>
<td>48</td>
</tr>
<tr>
<td>5.3</td>
<td>Comparison between theoretical and measures reflected shock pressures)</td>
<td>52</td>
</tr>
<tr>
<td>5.4</td>
<td>Diaphragm resonant frequencies determined from power spectrum density analysis (a resonant frequency of 0Hz indicates that no clear frequency was identified)</td>
<td>58</td>
</tr>
<tr>
<td>5.5</td>
<td>Response times for sensor outputs for each of the Shock Tube tests</td>
<td>63</td>
</tr>
<tr>
<td>7.1</td>
<td>Hydraulic pressures and equivalent engine output power for engine tests</td>
<td>80</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

This project investigates the performance characteristics of piezoresistive pressure transducers under high temperature operation and transient pressure measurement. Static calibrations and temperature compensation will be investigated as well as the dynamic response characteristics of the piezoresistive pressure transducers. These sensors will be applied to measurement of the cylinder pressures of an internal combustion engine and pressures within the USQ Gun Tunnel. The measurements taken with these pressure sensors can then be analysed and compared with similar data produced from other available types of transducers and various theoretical methods. The performance and suitability of piezoresistive pressure sensors for these applications can then be evaluated.

1.0.1 Project Aims and Objectives

This project aims to identify the frequency and temperature response characteristics of low cost piezoresistive pressure transducers and provide accurate calibration to allow these pressure sensors to be used with a high degree of confidence in fast-response thermofluids experiments.

The specific objectives of the project are as follows -

1. Review existing techniques for temperature measurement and compensation in
piezoresistive pressure measurement devices.

2. Devise appropriate electrical circuits to implement such techniques.

3. Devise suitable apparatus for quasi-static calibration of pressure transducers for both pressure and temperature sensitivity.

4. Perform calibrations on selected transducers.

5. Investigate the dynamic response of sensors of various configurations (added grease, modified cases etc.) using a shock tube calibration.


7. Analyse the measurements from the Gun Tunnel and compare with data obtained from a piezoelectric sensor.

8. Obtain pressure measurements in an IC engine.

9. Analyse the measurements from the IC engine and compare with data obtained from a piezoelectric sensor.

\[ \text{as time permits} \]

10. Compare the measurements from the Gun Tunnel with predictions based on a computational model (Lagrangian quasi one dimensional).

11. Compare the measurements from the IC engine with predictions based on a computational model (thermodynamic engine simulation).

\section*{1.1 Overview of the Dissertation}

This dissertation is organized as follows:

\textbf{Chapter 2} covers the literature review, background and assessment of consequential effects.

\textbf{Chapter 3} introduces the Design Methodology for this project.
1.1 Overview of the Dissertation

Chapter 4 discusses static sensor calibration and temperature compensation techniques for piezoresistive sensors.

Chapter 5 covers the testing and analysis of the dynamic response characteristics of the piezoresistive sensors.

Chapter 6 investigates the application of measuring pressures within the Gun Tunnel using piezoresistive pressure sensors.

Chapter 7 examines the use of piezoresistive pressure transducers in the measurement of cylinder pressures of an IC engine.

Chapter 8 draws conclusions for this dissertation and suggests possible further work.
Chapter 2

Background, Literature Review and Assessment of Consequential Effects

2.1 Project Background

Experimental testing facilities (including Gun Tunnels and Shock Tubes) and common machinery (such as the internal combustion engine) may require the measurement of internal pressures (both static and dynamic). This allows an analysis of their performance and provides further understanding of the thermofluids process that occur.

Measurement of pressures in the cases outlined above requires fast-response sensors that are able to withstand extreme operational conditions (such as high operating temperatures and fast fluctuations of pressure). While some expensive pressure sensors have been developed that are capable of responding to fast-response situations (such as high-end piezoelectric pressure sensors), the piezoresistive pressure transducer possibly offers a low cost solution. Generally, a low cost piezoresistive pressure sensor costs $100 to $200. A piezoelectric sensor may cost approximately $2000. If a pressure measurement experiment also risks sensor damage, the use of an accurate low cost pressure sensor would be ideal.
2.2 Literature Review

Typically, piezoresistive pressure transducers have been used for the measurement of static or quasi-static pressure levels. This project aims to test the dynamic response characteristics of the sensors and investigate the feasibility of using these piezoresistive sensors for fast response measurements. The temperature effects on the sensors will also be analysed. This will ultimately allow a temperature compensation technique that maintains accurate pressure measurements in a wide variety of harsh operational environments.

2.2 Literature Review

2.2.1 Background - Piezoresistive Pressure Transducers

The typical fast-response piezoresistive pressure transducer relies on accurately measuring the deflection of a diaphragm (typically silicon) that is caused by fluid pressures. These sensors are generally low cost and can be implemented in a wide variety of applications. A diagram of a typical piezoresistive pressure transducer is shown in figure 2.1.

![Figure 2.1: The Sensym 13U Stainless Steel Pressure Transducer (Honeywell/Sensym)](image)

Some advantages associated with the piezoresistive pressure transducer are (Microsystems),

- Low-cost sensor fabrication opportunity.
- Mature processing technology.
Different pressure levels can be achieved according to the application.

- Wide range of pressure sensitivities.
- Read-out circuitry can be either on-chip or discrete.

There are also some disadvantages of piezoresistive pressure sensors (MAXIM 2001),

- Strong nonlinear dependence of the full-scale signal on temperature (up to 1%/kelvin)
- Large initial offset (up to 100% of full scale or more)
- Strong drift of offset with temperature

The disadvantages associated with temperature dependance can be overcome (or at least, greatly reduced) using the temperature compensation techniques discussed in later sections.

The basic construction of the piezoresistive pressure transducer is shown in figure 2.2.

![Basic Structure of Piezoresistive Pressure Transducer (MAXIM 2001)](image)

**Figure 2.2:** Basic Structure of Piezoresistive Pressure Transducer (MAXIM 2001)

Using diffusion methods, 4 piezoresistive elements are positioned on the top surface of the diaphragm. The elements change their resistance according to the level of strain. Therefore, as the diaphragm deflects (due to the fluid pressure), the resistance of each of the elements change.

The typical electrical circuit of a piezoresistive pressure transducer can be seen in figure 2.3. The design of the silicon diaphragm causes two resistive elements to be placed
under compression and two to be placed under tension as the diaphragm deflects. This causes the resistance to increase in two elements, and decrease in the remaining two. This change in resistance is represented by $\Delta R$ in figure 2.3. The shift in the values of resistance causes a voltage difference between $V_1$ and $V_2$. This voltage difference is measured as the value of $V_{out}$. The value of $V_{out}$ is linearly related to the applied fluid pressure.

![Figure 2.3: Wheatstone Circuit of the Pressure Transducer (Honeywell)](image)

The transducer sensitivity can be determined through a static calibration process. The value of $V_{out}$ may then be used to calculate the fluid pressure applied to the transducer.

Advances in production technology, such as the rapid developments in the semiconductor industry in the 1960s (Ainsworth et al. 2000), have enabled piezoresistive pressure transducers to become more compact, improved the quality of construction and minimizing the cost of production.

### 2.2.2 Temperature Compensation

One major issue in the use of piezoresistive pressure transducers is their temperature sensitivity. The output of the sensor may therefore require compensation for temperature effects. Temperature related errors may severely compromise the sensor accuracy under operation in extreme hot or cold environments.

Figure 2.4 displays temperature compensated and uncompensated sensor outputs. These plots demonstrate the high degree of temperature sensitivity of a piezoresistive pressure transducer.
The output from a piezoresistive pressure transducer relies on two basic characteristics, the sensor Span (or sensitivity) and the sensor Offset (the sensor output at zero absolute pressure) (Ainsworth, Miller, Moss & Thorpe 2000, Denos 2002, Clark 1992). The values for Span and Offset change with temperature therefore errors are introduced when taking pressure measurements from relatively hot or cold environments. Compensation methods have been developed to take the temperature sensitivity of Span and Offset into account. These techniques allow a more consistent accuracy from the pressure transducers.

The temperature compensation method developed by (Clark 1992) assumes a linear relationship between Offset and operational temperature and correlates transducer sensitivity and temperature with a third-order polynomial function. Ainsworth et al. (2000)
and Denos (2002) assumed a linear relationship between sensor Offset and Span with temperature, however these investigations incorporated a much smaller temperature range. Each of these temperature compensation methods allows a post-experimental routine, where the recorded sensor output voltage and temperature can be used to accurately determine fluid pressure.

![Basic circuit to determine $V_{\text{sense}}$ (Ainsworth et al. 2000)](image)

**Figure 2.5:** Basic circuit to determine $V_{\text{sense}}$ (Ainsworth et al. 2000)

To indicate the temperature of the sensor (and allow the temperature correction to be applied), the conditioning circuit shown in figure 2.5 was implemented by both Ainsworth et al. (2000) and Denos (2002). This circuit incorporates the pressure transducer into a Wheatstone bridge. The overall resistance of the pressure transducer will vary with temperature, and the temperature of the other resistors in the external circuit will remain constant (causing the resistance of the external circuit to remain constant). A change in the sensor temperature will therefore result in a change in the voltage, $V_{\text{sense}}$. The value of $V_{\text{sense}}$ is then used to calculate the temperature of the sensor. A temperature compensation routine can ultimately be applied to the pressure sensor output (demonstrated by Ainsworth et al. (2000) and Denos (2002)).

Temperature sensitivity compensations created by Denos (2002) also investigate calibrations under a temperature transient. This experimental process involved exposing the piezoresistive pressure transducers to a rapidly applied high temperature test fluid. While these experiments provided useful insight into the behavior of the pressure sensors, the time span involved in the transient temperature calibrations is much longer than typically encountered in a thermofluids experiment (such as a shock tube test).
2.2 Literature Review

Temperature calibrations conducted by Ainsworth et al. (1991) assumed that with short experimental run times, only minor temperature changes would be expected. For experimental situations with a significant and sustained operational temperature (e.g., testing in-cylinder engine pressures), the static temperature compensation methods mentioned previously can be applied.

2.2.3 Dynamic Response Calibration

The dynamic response characteristics of the piezoresistive pressure transducer determine its suitability for use in fast-response thermofluids experiments.

Shock tubes can be used in experimental testing for the analysis of the dynamic response of the pressure transducers (e.g., Ainsworth et al. 1991). The results from these tests reveal that certain frequencies become dominant in the response of the pressure sensor (these are the resonant frequencies of the pressure transducer). A typical sensor response to a step input can be observed in figure 2.6 and the related power spectrum demonstrating the resonant frequency is given in figure 2.7.

![Figure 2.6: Output of a piezoresistive pressure transducer after a step input pressure signal (Ainsworth et al. 2000)](image)

Another method developed for testing the sensor resonant frequency involves exposing the piezoresistive sensor to a constant noise source and measuring the response (Boerrigter & Charbonnier 1997). The noise source, created by an impinging air jet,
creates sounds waves of variable frequency. These sound waves then cause pressure variations at the pressure transducer. This allows the amplitude response and phase shift of the transducer to be analysed over a wide range of operational frequencies. As stated by Boerrigter & Charbonnier (1997), this has advantages over a shock tube tests since this technique easily identifies the resonant frequencies of other bodies (such as the air adjacent of the transducer) and the pressure and temperature of the test are known (the precise shock conditions in a shock tube test are difficult to determine).

Analytical techniques for the calculation of dynamic response were also demonstrated by Ainsworth et al. (2000) and Boerrigter & Charbonnier (1997). Ainsworth et al. (2000) have taken the approach of approximating the piezoresistive pressure transducer with a transfer function, which provides data about the expected frequency response of the system. This approach gives theoretical simulations for the transducer phase shift and amplitude. Boerrigter & Charbonnier (1997) developed an analytical model from key dynamics and fluid mechanics formulas that can also ultimately be used to predict the frequency response of a pressure measurement system.

From the work of Boerrigter & Charbonnier (1997), it appears that the frequency response of a pressure transducer may have two critical points - the resonant frequency of the air around or within the transducer, and the resonant frequency of the diaphragm
of the transducer itself. Articles from Boerrigter & Charbonnier (1997) investigate the use of analytical calculations to determine the resonant frequency of the air in front of the diaphragm. Once the resonant frequencies of the piezoresistive pressure transducer have been measured, it can be determined whether these frequencies are related to the resonance of the air around the sensor or the resonance of the silicon diaphragm.

A layer of grease or a flexible compound may be used to cover the diaphragm on the pressure sensor. This procedure is designed to protect the pressure sensor from particles that may impact on the diaphragm and damage the sensor (Ainsworth et al. 2000, Buttsworth & Jacobs 2000). Experiments involving sensors with and without silastomer demonstrated that the silastomer layer significantly increased the damping ratio of the sensor response (Ainsworth et al. 2000).

2.3 Assessment of Consequential Effects

While this project focuses largely on short term results and immediate outcomes, long term effects of this research must also be considered. These effects include the aspects of sustainability, ethical responsibility and safety issues.

2.3.1 Substantiality

Environmental sustainability is of continually increasing importance to modern engineering practices. The short, medium and long term environmental consequences of an engineering task (such as the work undertaken on this project) must be anticipated. Where negative effects are apparent, actions need to be taken to minimize or remove any environmental damage.

While this project has a minimal environmental impact in terms of direct pollution created or environmental degradation caused, there are other non-direct environmental impacts associated with this research topic, including -

- The use of finite resources for the construction of the testing equipment
2.3 Assessment of Consequential Effects

- The resource requirements for experimental testing

The components used in this project (the pressure sensors and the developed testing apparatus) make use of finite resources for their production (metals and plastics). Fortunately these products are mostly recyclable. The pressure sensors themselves can be reused for different pressure measurement applications and offer a reasonable service life (depending on the severity of the testing environment). The other materials used for the construction of the testing apparatus are readily recyclable (plastics, metals and electrical components) therefore the waste from this project can be minimized.

Some of the experimental testing procedures may require non-renewable resources. This project will require the use of internal combustion engines (for use in pressure testing and for powering other experiments) which use fossil fuels and produce harmful emissions. While these are negative environmental effects, these experiments will only be conducted over a short period during the experimental stages of the project.

The results from this project may ultimately contribute to environmental sustainability. If these pressure sensors are widely available at low cost, machinery and manufacturing process could be more readily monitored and their efficiency could be maximized. This could lead to a reduction of pollutants created and contribute towards a cleaner environment.

2.3.2 Ethical Responsibility

Most new technologies have associated ethical implications related to the particular outcomes of that development. Therefore an ethical responsibility exists where the engineer must consider the people who are affected.

This project makes heavy use of relatively new technologies and the possible outcomes of this research may also bring further advancement to the area of piezoresistive pressure sensor technology. The range of possible ethical consequences were considered before commitment to this project.

It is possible that some people may be disadvantaged if the piezoresistive sensor tech-
2.3 Assessment of Consequential Effects

The piezoresistive technology becomes widely implemented. Ultimately this project may allow a reduction in the use of highly expensive pressure transducers. This may adversely affect some suppliers and sensor producers. Fortunately the suppliers and manufacturers typically use a wide range of products, therefore if a small number of items became obsolete due to the piezoresistive technology, the consequences would be minimal.

One positive outcome that relates to ethical responsibility is the production of a reliable low-cost technology. This allows the advancements of this modern technology to become available to a wider range of the community.
2.4 Chapter Summary

This chapter has investigated background knowledge and previous research related to the field of piezoresistive pressure transducers. Past experiments and models used to test the dynamic characteristics and temperature compensations for piezoresistive sensors provide possible techniques that could be used for this project or similar research.

The assessment of consequential effects has drawn attention to the critical aspects of this project that could possibly lead to unwanted ethical, social or environmental damage. Now that these factors have been identified, steps can be taken to ensure that any negative effects of this project are eliminated or minimized.
Chapter 3

Design Methodology

3.1 Static Calibrations and Temperature Compensation for Pressure Sensors

The pressure and temperature sensitivity of piezoresistive pressure transducers can be determined through a series of static calibrations. These calibrations allow accurate results to be obtained from experimental testing.

The static calibration process will initially begin by testing the pressure sensitivity of the pressure transducers at room temperature (approximately 25°C). These static tests will be conducted using the ‘Dead Weight’ tester (shown in figure 3.1). The Dead Weight testers allows precise levels of pressure to be applied to the pressure sensor.

During the static calibration process, each pressure sensor was attached to the hydraulic fitting on the Dead Weight tester. A particular mass was placed on one of two hydraulic cylinders (shown in figure 3.1). The wheel of the Dead Weight Tester is turned inwards until the mass is freely suspended by the pressure of the hydraulic oil. Since the oil pressure suspends a mass of known value, the pressure of the oil can be accurately determined. Each mass for the Dead Weight tester has predetermined corresponding pressure values. To avoid any effects of temperature sensitivity within the The Dead Weight tester, this apparatus remained at approximately room temperature during all
3.1 Static Calibrations and Temperature Compensation for Pressure Sensors

Figure 3.1: The ‘Dead Weight’ tester used for the static calibrations

calibration experimentation.

The output voltage of the pressure transducer($V_{out}$) relates directly to the applied pressure. This typically results in a highly linear relationship between these two variables. The output of the transducer can be correlated to pressure using the equation 4.1 (Ainsworth et al. 2000, Denos 2002),

$$V = SP + O$$  (3.1)

In equation 4.1, ‘$V$’ is the output voltage (or $V_{out}$), ‘$S$’ is the sensor span (or sensitivity) and ‘$O$’ is the sensor offset (the voltage output, $V_{out}$, at zero absolute pressure). This function can be used to accurately determine the pressure from the sensor output voltage while the pressure transducer is at room temperature.

As the temperature of the sensor changes, the values for Span and Offset also change. It is critical to determine the how these characteristics change with temperature. High temperature thermofluids experiments (such as testing the in-cylinder pressures on the IC engine) will produce inaccurate results if no temperature corrections are applied.

The operational temperature of the sensor must be determined to perform the temperature calibration process. One method is to incorporate the pressure sensor into
3.1 Static Calibrations and Temperature Compensation for Pressure Sensors

A circuit as shown in figure 3.2. This electrical circuit is adapted from the work of Ainsworth et al. (2000).

As the overall resistance of the pressure transducer changes with temperature, the value for \( V_{\text{sense}} \) will also shift.

A range of different pressures can be applied to the pressure transducer while it is held at selected constant temperatures (approximately ranging from room temperature to 150°C). This will be achieved by placing the pressure transducer in the oven shown in figure 3.3, and attaching a remote connection to the Dead Weight tester (figure 3.1).

The relationship between sensor output voltage, and applied pressure, allow values for Span and Offset to be calculated at a range of different testing temperatures. The rate of change of sensor Span and Offset with temperature can then be determined.

One particular method, developed by Ainsworth et al. (2000), applied the temperature correction directly to the value of \( V_{\text{out}} \). A function was developed that uses the values of \( V_{\text{out}} \) and \( V_{\text{sense}} \) to provide a correction to \( V_{\text{out}} \) based on the temperature of the
3.1 Static Calibrations and Temperature Compensation for Pressure Sensors

Figure 3.3: Oven used for temperature calibrations

sensor. The temperature of the sensor is determined by the corresponding value for $V_{\text{sense}}$. This corrected value for $V_{\text{out}}$, known as $V^*_\text{out}$, is the predicted output that the sensor would produce if it were at room temperature. This function is shown in equation 3.2.

$$V^* = V \left(1 - \frac{1}{S_{25}} \frac{dS}{dT} \Delta T\right) - O_{25} \left(1 - \frac{1}{S_{25}} \frac{dS}{dT} \Delta T\right) \left(1 - \frac{1}{S_{25}} \frac{dS}{dT} \Delta T\right)$$ (3.2)

The value of $V^*$ (or $V^*_\text{out}$) can then be used with the room temperature values of span ($S_{25}$) and offset ($O_{25}$) to allow the true experimental pressure to be determined (equation 3.3).

$$V^* = S_{25}P + O_{25}$$ (3.3)
3.2 Testing of Dynamic Response Characteristics

The dynamic response characteristics of the piezoresistive pressure transducers determine the behavior of the pressure sensors under high frequency changes in fluid pressures. Dynamic response testing allows the maximum operational frequencies of the pressure transducers to be deduced. As experimental pressure fluctuation frequencies reach the maximum operational frequency of the pressure transducer, errors begin to occur in the output of the sensor.

The dynamic response properties of the piezoresistive pressure transducers will be tested using a shock tube (as shown in figure 3.4).

![Figure 3.4: Basic Shock Tube design, similar to the apparatus used for this project (Boerrigter & Charbonnier 1997)](image)

A shock wave is produced within the tube when a diaphragm is ruptured. This wave of pressure travels at high speed along the tube and reflects off the end face. The pressure transducer, mounted level with the end face of the tube, undergoes an approximate step input (since the change in pressure is very rapid). The response of the transducer to this input then allows the dynamic response characteristics to be determined. These characteristics include values such as response time and resonant frequency.

A power spectrum of the sensor response can be derived from the shock tube test results. This indicates the dominant frequencies, allowing the resonant frequency of the pressure transducer to be identified. This resonant oscillation is due to the vibration of the silicon diaphragm of the sensor. Significant errors in the piezoresistive sensor output (possibly upwards of 10%) will occur if the measured fluid pressures begin to fluctuate at a level near the resonant frequency of the sensor (within the same order of magnitude).
3.3 Pressure Testing with the USQ Gun Tunnel

The test results from the shock tube can also be used to find the response time of the pressure transducers. This will determine the suitability and general accuracy of the pressure sensors under fast response testing applications. In these transient pressure measurement applications short response times are essential for recording an accurate set of readings.

Shock tube tests can also be conducted to test the dynamic response characteristics of modified pressure sensors. Various configurations of sensors, including sensors with modified cases and added grease or silastomer, will be tested to investigate the effects of these changes on the sensor response. These modifications are expected to provide protection to the silicon diaphragm of the sensor (with the addition of grease or silastomer) and possibly improve the response time of the sensors (with case modifications).

3.3 Pressure Testing with the USQ Gun Tunnel

The static calibration operations and dynamic response analysis lead to testing in facilities such as the USQ Gun Tunnel. This apparatus (shown in figure 3.5) (Buttsworth n.d.) is capable of producing a high speed, short duration gas flow.

![The USQ Gun Tunnel used for experimental testing](image)

*Figure 3.5: The USQ Gun Tunnel used for experimental testing*
The short period of the actual test flow (typically milliseconds) demands that the pressure sensors used to analyse the test gas has a very short response time. It is assumed that thermal effects from the hot gases on the sensor are negligible, since the short test times will not allow the pressure transducer to significantly change temperature while results are being recorded.

The results obtained from the Gun Tunnel with the piezoresistive pressure sensor are then able to be compared to the output from a piezoelectric pressure transducer (an expensive sensor, well suited to this measurement application). This gives an indication of the accuracy of the static calibration of the piezoresistive sensors and also shows a comparison between the dynamic characteristics of the two sensors.

If time permits, a theoretical analysis of the Gun Tunnel may also be conducted, using computational methods. This allows a comparison between theoretical pressures and the results from the output from the piezoresistive pressure transducer.

3.4 Pressure Testing with an IC Engine and Theoretical Analysis

Pressure measurement within an internal combustion engine tests the effectiveness of the static calibrations and the sensor dynamic response characteristics. This application also tests the temperature compensation techniques for the piezoresistive sensors. The engine (specifications shown in table 3.1) has been modified to allow pressure transducers to be mounted in the head of the engine block.

In-cylinder pressure measurements can be taken from the engine during motored (un-fired) and fired runs. To allow the pressure measurements to be coordinated with the position of the cylinder, a basic shaft-encoder can be attached to the drive shaft of the engine. The signal from the encoder can be combined with the corresponding pressure sensor outputs to determine the pressure of the engine at different stages of operation.

Computational calculations, consisting of a thermodynamic engine simulation, can verify the experimental results from the engine. A comparison between the results from
3.4 Pressure Testing with an IC Engine and Theoretical Analysis

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Make</td>
<td>Kubota</td>
</tr>
<tr>
<td>Model</td>
<td>GS200</td>
</tr>
<tr>
<td>Type</td>
<td>Four Stroke, air cooled, spark ignition, single piston, side valve, horizontal shaft</td>
</tr>
<tr>
<td>Rated Power</td>
<td>3.9 kW @ 3600 rpm (max), 2.8 kW @ 3600 rpm (continuous)</td>
</tr>
<tr>
<td>Rated Torque</td>
<td>10.5 Nm @ 3000 rpm</td>
</tr>
<tr>
<td>Bore</td>
<td>69 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>54 mm</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>6:1</td>
</tr>
<tr>
<td>Swept Volume</td>
<td>201 cc</td>
</tr>
<tr>
<td>Conrod Length</td>
<td>93.9 mm</td>
</tr>
</tbody>
</table>

**Table 3.1:** Engine Specifications for the Kubota GS200 Petrol Engine

this theoretical approach and the measured pressure levels provides an indication of the accuracy of the piezoresistive pressure sensor.
3.5 Chapter Summary

The design methodology has introduced the various experiments and calculations that will provide the analytical data for this project. The results obtained from static calibrations and temperature compensations, dynamic response characteristics, testing in the USQ Gun Tunnel and testing of an internal combustion engine are discussed in the following chapters.
Chapter 4

Static Calibration and Temperature Compensation

4.1 Chapter Overview

This chapter investigates the static calibrations of the various piezoresistive pressure transducers that are used for this project. Temperature calibrations are also investigated, since the operating temperature of the sensor also affects the transducer sensitivity and other characteristics. The calibrations and temperature compensation techniques developed in this chapter form the basis for the following sections, as this allows an accurate means of converting the sensor output voltage to fluid pressures.

4.2 Initial Static Calibrations

The initial static (or quasi-static) pressure calibrations were conducted using the Dead Weight pressure tester (figure 3.1). These calibrations were conducted for all pressure transducers to determine their related values for Span and Offset.

The static calibrations were conducted at room temperature (approx 25°C) since this would be the approximate sensor operating temperature for the thermofluids experi-
ments conducted in the Shock Tube and the USQ Gun Tunnel. While the actual gas temperatures during these experiments may have significantly exceeded room temperature values, the poor heat transfer properties of air and the very short time span over which the piezoresistive sensors were exposed to this flow allows a negligible increase in overall sensor temperature. The calibration temperature may not have precisely match the testing temperatures, however this small temperature variation would cause minimal variation in the properties of the pressure sensors.

The static calibrations for each type of piezoresistive pressure transducer were conducted in a similar manner. As introduced in the Design Methodology section (Chapter 3), the output of a typical piezoresistive pressure transducer is quantified by the voltage level $V_{out}$. The basic relationship between sensor output ($V_{out} \text{ or } V$) and pressure ($P$) is shown in equation 4.1.

$$V = SP + O$$

(4.1)

The values for Span ($S$) and Offset ($O$) can be determined from the coefficients derived from a linear regression of data points of pressure against $V_{out}$. For equation 4.1, the units for $V_{out}$ or $V$ are mV, the units for Span are mV/Pa and the unit for Offset are mV. The values determined for Span and Offset for each of the pressure sensors were divided by the supply voltage to the sensor (15V for 13U3000 and 13U0500 and 12V for SX150AHO). These values would need to be multiplied by the supply voltage in order to use equation 4.1 with the experimental data.

The values for span and offset were determined for various pressure transducers that were used during the course of this research. The three types of transducers used in this project are as follows,

- Sensym, SX150AHO (150 psi piezoresistive pressure sensor)
- Sensym, 13U3000 (3000 psi piezoresistive pressure sensor)
- Sensym, 13U0500 (500 psi piezoresistive pressure sensor)

(The full specification sheet for each of these sensors can be seen in Appendix B)
4.2 Initial Static Calibrations

4.2.1 Detailed Experimental Design

The sensor was attached to the Dead Weight Tester and a range of pressures were applied. The sensor output ($V_{out}$) was recorded for each pressure value. While during the initial experimentation stage, $V_{sense}$ was recorded (a value that can be used to determine the operating temperature of the sensor), it served no use in the room temperature calibrations (the value of $V_{sense}$ is used extensively for the temperature calibrations in later sections). As expected, the values for $V_{sense}$ remained relatively constant for each the quasi-static room temperature calibrations (due to constant temperatures).

A basic block diagram in figure 4.1 demonstrates the process by which the values of $V_{out}$ and $V_{sense}$ were recorded.

![Block diagram](image)

**Figure 4.1:** A block diagram, showing the approached used for the static calibrations

The conditioning circuit (figure 3.2) provides the output signals from the sensor, these signals were then directed through an Instrumental Amplifier (INA114 - specifications in Appendix B). The gain (amplification) was set to 1, however the amplifier circuit enables greater values of gain for future experiments. A photograph of the circuit used is shown in figure 4.2.

The circuit shown in figure 4.2 indicates the power supply points, ground, the connecting wires to the sensor, the amplifier integrated circuits (one for $V_{out}$ and one for $V_{sense}$), and the connectors for the output signals ($V_{out}$ and $V_{sense}$). This circuit also featured a potentiometer to allow $V_{sense}$ to be trimmed close to 0V at room temperature.
4.2 Initial Static Calibrations

Figure 4.2: A photograph of the electrical circuit used to produce the sensor outputs, $V_{out}$ and $V_{sense}$

Each sensor was tested over a range of pressures that incorporated the majority of the pressure range for each particular sensor. Once the output values of the sensor had been recorded for each pressure value, MATLAB (version 6) was used to perform a simple linear regression of $V_{out}$ (y-axis) against absolute applied pressure (x-axis). The MATLAB function used for this process, 'load_cal2', is displayed in Appendix C. A general first order equation (linear) is in an equivalent form to the equation used to relate pressure and sensor output voltage (equation 4.1). This allows the values for Span and Offset to be determined directly from the coefficients derived from the first order regression.

The results of the static calibrations for each of the sensors are discussed in the following subsections.

4.2.2 Static Calibration of Unmodified SX150AHO

This particular sensor was used extensively in shock tube testing. Various different modified forms of this sensor were utilized (with modified cases, added grease and added latex compounds). The results from the unmodified sensor are shown in this
4.2 Initial Static Calibrations

section, purely demonstrating the techniques used for the static calibration at room temperature. The values configurations and calibrations for other modified SX150AHO sensors will be introduced in the Chapter 5, where these sensors are tested in the shock tube apparatus.

To allow the SX150AHO sensor to be attached to the Dead Weight tester, a unique part was constructed. The detail drawing for this part (SX150AHO Pressure Attachment) is shown in Appendix D.

The relationship between output voltage $V_{out}$ and applied pressure is shown in figure 4.3. The supply voltage to the sensor was 12V.

![Figure 4.3: Static calibration of Sensym SX150AHO sensor](image)

The negative slope shown in figure 4.3 is simply due to the polarity of the connection to the pressure sensor (by reversing the electrical connection, the plot would show a positive trend). For this particular data set, the room temperature values for Span and Offset were determined as follows (per unit supply voltage),

- **Span** = -2.29e-5 mV/V.Pa
- **Offset** = 3.83 mV/V
4.2 Initial Static Calibrations

4.2.3 Static Calibration of 13U3000

The Sensym 13U3000 piezoresistive pressure transducer was used for pressure measurement in the USQ Gun Tunnel (Chapter 6). Since it was used in previous research for engine testing, this particular sensor had a layer of silastomer (approximately 2mm thick) on the diaphragm to protect it from high gas temperatures and foreign particles in the test fluid. The Span and Offset determined by this stage of experimentation were used to determine the pressures from the sensor output recorded from the Gun Tunnel Test.

Output voltage $V_{out}$ and applied pressure are shown in figure 4.4. The supply voltage to the sensor was 15V.

![Calibration with Increasing Pressure](image)

**Figure 4.4:** Static calibration of Sensym 13U3000 sensor

For these data points, the room temperature values for Span and Offset were determined as follows -

- Span = $1.19 \times 10^{-7}$ mV/V.Pa
- Offset = 0.246 mV/V
4.2 Initial Static Calibrations

4.2.4 Static Calibration of 13U0500

The Sensym 13U0500 pressure sensor was used to determine in-cylinder pressure for an internal combustion engine (Chapter 7). Similar to the 13U3000 sensor, this sensor also had a layer of silastomer (approximately 3mm thick) on the diaphragm for added insulation and protection.

Since this sensor was primarily used in the engine testing, it mainly operated at high temperatures. The room temperature static calibration for this sensor simply allows for a comparison of the values for Span and Offset for when the sensor is at higher temperatures during temperature compensation calibrations (discussed in the following section).

For the room temperature calibration, the output voltage $V_{out}$ against absolute pressure is shown in figure 4.5. The supply voltage to the sensor was 15V.

![Figure 4.5: Static calibration of Sensym 13U0500 sensor](image)

The related values for Span and Offset were then determined -

- Span = $1.15 \times 10^{-5}$ mV/V.Pa
- Offset = 0.74 mV/V
4.3 Temperature Compensation Calibrations

During thermo°uids experiments, a range of di®erent temperatures will be encoun-
tered. Piezoresistive pressure transducers must be calibrated for temperature effects to
improve the accuracy of their results. Changes in temperature will alter the coefficients
for sensor Span and Offset, therefore the effect of temperature on these values must be
quantified.

The sensor used for the temperature calibrations is the Sensym, 13U0500, as this sensor
is used for testing the pressures inside the cylinder of the internal combustion engine
(discussed in Chapter 7). While the other thermo°uids experiments may encounter a
range of temperatures (shock tube and Gun Tunnel experiments), the 13U0500 is the
only sensor where the actual sensor operating temperature signi®cantly exceeded room
temperature. A layer of silastomer was placed over the pressure sensitive diaphragm to
protect the sensor from particles in the test °uid and high gas temperatures (en coun-
tered during engine testing - Chapter 7)

4.3.1 Detailed Experimental Design

To determine how Span and Offset were related to sensor temperature, the sensor was
held at a range of constant temperatures (room temperature to approximately 150°C)
while quasi-static pressure tests were conducted. Span and Offset were subsequently
determined for a range of operating temperatures.

To allow the sensor to be held at a variety of steady temperatures while applying a
range pressures to the sensor, a testing apparatus was developed. A small oven was
modi®ed to allow the pressure sensor to be heated by the oven while also being remotely
connected to the Dead Weight tester. This setup can be observed in ®gure 4.6.

A thermocouple was situated immediately behind the pressure sensor to indicated the
temperature of transducer (the temperature dial on the oven itself was found to be
highly inaccurate). Pressure testing at each temperature was only conducted once the
temperature reading from the thermocouple became steady.
4.3 Temperature Compensation Calibrations

Since the thermostat control for the oven continuously switched the heating elements on and off, temperature fluctuations were present within the oven. To overcome this temperature variation, the sensor was positioned within an insulated copper tube inside the oven (visible inside the oven in figure 4.6), effectively smoothing the temperature fluctuations and providing steady temperatures for experimental testing. Detailed drawings of the insulating tube assembly and individual parts are shown in Appendix D.

A stainless steel tube, providing the hydraulic connection between the Dead Weight tester and the pressure transducer inside the oven, was deliberately designed to allow a reasonable length of the tubing inside the oven. The length of tubing inside the oven allowed the hydraulic oil to be raised to the oven temperature at the point where it came in contact with the pressure sensor. This ensured that the sensor was held at a predictable temperature. Exposing the sensor to cool hydraulic fluid may have adversely affected the accuracy of the temperature calibration.

As discussed in the Design Methodology section (Chapter 3) the value for $V_{\text{sense}}$ can be used to indicate the temperature of the pressure transducer (see figure 3.2). This value was recorded at each different sensor temperature. The voltage supplied to the complete conditioning circuit was 30V (approximately 15V being supplied to the sensor). The
values recorded for $V_{\text{sense}}$ were adjusted for the circuit supply voltage (divided by 30V), causing the unit of $V_{\text{sense}}$ to be mV/V.

To test for temperature effects, the pressure transducer was held at 4 different temperatures, while a range pressures were applied at each temperature. The first temperature test was conducted at approximately room temperature (the pressure test was performed with the oven switched off). Ideally a larger range of temperatures could be tested, however due to the insulation around the pressure sensor, a considerable amount of time (about $1\frac{1}{2}$ hours) was required for the sensor to reach a new steady temperature. This restricted temperature testing to a range of only 4 different temperatures.

The maximum temperature for testing was limited below 150°C, since above this temperature the plastic insulation on the electrical wires begins to melt. At temperatures approaching 200°C, there is also a risk of melting the electrical soldering on the pressure sensor.

4.3.2 Analysis of Temperature Effects

After conducting pressure tests at a range of different temperatures, the changes in Span and Offset with temperature were investigated. For each set of data at a particular temperature (values for $V_{\text{out}}$, $V_{\text{sense}}$ and the applied pressure values) an analysis was conducted to determine the values for Span and Offset (the process for determining Span and Offset was identical to that discussed in the Static Calibration section). Span, Offset and $V_{\text{sense}}$ were then related to the operating temperature of the pressure sensor at each of the four tested temperatures (the operating temperature of the sensor was the steady temperature value displayed from the thermocouple instrumentation).

A MATLAB script ‘temp_cal2’, developed to analyse the temperature effects on the sensors is displayed in Appendix C.

The plot shown in figure 4.7 demonstrates a highly linear relationship between $V_{\text{sense}}$ and temperature. For each particular temperature $V_{\text{sense}}$ remained relatively constant during the static calibration process, therefore the average $V_{\text{sense}}$ at each testing temperature was used.
4.3 Temperature Compensation Calibrations

A linear regression of these results (via MATLAB version 6) provides a temperature
coefficient for \( V_{\text{sense}} \). This is listed in table 4.1. This demonstrates that \( V_{\text{sense}} \) can
reliably be used to determine the operating temperature of the pressure sensor. This
technique is necessary where a direct measurement (such as that previously provided
by the thermocouple) isn’t possible.

The relationship between sensor Span and temperature is displayed in figure 4.8. This
also demonstrates a linear trend. The gradient of a linear regression provides the value
for change in Span with change in temperature (\( \frac{dS}{dT} \)). Ainsworth et al. (2000) utilized a
fractional span sensitivity, where the rate of change of Span with temperature is divided
by the value of Span at room temperature (\( \frac{1}{S_{25}} \frac{dS}{dT} \)). This matches the format of the
temperature coefficient of Span specified by the manufacturer. The value for fractional
Span sensitivity is listed in table 4.1.

The association between sensor Offset and temperature demonstrates a higher order
relationship (figure 4.9). While it is certainly possible to fit a second order curve to this
data, for the purposes of this project, future values for Offset will simply be determined
by a process of linear interpolation between these experimental data points. Both the
manufacturer’s specifications (see Appendix B) and Ainsworth et al. (2000) recognize
4.3 Temperature Compensation Calibrations

The Positive Linear Relationship between Span and Sensor Temperature

Figure 4.8: The Positive Linear Relationship between Span and Sensor Temperature

a linear rate of Offset change with temperature. This is may be accurate for this set of results when considering a linear regression of the temperature range of approximately 300K to 370K (or 27°C to 97°C).

The basic circuit for determining $V_{\text{sense}}$ can be analysed to allow the temperature coefficient of resistance of the pressure sensor to be determined (allowing a comparison with the manufacturers specifications). Equation 4.2 (Ainsworth et al. 2000) can be used to associate $V_{\text{sense}}$ and the temperature coefficient of resistance with the temperature changes of the pressure sensor. ‘$V_0$’ is the supply voltage to the conditioning circuit (figure 3.2), ‘$\Delta T$’ is the change in sensor temperature, ‘$\alpha$’ is the temperature coefficient of resistance.

\[
\Delta T = \frac{1}{\alpha} \frac{4V_{\text{sense}}}{V_0 - 2V_{\text{sense}}} \tag{4.2}
\]

By substituting the full temperature change of the experiment, and the change of $V_{\text{sense}}$ over this temperature, into equation 4.2 (since this equation assumed that $V_{\text{sense}}$ was zero at room temperature), the value for the temperature coefficient of resistance of the sensor can be determined (for this particular equation, the units for $V_{\text{sense}}$ must be kept as Volts). The temperature coefficient of resistance is compared with the
4.3 Temperature Compensation Calibrations

Figure 4.9: The Relationship between Offset and Sensor Temperature

Manufacturer’s specifications in table 4.1.

In table 4.1 the temperature coefficients for Span and Offset are given proportional to the sensor supply voltage, however the specific supply voltage to the sensor was dependant on the value of $V_{sense}$ (refer to figure 3.2). In these cases, the value of $V_{sense}$ was subtracted from 15V to give the actual sensor supply voltage. The values of Span and Offset were then divided by this value (15V - $V_{sense}$). The values given for $V_{sense}$ (in mV/V) were divided by the voltage supply to the original circuit (30V).

<table>
<thead>
<tr>
<th>Sensor Characteristics</th>
<th>Experimental Values</th>
<th>Manufacturer’s Spec. (0 to 82°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp. Coefficient of $V_{sense}$</td>
<td>0.795 mV/V.°C</td>
<td>N/A</td>
</tr>
<tr>
<td>Temp. Coefficient of Resistance</td>
<td>3928 ppm/°C</td>
<td>3420 ppm/°C (Typical)</td>
</tr>
<tr>
<td>Temp. Coefficient of Span</td>
<td>1371 ppm/°C</td>
<td>720 ppm/°C (Typical)</td>
</tr>
<tr>
<td>Temp. Coefficient of Offset</td>
<td>7.26 µV/V.°C</td>
<td>30 µV/V.°C (Typical)</td>
</tr>
</tbody>
</table>

Table 4.1: Sensor Characteristics for Sensym 13U0500 Piezoresistive Pressure Transducer - Experimental Values and Manufacturer’s Specifications (Experimental Offset coefficient for 27 to 97°C, Manufacturer’s Spec. Offset coefficient for 0 to 82°C)

The results shown in table 4.1 offer a direct comparison to the manufactures specifications. While there are some differences between these results, the manufacturer’s performance characteristics are taken at a supply voltage of 5V (the experiments conducted for this research used a sensor supply voltage of approximately 15V). Other
causes for the differences between the experimental results and the manufacturer’s specifications may be due to the silastomer that was applied to the diaphragm of the sensor. While the silastomer should not affect the temperature coefficient of resistance, it may have affected the temperature coefficients of Span and Offset. The differences in these results reinforce the need for conducting the temperature calibrations to determine the sensor characteristics, instead of relying on the manufacturer’s specifications. This is especially necessary if modifications (such as adding silastomer to protect the diaphragm) have been made.

4.3.3 Application of Temperature Calibrations

The experimental data provided by the previous subsection provides a means of determining an accurate value from a pressure transducer as it operates over a wide range of temperatures.

Initially, the operating temperature of the pressure sensor can be determined with calculations involving the value of $V_{\text{sense}}$. Once $V_{\text{sense}}$ at room temperature has been recorded, equation 4.3 can be used to determine the operating temperature of the sensor.

\[
\Delta T = \frac{V_{\text{sense}} - V_{\text{sense}(25)}}{dV_{\text{sense}}/dT} \tag{4.3}
\]

$V_{\text{sense}(25)}$ is the value of $V_{\text{sense}}$ at room temperature (originally trimmed to be close to 0V), $\Delta T$ is the change in room temperature from 25°C.

Once the temperature of the sensor has been determined, the particular values of Span and Offset related to this temperature can then be calculated or interpolated from the range of known experimental values.

The basic formula for determining pressure from the output of a piezoresistive pressure transducer ($V_{\text{out}}$) is shown in equation 4.4 (derived from equation 4.1).
4.3 Temperature Compensation Calibrations

\[ P = \frac{V - O}{S} \]  

(4.4)

The basic equation for determining pressure (equation 4.4) does not take any changes in Span and Offset into account, therefore it cannot be used if the sensor is operating at temperatures other than room temperature. This equation must be modified to allow for the temperature sensitivity of Span and Offset.

If the temperature is less than approximately 370K, giving a constant rate of change in sensor offset (as displayed in table 4.1), equation 4.5 (Ainsworth et al. 2000) can be used to calculate an accurate pressure reading.

\[ P = \frac{1}{S_{25} + \left( \frac{dS}{dT} \right) \Delta T} \left[ V - \left( O_{25} + \frac{dO}{dT} \Delta T \right) \right] \]  

(4.5)

In equation 4.5, ‘\( S_{25} \)’ and ‘\( O_{25} \)’ are the span and offset of the sensor at room temperature (25°C).

If the sensor operational temperatures reach the region where Offset temperature sensitivity becomes non-linear (above 370K), equation 4.5 must be modified. This results in equation 4.6, where the value for offset (\( O_{\text{interp}} \)) will be determined by linearly interpolating from the existing experimental data points.

\[ P = \frac{1}{S_{25} + \left( \frac{dS}{dT} \right) \Delta T} \left[ V - O_{\text{interp}} \right] \]  

(4.6)

While the Design Methodology (Chapter 3) introduced a different equation for determining the temperature effects (equation 3.2), due to the non-linear behavior of Offset above approximately 370K, equations 4.5 and 4.6 will be used.

4.3.4 Temperature Compensation Effectiveness

To test the effectiveness of the temperature compensation routine, the errors between the compensated and uncompensated signals were compared. The experimental data collected for the temperature calibration process was used to indicate the effects of the sensor temperature compensation.
4.3 Temperature Compensation Calibrations

The quasi-static pressure tests, conducted at a range of temperatures, provided a range of sensor outputs to test the temperature compensation techniques. This allowed a comparison between the calculated fluid pressure (determined from the sensor output) and the actual applied pressure (from the Dead Weight tester).

To simulate an uncompensated pressure sensor, the Span and Offset at 25°C were applied to the sensor outputs for each tested operational temperature. These values were compared to the actual applied pressure for each quasi-static calibration. The error associated with the uncompensated sensor is shown in figure 4.10.

![Figure 4.10: Error from an uncompensated piezoelectric sensor](image)

The temperature compensation routine was applied to the experimental data. The values for applied pressure were determined using equation 4.6. The error associated with the compensated sensor is displayed in 4.11.

The figures for the uncompensated and compensated sensor error demonstrate the capabilities of the temperature compensation routine. The pressure error was reduced from a maximum of 13.5% to less than 1%. While the magnitude of the compensated error is greater than the error determined in other similar experiments (see figure 2.4), the temperature range used for this experimentation was relatively large, reducing the accuracy of the temperature compensation.
Figure 4.11: Error from a compensated piezoelectric sensor
4.4 Chapter Summary

Static Calibrations for are vital to ensure the accuracy of pressure tests using piezoresistive pressure transducers. Room temperature static calibrations were conducted for each of the piezoresistive pressure transducers used during this project, providing values of sensor Span and Offset. These room temperature calibrations are sufficient for experimental testing in the Shock Tube and the Gun Tunnel since the sensor temperature in these experiments remains relatively close to room temperature during the actual measurement of pressures.

Temperature calibrations become necessary once the piezoresistive pressure sensor operates at temperatures significantly different to room temperature (this will be the case for the pressure sensor used for testing pressures within the cylinder of the internal combustion engine). The temperature calibrations identified the relationship between the sensor characteristics (Span and Offset) and temperature. This allowed these sensor properties to be determined according to the particular operating temperature. To identify the operating temperature of the sensor, the value of $V_{\text{sense}}$ was correlated to temperature, allowing the temperature of the sensor to be determined if $V_{\text{sense}}$ was recorded.

Overall, these calibrations form the foundation of the work conducted in later sections of this dissertation. This chapter has provided an accurate means of determining the pressures measured by the sensor over a range of static conditions and operating temperatures. Other characteristics, such as the sensor dynamic response, can be now be thoroughly investigated in the following chapters.
Chapter 5

Dynamic Response Characteristics

5.1 Chapter Overview

This chapter explores the dynamic response characteristics of the piezoresistive pressure transducers. Using USQ’s shock tube facility, various aspects of sensor response will be investigated, including sensor resonant frequency and response time. These characteristics reveal the capabilities of the pressure sensors under transient fluid pressures and dictate the level overall performance of the piezoresistive pressure transducers during fast-response thermofluids experiments.

5.2 Shock Tube Testing

The shock tube (introduced in the Design Methodology section (Chapter 3)) allows the sensor response to be analysed in detail. A photograph of the shock tube used for these experiments can be seen in figure 5.1.

The particular piezoresistive pressure sensor used to test the dynamic response characteristics, was the Sensym SX150AHO sensor. Ideally, the dynamic response characteris-
5.2 Shock Tube Testing

Figure 5.1: Photograph of the shock tube used to test the sensor dynamic characteristics

tics for all three types of sensors could be investigated, however due to time constraints, only one type of sensor was tested with the shock tube. The dynamic characteristics of the SX150AHO sensor can however be generally related to the behavior of the other types of piezoresistive sensors.

5.2.1 Detailed Experimental Design

The SX150AHO pressure sensor is mounted to a plate that is attached to the end of the shock tube (the foreground of the picture in figure 5.1). The top surface of the sensor was level with the interior side of the plate (this positioned the pressure sensitive chip of the transducer approximately 3mm from the interior face of the mounting plate). Details of the shock tube mounting plate and the related mounting screw are shown in Appendix D.
Piezoelectric sensors are fitted along the tube at known locations. These sensors were used to determine shock speeds along the tube (by determining the shock speed, a theoretical analysis of the shock wave can be applied). The positioning of the piezoresistive and piezoelectric pressure transducers are shown in figure 5.2.

In all shock tube experiments, air was the test gas used. The diaphragm placed in the shock tube consisted of four sheets of common Cellophane (with the exception of the first shock tube test that used only three sheets).

For each shock tube test, pressure was increased in the driver section of the tube until the diaphragm burst. The rupture of the diaphragm caused a shock wave to propagate down the tube towards the sensor. The shock wave then hit the end of the tube where the sensor was mounted (reflecting back up stream), causing an approximate ‘step’ input of pressure to the pressure sensor. The response of the sensor to this input was then analysed.

A block diagram of the shock tube experiments demonstrates how the data was collected (figure 5.3).

![Figure 5.2](image1.png)

**Figure 5.2:** Schematic diagram of Shock Tube showing positions of pressure sensors

![Figure 5.3](image2.png)

**Figure 5.3:** A block diagram, showing the method of pressure measurement for shock tube tests
5.2 Shock Tube Testing

5.2.2 Modification of Pressure Sensors

The stock SX150AHO sensor had a relatively small opening in its case, therefore the top of the case was removed in many instances to improve the filling time of the sensor (refer to figure 5.4. The filling time is the time taken for a higher pressure gas to fill the sensor.

Removing the top of the case further exposed the silicon diaphragm of the sensor to the test fluid. In these cases, to prevent foreign particles in the test gas from damaging the sensor, grease or latex were added (see figure 5.4). Epoxy resin was also added to the sensors in some configurations to protect the gold connecting leads on the chip (the electrical connections). The use of Margarine (thinned with additional Canola oil) to protect the silicon chip was also trailed. This provided a readily available low viscosity grease-like compound, however Margarine was later found to deliver inconsistent results.

![CROSS SECTIONS OF SOME CONFIGURATIONS OF SX150AHO SENSORS USED FOR SHOCK TUBE TESTS](image)

**Figure 5.4:** Modification of SX150AHO sensors

Once a sensor was modified or a new sensor was required, a static calibration (at room temperature) was conducted to redetermine the values of Span and Offset for that particular transducer (the static calibration process described in Chapter 4). A summary of these sensor modifications and their related calibration number can be
viewed in table 5.1.

<table>
<thead>
<tr>
<th>Calibration Number</th>
<th>Sensor Modification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Unmodified</td>
</tr>
<tr>
<td>2</td>
<td>Top of sensor removed</td>
</tr>
<tr>
<td>3</td>
<td>Top removed, Epoxy added around chip (wires and diaphragm exposed)</td>
</tr>
<tr>
<td>4</td>
<td>Top removed, Epoxy added around chip (wires covered, diaphragm exposed)</td>
</tr>
<tr>
<td>5</td>
<td>Sensor from (4), approx 1mm layer grease added over diaphragm</td>
</tr>
<tr>
<td>6</td>
<td>Sensor from (5), approx 3mm layer grease added over diaphragm (grease up to sensor lip)</td>
</tr>
<tr>
<td>7</td>
<td>Sensor from (2), thin layer latex (&lt;1mm) added over diaphragm</td>
</tr>
<tr>
<td>8</td>
<td>Sensor from (7), grease added up to sensor lip over diaphragm</td>
</tr>
<tr>
<td>9</td>
<td>Sensor, top removed, approx 3mm of Margarine added over diaphragm (up to sensor lip)</td>
</tr>
</tbody>
</table>

Table 5.1: Summary of sensor modifications used for shock tube tests

The analysis of the Shock Tube tests for each of the sensor configurations displayed in table 5.1 is detailed in the next section.

5.3 Analysis of Results

The summary shown in table 5.2 displays the type of sensor used for each Shock Tube test. The atmospheric pressure and temperature at the time of each test were also recorded to allow for analysis of the Shock Tube results. The MATLAB script associated with the analysis of the Shock Tube tests, "shock_analysis2" is shown in Appendix C.

The outputs recorded for each Shock Tube test can be seen in graphs in Appendix E. This includes short and long time span sensor responses, graphs of reflected shock pressures, graphs for each sensor response showing 10 and 90% response lines and a power spectrum analysis for each Shock Tube test.
### 5.3 Analysis of Results

<table>
<thead>
<tr>
<th>Shock Test Number</th>
<th>Related Calibration</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>Sensor had approx 2mm layer grease (cal. for 1mm layer of grease used)</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>7</td>
<td>Sensor had approx 1mm layer grease added (cal. for no grease used)</td>
</tr>
<tr>
<td>13</td>
<td>8</td>
<td>Sensor had approx 1mm layer grease added (cal. for no grease used)</td>
</tr>
<tr>
<td>14</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

**Table 5.2:** Shock Tube tests and corresponding sensors used

#### 5.3.1 Reflected Shock Pressures

A theoretical analysis was used to calculate the fluid characteristics of the shock wave generated in the Shock Tube. This analysis, consisting of basic gas equations, was provided in a series of MATLAB scripts produced by Dr. David Buttsworth. The program code for running this analysis ‘p,T_reflected’ is displayed in Appendix C.

By determining the inbound shock speed and inputting the ambient temperature and pressure, the reflected shock conditions of the test gas could be determined. This allowed the theoretical reflected shock pressure to be compared with the value indicated by the piezoresistive pressure transducer.

To determine the inbound shockwave speed, the time taken for the shock wave to travel along the tube was calculated. Two piezoresistive pressure transducers were located at known positions along the tube (figure 5.2). The silicon chip of the piezoresistive sensor was located 3mm behind the surface of the mounting plate, therefore 3mm was added to the original measurement from the piezoelectric sensor to the end of the
5.3 Analysis of Results

Shock Tube (173.5 mm in figure 5.2) (the distance between the second piezoelectric transducer and the piezoresistive transducer was therefore actually 176.5 mm). As the shock wave passed these sensors, a sudden increase in pressure occurred. A rapid increase in pressure also occurred in the piezoresistive pressure transducer (mounted at the end of the Shock Tube). By measuring the time between the sudden pressure changes in the sensors, the shock wave speed could be determined.

The measurement of shock speed between the three different sensors allowed three different shock speeds to be determined -

- Shock speed between the piezoelectric sensors
- Shock speed between the piezoelectric and piezoresistive sensor
- Estimated shock speed at the piezoresistive sensor

To estimate the shock speed at the piezoresistive sensor, a uniform deceleration of the shock wave was assumed. Therefore, given the time and location of the shock wave at the two piezoelectric sensors and the piezoresistive sensor, a third shock speed was calculated (the shock speed at the piezoresistive sensor). A second order polynomial was fitted to the points of time and displacement at each of the sensors. The gradient of this polynomial at the point of the piezoresistive sensor determined the shock speed at that point.

Since there was some degree of error in identifying the precise shock arrival times at each of the pressure transducers, a reflected shock pressure was determined from each of the calculated shock speeds.

To give a comparison between the theoretical analysis and the pressure sensor performance, an average pressure was taken from the piezoresistive sensor response after the signal had appeared to have settled sufficiently from the step input of the shock wave (the reflected shock pressure). A typical comparison between the theoretical and measured shock pressures can be observed in figure 5.5 (‘P5’ is the reflected shock pressure, ‘US1’ is the shock speed between the piezoelectric sensors, ‘US2’ is the shock speed between the piezoelectric and piezoresistive sensor and ‘USP’ is the estimated shock
5.3 Analysis of Results

speed at the piezoresistive sensor).

Figure 5.5: A typical sensor response and a comparison between measured and predicted reflected shock pressures.

Each sensor response was also recorded over a longer time scale. An average shock pressure was determined for each set of long time scale data from 0.5ms to 1.5 ms (graphs shown in Appendix E). This pressure average was also compared to the theoretical reflected shock pressures. For most Shock Tube tests, the sensor response had settled well before this time window, therefore the average shock pressures determined over the long time scale were generally not accurate. A plot of a typical long time sensor response (showing theoretical and measured pressures) can be observed in 5.6.

A comparison between the theoretical and measured shock pressures (short time scale) for all Shock Tube tests are shown in table 5.3.

- 'P5 1' is the reflected shock pressure based on the shock speed between the piezoelectric sensors
- 'P5 2' is the reflected shock pressure based on the shock speed between the piezoelectric and piezoresistive sensors
- 'P5 P' is the reflected shock pressure based on the estimated shock speed at the
5.3 Analysis of Results

Figure 5.6: A typical long time scale sensor response and a comparison between measured and predicted reflected shock pressures.

- 'P5 measured’ is the measured reflected shock pressure from the piezoresistive sensor output.

A comparison between the theoretical and measured reflected shock pressures in table 5.3 reveals some differences in results, however in most cases, the estimated shock pressure at the piezoresistive pressure transducer (P5 P) provided a reasonable estimation of the experimental value. It may also be noted that for some shock tests the shock speed (and therefore the shock pressure) appeared to increase along the Shock Tube. This scenario can obviously not occur and appears purely as a result of errors from the estimation the shock arrival times at the sensors.

The estimated reflected shock pressures for the Shock Tubes tests 1 and 2 were the average pressures taken from 300 to 400 μs (this was taken from the long time span data). This time window was selected due to the estimated filling time of the sensor. Filling time equations developed by Dr. David Buttsworth (derived from basic gas and energy conservation equations) were used to calculate the filling time of the unmodified
5.3 Analysis of Results

<table>
<thead>
<tr>
<th>Shock Test Number</th>
<th>P5 (kPa)</th>
<th>1 (kPa)</th>
<th>2 (kPa)</th>
<th>P (kPa)</th>
<th>P5 measured (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>354.0</td>
<td>324.5</td>
<td>318.7</td>
<td>316.6</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>411.5</td>
<td>383.7</td>
<td>378.1</td>
<td>375.0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>417.1</td>
<td>384.6</td>
<td>378.1</td>
<td>421.1</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>340.0</td>
<td>353.5</td>
<td>356.3</td>
<td>338.3</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>417.5</td>
<td>410.5</td>
<td>409.1</td>
<td>402.4</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>387.1</td>
<td>377.3</td>
<td>375.3</td>
<td>371.9</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>422.0</td>
<td>410.5</td>
<td>408.2</td>
<td>405.7</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>413.9</td>
<td>394.4</td>
<td>390.4</td>
<td>394.8</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>388.8</td>
<td>378.1</td>
<td>376.1</td>
<td>368.8</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>375.7</td>
<td>378.1</td>
<td>378.6</td>
<td>382.0</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>406.3</td>
<td>403.9</td>
<td>403.4</td>
<td>411.0</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>353.4</td>
<td>341.4</td>
<td>339.0</td>
<td>339.0</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>361.0</td>
<td>355.9</td>
<td>354.9</td>
<td>355.0</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>353.4</td>
<td>355.9</td>
<td>356.4</td>
<td>358.3</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>368.8</td>
<td>355.9</td>
<td>353.3</td>
<td>366.0</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>419.8</td>
<td>355.9</td>
<td>343.3</td>
<td>442.2</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>349.7</td>
<td>327.5</td>
<td>323.1</td>
<td>369.0</td>
<td></td>
</tr>
</tbody>
</table>

**Table 5.3:** Comparison between theoretical and measured reflected shock pressures

SX150AHO sensor (the equations, contained in a MATLAB script, involved calculation of sonic and subsonic flow through a converging diverging nozzle). To use the filling time equations with the shock tube data, the MATLAB script ‘Fill.time’ was written (shown in Appendix C). A comparison was made between the theoretical internal pressure as the sensor fills, and the recorded sensor output (converted to pressure). This revealed that the true reflected shock pressure may not be recorded by the sensor until approximately 300 µs after the arrival of the shock (hence taking the average reflected shock pressure from 300 to 400 µs). The relationship between the theoretical filling pressure and the sensor output can be observed in figure 5.7.

Since the internal pressure of the sensors in shock tests 1 and 2 do not appear to closely follow the results derived from the filling equations, the effect of the shock wave entering the sensor may have introduced additional air mass or pressure into the sensor (the filling equations don’t take the effect of the shock wave into account). While the gas flow processes during the period of the shock wave entering the unmodified sensor are not exactly known, if the internal pressure of the pressure sensor increased significantly due to the effects of the shock wave, it is possible that the remainder of the sensor response is still governed by the filling equations. The graph shown in figure
5.3 Analysis of Results

Figure 5.7: Comparison of sensor response and theoretical internal pressure over time for shock test 2

5.8 gives a possible theoretical filling situation. In this case, the shock wave is assumed to rapidly increase the sensor pressure to 250 kPa before the theoretical filling process is applied.

The point in time at which the average reflected shock pressure was taken, may account for some of the discrepancy between the practical and theoretical results. The windows of time used to determine the average pressures were only based on estimations that the sensor response had sufficiently settled. Shock tests 1 and 2 measured the average reflected shock pressures from 300 to 400 µs. Shock tests, 3 to 13, measured the average reflected shock pressures from 50 to 100 µs after the arrival of the shock wave. Shock tests 14 to 17 measured the average reflected shock pressure from 160 to 210 µs due to the longer settling time of these sensor responses. By taking an average pressure over slightly different windows of time, a variety of values for the measured reflected shock pressure could be obtained, introducing some error into the results.

The differences between the actual and predicted results may also be due to the idealized assumptions used in the theoretical analysis.

The general similarity demonstrated between the average reflected shock pressure mea-
5.3 Analysis of Results

Figure 5.8: Comparison of sensor response and a possible theoretical model of internal pressure over time for shock test 2, given that the shock wave increases the internal pressure of the sensor to 250kPa.

The pressure measured and the predicted shock pressure (taking the estimated shock speed at the piezoresistive sensor), suggests high reliability and accuracy from the piezoresistive pressure transducers.

5.3.2 Identification of Resonant Frequencies

The resonant frequency of the silicon diaphragm of the piezoresistive pressure transducer is a factor which determines the maximum operational frequency of the pressure sensor. If these sensors are to be used in fast-response thermofluids experiments, such as pressure measurement in an internal combustion engine, the errors associated with various frequencies of pressure fluctuations should be determined.

The oscillations of the output signal from the pressure transducers are due the vibration of the silicon diaphragm and the resonance of other bodies (such as the air) adjacent to the sensor. The sensor output from Shock Tube test number 4 (figure 5.9) demonstrates the existence of multiple modes of vibration.

The high frequency oscillations visible in figure 5.9 were found to be due to the os-
5.3 Analysis of Results

Figure 5.9: Sensor output from Shock Tube test 4, demonstrating multiple modes of vibration of the silicon diaphragm. The lower frequency oscillations are likely to be caused by the acoustic resonance of air in front of the sensor. Various sensor configurations with a bare silicon chip (no added grease or silastomer) demonstrated similar high frequency oscillations but different lower frequency modes, verifying that the high frequency vibration mode was not related to the configuration of the sensor. This high frequency resonance must therefore be due to the resonance of the silicon diaphragm.

The resonant frequencies of air in front of the pressure transducers can be estimated. For the unmodified pressure transducer, a model of air resonating in a cavity with a small opening can be applied with equation 5.1 (‘v’ is the speed of sound, ‘A’ is the area of the inlet, ‘L’ is the length of the inlet, and ‘V’ is the volume of the cavity) (HyperPhysics 2003),

\[ f = \frac{v}{2\pi} \sqrt{\frac{A}{VL}} \]  

(5.1)

Applying this equation to the reflected shock conditions and the geometry of the unmodified sensor, the resonant frequency equated to approximately 8 kHz (period of
1.25e-4 s). Oscillations close to this frequency are partially visible in the Shock Tube data from the unmodified sensors (Shock Tube tests 1 and 2).

For the sensors with the top of the transducer case removed, a model of air resonating as a column can be applied. The model simulates the resonance of air in a cylinder with one closed end. The resonant frequency can be determined with equation 5.2 (‘n’ is the mode of vibration (n = 1,3,5 etc), 'v' is the speed of sound, 'L' is the length of the cylinder of air) (HyperPhysics 2003),

\[ f = \frac{nv}{4L} \] (5.2)

After applying this equation, the resonant frequency equated to approximately 25 kHz (period of 4e-5 s). Oscillations of similar frequency may be noted in the Shock Tube data from the sensors where the top of the case has been removed and little material (grease etc.) was added (Shock Tube tests 3,4,5,6,7,8,11,12 and 13).

A MATLAB script was developed to analyse the power spectrum density of the sensor responses (this script, ‘psd_display.m’, is displayed in Appendix C). The power spectrum density analysis calculates the magnitude of a range of frequencies, that when added together, produce the sensor output signal. This analysis can be used to identify the resonant frequencies of the response, since these frequencies will be represented by a peak on the power spectrum density plot.

An analysis of the power spectrum density for the various sensor outputs reveals the high frequency resonance of the diaphragm (the lower frequency oscillations related to the resonance of other bodies have very few oscillations, therefore these frequencies are not obvious on the power spectrum density analysis). A very high frequency resonance (several MHz) was identified in most sensor responses however this was found to be signal noise and was not included in the resonant frequency analysis. The power spectrum density of Shock Tube test 4 (shown in figure 5.9) is displayed in figure 5.10.

The power spectrum density in figure 5.10 shows a clear peak about the resonant frequency of the silicon diaphragm at 246.7 kHz (the high frequency oscillations visible in the sensor output). The diaphragm resonant frequencies were recorded for each
Figure 5.10: The power spectrum density of Shock Tube test 4, showing the resonant frequency of the silicon diaphragm

Shock Tube test (displayed in table 5.4). In the cases where the frequency is 0 Hz, no clear resonant frequency was identifiable.

These results demonstrate how the resonant frequency of the sensor can be affected by adding different substances (such grease epoxy or latex) to the sensor. The first four Shock Tube tests have identical resonant frequencies, since each of these sensor configurations added no substances to the sensor diaphragm. This suggests the resonant frequency of the unmodified silicon diaphragm is 246.7 kHz. Sensors with added layers of grease or latex demonstrated lower resonant frequencies (due to the addition of mass attached to the diaphragm).

The sensor used in Shock Tube test 7 recorded a higher than normal resonant frequency. This is due to the epoxy resin that was added to the sensor, since some epoxy was placed around the edges of the chip, effectively decreasing the size of the flexible diaphragm and therefore increasing the resonant frequency. Unfortunately the value of Offset for the sensors with the epoxy resin was very sensitive the clamping force used to hold the sensors in place. This occurred since the epoxy provided a ridged connection between the silicon chip and the body of the sensor. The drawback of mounting sensitivity made
Table 5.4: Diaphragm resonant frequencies determined from power spectrum density analysis (a resonant frequency of 0Hz indicates that no clear frequency was identified)

<table>
<thead>
<tr>
<th>Shock Test Number</th>
<th>Resonant Frequency (kHz)</th>
<th>Sensor Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>246.7</td>
<td>Unmodified</td>
</tr>
<tr>
<td>2</td>
<td>246.7</td>
<td>Unmodified</td>
</tr>
<tr>
<td>3</td>
<td>246.7</td>
<td>Top of Case Removed</td>
</tr>
<tr>
<td>4</td>
<td>246.7</td>
<td>Top of Case Removed</td>
</tr>
<tr>
<td>5</td>
<td>240.0</td>
<td>Epoxy Added, Wires Exposed</td>
</tr>
<tr>
<td>6</td>
<td>240.0</td>
<td>Epoxy Added, Wires Exposed</td>
</tr>
<tr>
<td>7</td>
<td>263.3</td>
<td>Epoxy Added, Wires Covered</td>
</tr>
<tr>
<td>8</td>
<td>133.3</td>
<td>Epoxy Added, 1mm Grease</td>
</tr>
<tr>
<td>9</td>
<td>106.7</td>
<td>Epoxy Added, 2mm Grease</td>
</tr>
<tr>
<td>10</td>
<td>20 (1)</td>
<td>Epoxy Added, 3mm Grease</td>
</tr>
<tr>
<td>11</td>
<td>183.3</td>
<td>Latex Added &lt;1mm</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>Latex Added, 1mm Grease</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>Latex Added, 1mm Grease</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>Latex Added, 3mm Grease</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>Latex Added, 3mm Grease</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>3mm Margarine</td>
</tr>
<tr>
<td>17</td>
<td>136.7</td>
<td>3mm Margarine</td>
</tr>
</tbody>
</table>

note 1: On observation of the sensor response of Shock Tube test 10, a resonance of approximately 20 kHz is present (this does not appear on the power spectrum density analysis due to the small number of oscillations). Since the resonance of this particular sensor with no grease is 263.3 kHz (test 7), with a 1 mm layer of grease is 133.3 kHz (test 8) and a 2 mm layer of grease is 106.7 kHz (test 9), it is possible that the resonant frequency of the sensor diaphragm in test 10 (with a 3 mm layer of grease) is approximately 20 kHz (due to the trend of a decreasing resonant frequency with an increasing vibrating mass).
the used of these sensors less attractive.

The sensors with Margarine (tests 16 and 17) delivered inconsistent results. While the twin peaks evident in the sensor responses in tests 16 and 17 may be due to some form of resonance (refer to plots shown in Appendix E), the true cause of the secondary peak in the sensor response remains unknown. Since the results of sensors with Margarine are inconsistent and difficult to predict, the future use of Margarine in sensors will be avoided.

Fast response piezoelectric sensors exhibit similar resonant frequencies to the values determined for the piezoresistive transducers. The PCB 112B11 piezoelectric sensor, used for the engine and Gun Tunnel pressure measurements (specifications in Appendix B), has a resonant frequency of \( \geq 200 \text{ kHz} \). This suggests that the transient pressure measurement performance from the low cost piezoresistive devices may be similar to expensive piezoelectric sensors.

### 5.3.3 Errors Related to Frequency of Measured Pressures

Errors in the output of the piezoresistive pressure transducers occur as the frequency of pressure fluctuations in the test fluid begins to approach the resonant frequency of the diaphragm within the sensor. A second order system can be used to simulate the dynamic characteristics of the silicon diaphragm of a piezoresistive pressure transducer (Ainsworth et al. 2000). The transfer function of such a system can be displayed by equation 5.3 (Ainsworth et al. 2000).

\[
F(j\omega) = \frac{1 - \left(\frac{\omega}{\omega_0}\right)^2 - j2h \left(\frac{\omega}{\omega_0}\right)}{\left[\left(1 - \left(\frac{\omega}{\omega_0}\right)^2\right)^2 + 4h^2 \left(\frac{\omega}{\omega_0}\right)^2\right]^{1/2}}
\]  

(5.3)

In equation 5.3 \( \omega_0=(k/m)^{1/2} \) was the undamped natural frequency and \( h=(c/2mk)^{1/2} \) was the damping ratio.

For typical step response signals it is possible to determine the damping ratio, however the outputs from many of the Shock Tube tests do not allow the damping ratio to be
accurately calculated. From examining the sensor responses, it is possible to deduce that the addition of grease or latex to the sensor typically increased the damping ratio (due to the fewer high frequency oscillations present in the sensor response).

The relative amplitude ratio and phase shift for the transfer function in equation 5.3 are shown in figure 5.11.

![Figure 5.11: The amplitude ratio and phase shift for relative frequency ratios (Ainsworth et al. 2000)](image)

Since the sensors tested in Shock Tube mostly exhibit a very low damping ratio (possibly around 0.01), the error related to the relative amplitude ratio (figure 5.11) increases rapidly as the testing frequency approaches the resonant frequency of the sensor diaphragm. The phase angle of the sensor response also changes dramatically as the testing frequency nears the undamped natural frequency of the sensor (in cases where the damping ratio is small, the undamped natural frequency and the resonant frequency of the sensor diaphragm are very similar). Therefore, to ensure high accuracy for any
5.3 Analysis of Results

results obtained from these piezoresistive pressure sensors, the frequency of pressure fluctuations should not exceed a value that is approximately an order of 10 below the resonant frequency of the transducer (1/10 of the diaphragm resonant frequency).

To estimate the error related to a particular test frequency, equation 5.4 can be used (Balachandran & Magrab 2004, eq. 5.99). This equation approximates the amplitude error of a system with a small damping ratio.

\[
\frac{f_a}{f_n} = \sqrt{1 - \frac{1}{1 + d}}
\]

(5.4)

In equation 5.4, ‘\(f_a\)’ is applied frequency of pressure fluctuation, ‘\(f_n\)’ is the natural frequency of the diaphragm (since the damping ratio is typically very small, the natural frequency is approximately the resonant frequency of the sensor) and ‘\(d\)’ is the error in the sensor response. If the experimental pressure fluctuations are at 1/10 of the sensor natural frequency (\(\frac{f_a}{f_n} = 0.1\)), the approximate error is 1.01%.

The various sensor configurations tested typically demonstrated relatively high resonant frequencies. This suggests that piezoresistive pressure transducers may be able to accurately record high frequency pressure fluctuations.

5.3.4 Sensor Response Time

The sensor response time (or rise-time) was identified as the time taken for the sensor output to rise from 10 to 90% of its full scale response after a step input. The response times for each of the sensor configurations were analysed to test the suitability of these sensors to fast-response measurement situations.

As shown in figure 5.12, the 10 and 90% levels were based on the average reflected shock pressure (the average pressure taken from a window of time after the response of the sensor had sufficiently settled).

Initially a smoothed sensor response line was used to indicate the points where the response crossed 10 and 90%. This was later found to introduce errors in situations
where particular sensors had very fast response times (the smoothing of the data effectively increased the measured response time). The response times for each of the Shock Tube test results were measured by recording the time that the sensor response (not smoothed) first crossed the 10% line, to the time that the sensor response first crossed the 90% line. In some situations the 10% line was beneath the amplitude of the noise generated before the step input (meaning that the sensor output appeared to cross the 10% line several times before the actual response of the sensor). To obtain useful results from these cases, the output associated with the actual step response of the sensor was identified (the signal which is clearly not associated with noise), and the time at which this line crossed the 10% line was recorded. A summary of the response times for each of the sensors tested can be seen in table 5.5.

The sensor response times displayed in table 5.5 can be explained by examining each sensor configuration. The relatively slow response times of tests 1 and 2 are due to the small opening in the unmodified sensors and the resulting filling time (explained previously in the subsection 5.3.1). The sensors with the top of the case removed and none/or little material covering the sensor recorded the fastest response times. The sensor response times typically decreased as more material (grease etc.) was added

Figure 5.12: The 10 and 90% lines used to measure the response time of the sensor
### 5.3 Analysis of Results

<table>
<thead>
<tr>
<th>Shock Test Number</th>
<th>Response Time (µs)</th>
<th>Sensor Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.96</td>
<td>Unmodified</td>
</tr>
<tr>
<td>2</td>
<td>12.52</td>
<td>Unmodified</td>
</tr>
<tr>
<td>3</td>
<td>0.38</td>
<td>Top of Case Removed</td>
</tr>
<tr>
<td>4</td>
<td>0.38</td>
<td>Top of Case Removed</td>
</tr>
<tr>
<td>5</td>
<td>0.57</td>
<td>Epoxy Added, Wires Exposed</td>
</tr>
<tr>
<td>6</td>
<td>0.67</td>
<td>Epoxy Added, Wires Exposed</td>
</tr>
<tr>
<td>7</td>
<td>0.35</td>
<td>Epoxy Added, Wires Covered</td>
</tr>
<tr>
<td>8</td>
<td>1.51</td>
<td>Epoxy Added, 1mm Grease</td>
</tr>
<tr>
<td>9</td>
<td>2.20</td>
<td>Epoxy Added, 2mm Grease</td>
</tr>
<tr>
<td>10</td>
<td>9.69</td>
<td>Epoxy Added, 3mm Grease</td>
</tr>
<tr>
<td>11</td>
<td>0.61</td>
<td>Latex Added &lt;1mm</td>
</tr>
<tr>
<td>12</td>
<td>0.90</td>
<td>Latex Added, 1mm Grease</td>
</tr>
<tr>
<td>13</td>
<td>1.12</td>
<td>Latex Added, 1mm Grease</td>
</tr>
<tr>
<td>14</td>
<td>55.46</td>
<td>Latex Added, 3mm Grease</td>
</tr>
<tr>
<td>15</td>
<td>40.51</td>
<td>Latex Added, 3mm Grease</td>
</tr>
<tr>
<td>16</td>
<td>3.36</td>
<td>3mm Margarine</td>
</tr>
<tr>
<td>17</td>
<td>21.45</td>
<td>3mm Margarine</td>
</tr>
</tbody>
</table>

Table 5.5: Response times for sensor outputs for each of the Shock Tube tests

to the sensor diaphragm (since this added more mass to the diaphragm). This can be observed when comparing the response times of tests 7,8,9 and 10 (no grease, thin layer of grease (1 mm), medium layer of grease (2 mm) and thick layer of grease (3 mm) respectively). The combination of grease and latex within the sensor gave the slowest response times (tests 14 and 15) while the sensors containing margarine demonstrated further inconsistency in their results.

The manufacturer’s specifications for the unmodified sensors (tests 1 and 2) quote a response time of 0.1 ms, significantly longer than the response times determined experimentally (12.98 µs for test 1 and 12.52 µs for test 2). This difference may be due to the manufacturer stating a response time associated with a worst-case scenario, to avoid litigation if the sensors did not perform to their specifications under some circumstances.

Overall, the experimental results demonstrate that the response time of the transducers can be significantly improved through some simple modifications to the pressure sensors. The response times for several of the modified sensors are also relatively fast, proving that these piezoresistive sensors are capable of providing accurate readings under rapidly changing pressures.
5.3 Analysis of Results

The response times of fast-response piezoelectric sensors are similar to the response times of the piezoresistive sensors used in the Shock Tube experimentation. The PCB 112B11 piezoelectric sensor, used for the engine and Gun Tunnel pressure measurements (specifications in Appendix B), has a response time of $\leq 3 \mu s$. The similarity of the piezoelectric and piezoresistive sensor response times indicates that the piezoresistive sensors are well suited to the measurement of transient pressures.
5.4 Chapter Summary

Overall, a sensor configuration can be selected which best matches the requirements for the pressure measurement situation.

If slower pressure changes are expected, the stock SX150AHO sensor could be used. This transducer would be most effective if the pressure fluctuations were below the resonant frequency of the air inside the pressure sensor - approximately 8 kHz.

The measurement of higher frequency pressure oscillations is best suited to sensors where the top of the transducer case has been removed. These sensors, where only a thin layer of latex or grease has been added, offer high resonant frequencies and fast response times. The addition of a thin layer of grease or latex on the silicon diaphragm can also significantly increase the damping ratio of the sensor if required. Thicker layers of grease may be used if dynamic performance becomes less critical and the sensor must be protected from high speed foreign particles in the test gas or high fluid temperatures.

The sensor with the epoxy resin covering the connecting leads did offered the highest resonant frequency and the fastest response time, however the issues related to the mounting sensitivity of these sensors (where the clamping force influences the sensor Offset) make the choice of using this configuration of sensor less viable.

The modification of the SX150AHO pressure transducer can dramatically alter the dynamic performance of the transducers. This may ultimately enable these low cost piezoresistive pressure transducers (approximately $150) to replace the high cost fast response sensors (such as piezoelectric sensors - approximately $2000) in the measurement of pressures in fast-response thermo fluids experiments.
Chapter 6

Pressure Measurement in the USQ Gun Tunnel

6.1 Chapter Overview

This chapter investigates the application of piezoresistive pressure transducers on dynamic pressure measurement within the USQ Gun Tunnel. The pressures produced during a Gun Tunnel test will be measured with a piezoresistive and a piezoelectric pressure transducer. The piezoelectric sensor used is a high end device with proven accuracy and fast response characteristics. This provided a bench mark by which the performance of the piezoresistive sensor could be compared.

6.2 Gun Tunnel Testing

The Operation of the Gun Tunnel produces a short duration test gas flow. A schematic diagram of the Gun Tunnel can be view in figure 6.1

As can be seen in the schematic diagram of the Gun Tunnel (figure 6.1), the apparatus consists of a driver tank, barrel, nozzle and dump tank. In the format used for this project, the end of the barrel was sealed off (not allowing the test gas to enter the
6.2 Gun Tunnel Testing

![Diagram of the USQ Gun Tunnel](image)

**Figure 6.1:** A schematic diagram of the USQ Gun Tunnel in the format used for this project (Top View)

converging diverging nozzle, testing section and the dump tank).

The particular sensor used for the Gun Tunnel testing was the Sensym 13U3000 (capable of withstanding a maximum pressure of 3000 psi). This sensor had a layer of silastomer (approximately 2mm thick) covering the pressure sensitive diaphragm to protect the sensor. Due to time constraints, this particular sensor was not analysed for its dynamic response characteristics. While a dynamic response analysis of this particular sensor would be ideal, the previous dynamic testing (using the shock tube) with the SX150AHO sensors represents the characteristics of typical piezoresistive pressure transducers. The results from the dynamic response testing suggested that a piezoresistive pressure transducer could provide acceptable results under transient pressure conditions (due to fast response times and high resonant frequencies), therefore this chapter aims to test this theory in a practical application.

The piezoelectric sensor used as the benchmark for the piezoresistive pressure transducer is a PCB 112B11. The specifications for this transducer are shown in Appendix B.

### 6.2.1 Detailed Experimental Design

The piezoresistive and the piezoelectric sensors were placed at opposite sides of the barrel a short distance before the cap at the end of the barrel. Both sensors were at the same length along the barrel section, and since the flow produced from the Gun Tunnel
within the barrel should be radially symmetric (about the axis of the barrel), the same fluid pressure should be simultaneously placed on both sensors during testing.

A photograph of the two pressure sensors mounted in the Gun Tunnel barrel is shown in figure 6.2. Detailed drawings of the mounting screw and barrel are shown in Appendix D.

![Mountings of piezoresistive and piezoelectric sensors in the Gun Tunnel barrel (note: the end of the barrel is unsealed at this stage)](image)

**Figure 6.2:** Mountings of piezoresistive and piezoelectric sensors in the Gun Tunnel barrel (note: the end of the barrel is unsealed at this stage)

Pressure was built up in the driver tank until the aluminium diaphragm ruptured. The gas from the driver tank then forced a piston along the barrel at high speed. The air in front of the piston was the measured test gas.

While in some Gun Tunnel experiments, the test section (in front of the piston) may be evacuated to a near vacuum prior to the test, this experiment initially had air in the barrel at room temperature and pressure.

A block diagram can be used to represent the method of data capture for this experimentation (figure 6.3)

While this experiment involved high gas temperatures, during the testing period where data was recorded from the piezoresistive sensor, the sensor did not have sufficient time to undergo a significant increase in temperature (pressures were recorded over
6.3 Analysis of Gun Tunnel Results

It was determined that a single Gun Tunnel test was sufficient to test the characteristics of the piezoresistive pressure transducer against the piezoelectric pressure transducer. The results obtained from the Gun Tunnel tests were analysed using a MATLAB script ‘gt28_analysis2’ (shown in Appendix C).

6.3.1 Comparison with Piezoelectric Sensor

The results obtained from the piezoresistive sensor compared well with the pressure readings taken with the piezoelectric sensor. A graph showing the piezoresistive and piezoelectric outputs is shown in figure 6.4.

The signal from the piezoelectric sensor was clipped at its peak pressure due to the settings of the oscilloscope (see figure 6.4). While this prevents a direct comparison between the recorded peak pressures of both sensors, the dynamic response of the piezoresistive sensor can still be compared to the pressure readings taken from the piezoelectric transducer at different points of the overall sensor response. Figure 6.5 displays the readings after the peak Gun Tunnel pressure. This offers a more detailed analysis.

Figure 6.3: A block diagram, showing the method of pressure measurement for the USQ Gun Tunnel

a time window of only 45 ms). Heat transfer calculations were performed to insure that the sensor could not significantly increase in temperature over this time (the 2mm silastomer layer over the sensor effectively insulates the transducer from any significant change in temperature during testing).
Some noise was present in the signal from the piezoresistive sensor, so a smoothing routine was applied to the data. The smoothed output from the piezoresistive sensor is compared with the piezoelectric signal in figure 6.6. If the piezoresistive sensors were to be applied in future thermofluids experiments, it may be possible to further reduce the signal noise to gain clearer results.

The plot in figure 6.6 demonstrates that the piezoresistive sensor is well suited to applications requiring the measurement of transient pressures. There are no obvious signs of phase lag in the piezoresistive sensor in comparison to the piezoelectric signal or diaphragm resonance due to high frequency pressure fluctuations. Figure 6.7 displays the readings after the peak Gun Tunnel pressure, offering a more detailed comparison between the sensor outputs.

On close inspection of the results, it may appear that the piezoresistive sensor has a faster response time than the piezoelectric. While it is possible that the piezoresistive sensor has a faster response time, the slower response of the piezoelectric transducer may be due to the geometry of the sensor mounting in the barrel. The hole exposing the piezoresistive sensor to the test gas was significantly larger than the hole for the
piezoelectric sensor (8.5mm in comparison to approximately 2mm). This size difference may have allowed the air cavity in front of the piezoresistive sensor change pressure at a slightly faster rate. The true response time of the piezoresistive and piezoelectric transducers could be determined by conducting shock tube tests for each of the sensors, however time constraints did not allow this testing.

6.3.2 Theoretical Analysis

Unfortunately, while a theoretical analysis of the Gun Tunnel test was planned using a Lagrangian quasi one dimensional computational model, essential program files required for these calculations could not be acquired. A theoretical analysis of this experimentation is fortunately not critical, since the output of the piezoresistive pressure transducer has already undergone a comparison with the results obtain from a reliable piezoelectric pressure sensor. The theoretical results would not have been expected to exactly match the pressure readings from the sensors (due to certain assumptions made for the theoretical model), therefore a more valuable analysis was available by simply comparing the outputs of the two types of pressure sensors.
6.3 Analysis of Gun Tunnel Results

Figure 6.6: A comparison between the smoothed piezoresistive data and the piezoelectric sensor output

Figure 6.7: A comparison between the smoothed piezoresistive and piezoelectric pressure sensors after the peak Gun Tunnel pressure
6.4 Chapter Summary

Testing with the USQ Gun Tunnel has demonstrated the capabilities of the piezoresistive pressure transducers under transient pressure measurement conditions. The results obtained from the piezoresistive sensor closely match the pressure readings produced by the piezoelectric pressure transducer. The piezoelectric sensor is a high end device, known for its accuracy and fast response characteristics, therefore the similarity of the results obtained using the piezoresistive sensor indicates that the piezoresistive technology may provide a cost-effective solution for pressure measurement in fast-response thermofluids experiments.
Chapter 7

Pressure Measurement of Internal Combustion Engine

7.1 Chapter Overview

This chapter investigates the use of piezoresistive pressure sensors for the measurement of in-cylinder pressures of an internal combustion engine. This explores the dynamic response characteristics of the pressure sensors under high frequency pressure fluctuations with the added complication of temperature compensation. The results obtained from piezoresistive pressure measurements within the cylinder of the internal combustion engine will be compared to the pressure readings from a piezoelectric sensor. This gives an indication of the accuracy obtained from the piezoresistive device. A theoretical engine model will also simulate the cylinder pressures, giving further material to assess the operation of the piezoresistive sensor.

The piezoelectric sensor used as the benchmark for the piezoresistive pressure transducer is a PCB 112B11 (the same sensor used for the Gun Tunnel experimentation).
7.2 Cylinder Pressure Testing

The particular engine used for this experiment was detailed in Chapter 3. The piezoresistive sensor used for the engine testing was originally the Sensym 13U3000 sensor. Since the cylinder pressures recorded in previous experiments did not exceed 500 psi, the Sensym 13U0500 sensor was used (maximum pressure 500 psi). This sensor delivered a better signal to noise ratio when compared to the 13U3000 (maximum pressure 3000 psi) since the testing pressures extended over a greater portion of the total sensor pressure range. A silastomer coating was applied to the pressure sensitive diaphragm of the transducer to protect the diaphragm against high gas temperatures and foreign particles.

7.2.1 Experimental Design

A piezoresistive and a piezoelectric pressure transducer were inserted into the head of the engine in similar locations (this can be seen in figure 7.1).

![Figure 7.1: A photograph showing the mounting of the piezoelectric (right) and piezoresistive (left) sensors on the engine](image)

Since the engine would normally operate at high temperatures, it was only tested over
7.2 Cylinder Pressure Testing

short periods of time to avoid overheating the pressure transducers.

A shaft encoder (figure 7.2) was used for this experiment to determine the cylinder position in comparison to the pressure readings and for determining the speed of the engine. This allowed the theoretical engine pressures to be applied to the experimental results. Details of the shaft encoder are included in Appendix D. Specifications for the optical sensor used on the encoder are displayed in Appendix B.

![Shaft Encoder attached to the engine](image)

**Figure 7.2:** The Shaft Encoder attached to the engine

A block diagram representing the method of data capture and pressure measurement is shown in figure 7.3.

During the engine testing process, four different tests were conducted,

1. Engine motored (by external electric motor), throttle closed
2. Engine fired, no load, throttle closed
3. Engine fired, loaded, throttle closed
4. Engine fired, loaded, throttle open
7.2 Cylinder Pressure Testing

Figure 7.3: A block diagram, showing the method of pressure measurement for the internal combustion engine

To load the engine, a hydraulic pump was used. This pump shifted a known volume of hydraulic oil (3.8e-6 m³) for each revolution at a known pressure (recorded from pressure gauges). To determine the power output of the engine, equation 7.1 was used.

\[ P = \Delta p Q \]  

(7.1)

In equation 7.1, ‘P’ is the engine output power, ‘\(\Delta p\)’ is the hydraulic oil pressure and ‘Q’ is the oil flow rate.

The layout of the engine testing apparatus can be seen in figure 7.4.

Figure 7.4: The layout of the engine testing apparatus

Due to the operational temperatures of the piezoresistive sensors, the temperature compensation routine (developed in Chapter 4) was used to increase the accuracy of the pressure measurements.
7.3 Analysis of Results

7.3.1 Comparison with Piezoelectric Sensor

Graphs were produced to compare the pressure recorded by the piezoresistive and piezoelectric sensors (figure 7.5 for engine test 1, figure 7.6 for engine test 2, figure 7.7 for engine test 3 and figure 7.8 for engine test 4). Due to high levels of signal noise from the piezoresistive sensor, some data smoothing was utilized. The effects of data smoothing unfortunately reduced the peak pressures displayed in the results for the piezoresistive sensors. To reduce the adverse affects of smoothing, a routine was developed to smooth the low pressure data to a higher extent then the high pressure data (the peak cylinder pressures). It may be possible to reduce the signal noise if the piezoresistive sensors were required for future applications. A MATLAB script, ‘engine_1’ (see Appendix C) was used to analyse the data collected from each of the engine tests.

![Cylinder pressures - motored, closed throttle](image)

**Figure 7.5:** Engine pressures determined from the piezoresistive and piezoelectric pressure transducers - motored, closed throttle

The readings obtained with the piezoelectric sensors drifted during the engine testing process (the offset of the piezoelectric measurements changed over time). To correct for this error, the pressures measured with the piezoelectric sensor were altered to match
Figure 7.6: Engine pressures determined from the piezoresistive and piezoelectric pressure transducers - fired, closed throttle, no load

Figure 7.7: Engine pressures determined from the piezoresistive and piezoelectric pressure transducers - fired, closed throttle, loaded
7.3 Analysis of Results

![Cylinder pressures – fired, loaded, open throttle](image)

Figure 7.8: Engine pressures determined from the piezoresistive and piezoelectric pressure transducers - fired, open throttle, loaded

The readings from the piezoresistive sensor over a short period of time (20 ms) midway through the exhaust stroke of the engine (relatively low pressure). Since the pressures during the exhaust stroke of the engine were very small compared to the peak engine pressures, any errors introduced to the piezoelectric readings were minimal.

For the loaded engine tests (3 and 4), the output power of the motor is shown in table 7.1.

<table>
<thead>
<tr>
<th>Engine Test</th>
<th>Hydraulic Oil Pressure (pa)</th>
<th>Output Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>7.58e6</td>
<td>659.8</td>
</tr>
<tr>
<td>4</td>
<td>11.72e6</td>
<td>1984.9</td>
</tr>
</tbody>
</table>

Table 7.1: Hydraulic pressures and equivalent engine output power for engine tests

The cylinder pressures recorded with the piezoelectric pressure transducer compared reasonable well with the results from the piezoresistive pressure sensor. The plots of in-cylinder pressure demonstrate that the piezoresistive sensors are capable of providing results similar to those recorded by the piezoelectric sensor. The plots also demonstrate that the results obtained from the piezoresistive sensors are more reliable at higher pressures, or situations where the signal amplitudes are much greater than the noise.
amplitude. While the peaks of the smoothed piezoresistive data reveal some error (due to the data being averaged over a certain number of data points), the peaks of the raw data (not smoothed) still compare well with the magnitude of the piezoelectric readings. Other differences in pressure readings may also be related to the positioning of the sensors within the head of the cylinder (the cylinder pressures may not be uniformly distributed).

Since the piezoelectric sensor is known for high accuracy and fast response times, the data indicates that the piezoresistive pressure transducer is capable of providing reasonably accurate measurements. The similarity of the results also suggests that the temperature compensation routines are effective. The piezoresistive signal shows no evidence of significant phase lag or amplitude errors associated with high frequencies of pressure fluctuation.

7.3.2 Theoretical Analysis

The theoretical analysis is based upon estimating the internal cylinder pressures using a thermodynamic engine simulation. This simulation was compiled into a series of MATLAB scripts by Dr. David Buttsworth. The engine simulation script allows a comparison of the theoretical pressures developed during motored and fired engine tests with the results obtained from the piezoelectric and piezoresistive pressure transducers. A MATLAB script for comparing the theoretical and measured engine pressures, `engine_2`, is displayed in Appendix C.

While four engine tests were conducted using various conditions, the motored engine test (engine test 1) and the loaded, open throttle test (engine test 4) give the greatest similarity to the theoretical model.

For the motored engine tests, a comparison between the measured and theoretical pressures is shown in figure 7.9.

For the fired engine tests, a comparison between the measured and theoretical pressures is shown in figure 7.10.
The precise values for engine parameters (such as the spark ignition angle, burn duration angle and initial pressure) were unknown, therefore these values were modified until the theoretical results closely matched the recorded values. Ideally these parameters could be determined to give a better indication of the sensor accuracy, however due to time constraints this was not possible.

The results obtained from the theoretical simulations closely match the pressure measurements from the piezoresistive and piezoelectric sensors (figure 7.9 and figure 7.10). While this does not give an accurate indication of sensor accuracy (due to the unknown engine parameters), the close match between the predicted and measured results indicates that pressure readings are close to the pressures expected from the engine.
Figure 7.10: A comparison between the theoretical and measured cylinder pressures - fired, open throttle, loaded
7.4 Chapter Summary

The pressure testing within the cylinder of an IC engine has provided a means for testing the dynamic response and temperature calibrations for the piezoresistive pressure transducers.

A comparison between the results of the piezoresistive and piezoelectric transducers demonstrated that the piezoresistive device is capable of reasonably accurate results. There were no obvious indications of phase lag or amplitude errors in the piezoresistive sensor output as a result of the high frequencies of pressure fluctuation. The accuracy of the readings obtained from the piezoresistive pressure sensors also indicates that the temperature compensation routine was effective.

A thermodynamic engine simulation provided a comparison between the practical and theoretical results. This demonstrated that the results obtained from the piezoresistive pressure sensor are approximately at the magnitude predicted by the model. The similarity between these results further reinforces the high performance from the piezoresistive sensors.
Chapter 8

Conclusions and Further Work

8.1 Achievement of Project Objectives

This dissertation has provided a detailed analysis of fast-response piezoresistive pressure transducers for thermofluids experiments. Objectives, set out in the initial pages of this report, have been met, providing an in-depth investigation into the operation and implementation of piezoresistive sensors.

The following objectives have been addressed:

1. Review existing techniques for temperature measurement and compensation in piezoresistive pressure measurement devices.

   A review of techniques previously used for temperature compensation was covered during the literature review (Chapter 2). This included past research conducted by Ainsworth et al. (2000), Denos (2002) and Clark (1992).

2. Devise appropriate electrical circuits to implement such techniques.

   Electrical circuits were successfully developed to provide pressure measurement and allow for accurate temperature compensation (Chapter 3, Figure 3.2). This circuit was used for the remaining pressure measurement experiments.

3. Devise suitable apparatus for quasi-static calibration of pressure trans-
ducers for both pressure and temperature sensitivity.

To perform the room temperature quasi-static calibrations, each of the piezoresistive pressure transducers were connected directly to the Dead Weight Tester. A small oven was modified to allow for a temperature calibration of the piezoresistive sensors, testing the temperature sensitivity of the transducers (Chapter 4). The temperature calibration apparatus allowed the sensor to be held at a particular temperature while a range of pressure were applied.

4. **Perform calibrations on selected transducers.**

Chapter 4 describes the experimental process of the quasi-static and temperature calibrations. This chapter also displayed the results of the calibrations and compared the experimental results with the manufacturer’s specifications.

5. **Investigate the dynamic response of sensors of various configurations (added grease, modified cases etc.) using a shock tube calibration.**

Using the shock tube facility, the dynamic response of the SX150AHO sensors were tested (Chapter 5). This included tests of sensors with various modifications, including additions of latex and grease and modified sensor cases.

6. **Obtain pressure measurements in a Gun Tunnel.**

A single test was conducted with the USQ Gun Tunnel (Chapter 6). This test recorded the pressures measured with a piezoresistive sensor piezoelectric sensor.

7. **Analyse the measurements from the Gun Tunnel and compare with data obtained from a piezoelectric sensor.**

Chapter 6 compared the pressure values recorded from the piezoelectric and piezoresistive sensors. This revealed that piezoresistive sensor was capable of producing similar results to the piezoelectric transducer (a more expensive sensor well suited to this pressure measurement application).

8. **Obtain pressure measurements in an IC engine.**

Pressure measurements were taken from an internal combustion engine under various conditions (motored, fired, loaded, unloaded etc.)(Chapter 7).

9. **Analyse the measurements from the IC engine and compare with data obtained from a piezoelectric sensor.**
8.2 Further Work

Chapter 7 investigated the comparison between the measurements obtained from the piezoresistive and piezoelectric transducers. The piezoresistive sensor compared relatively well with the output obtained from the piezoelectric sensor.

as time has permitted -

10. Compare the measurements from the Gun Tunnel with predictions based on a computational model (Lagrangian quasi one dimensional)

Due to time constraints and the unavailability of certain program files, a computational model for the analysis of the Gun Tunnel was not investigated.

11. Compare the measurements from the IC engine with predictions based on a computational model (thermodynamic engine simulation).

A thermodynamic engine simulation was used to provide theoretical results for the cylinder pressures of the IC engine. The actual pressure measurements from both the piezoelectric and piezoresistive sensors compared well with the predicted values.

8.2 Further Work

Future work on piezoresistive pressure sensing technology may be conducted in several areas. The areas of possible further research include an investigation into improving temperature calibration techniques, a more detailed analysis of dynamic response characteristics and the utilization of piezoresistive sensors with other fast-response thermofluid applications.

The temperature calibrations conducted with the modified oven apparatus were effective however they proved to be very slow, as discussed in Chapter 4. Further work could be conducted to develop a pressure testing apparatus that automatically sets the temperature of the sensor and applies a range of pressures while recording the sensor outputs (allowing the calibration process to be completely automated). The creation of such a device would greatly reduce the time and effort required to complete quasi-static pressure and temperature calibrations.
8.2 Further Work

The investigations into sensor dynamic response in this project compared the characteristics of various configurations of pressure sensors. Further work could be conducted with specific configurations to identify quantitative variables related to the dynamic behavior of the sensors (such as damping ratios and settling times). If such variables could be determined, the errors associated with high frequencies of pressure fluctuation could be calculated and tested with further experimentation. Research could also be conducted to compare the dynamic response characteristics of piezoresistive and piezoelectric sensors.

Piezoresistive pressure transducers have possible applications in a wide range of thermofluids experiments. An analysis of the piezoresistive pressure transducers under further pressure measurement applications (such as pressure measurement within the UQ T4 shock tunnel), would give another opportunity to test the suitability of these sensors and provide a better indication of the overall transducer versatility. It may be possible, with further research, for piezoresistive sensors to provide a cost effective replacement for more expensive pressure sensing technologies in a large variety of situations.
References


Buttsworth, D. (n.d.), *USQ Gun Tunnel*,


REFERENCES


Honeywell (n.d.), *Pressure and Force Sensors*,
Accessed 14/5/04.

Honeywell/Sensym (n.d.), *Low Cost, Stainless Steel Isolated Pressure Sensors*,
Accessed 15/5/04.

HyperPhysics (2003), *Resonance*,
http://hyperphysics.phy-astr.gsu.edu/hbase/sound/reson.html#resdef
Accessed 17/10/04.

MAXIM (2001), *Demystifying Piezoresistive Pressure Sensors*,
http://www.maxim-ic.com/appnotes.cfm/appnote_number/871
Accessed 14/5/04.

Microsystems (n.d.), *Piezoresistive Pressure and Temperature Sensor Cluster*,
http://www.microsystems.metu.edu.tr/piezops/piezops.html
Accessed 14/5/04.
Appendix A

Project Specification
ENG 4111/2 Research Project
PROJECT SPECIFICATION

FOR: Peter Colin Mckenzie HOCKINGS

TOPIC: Fast Response Piezoresistive Pressure Transducers for Thermofluids Experiments

SUPERVISORS:
Dr. David Buttsworth
Dr. Ahmad Shafian

ENROLMENT:
ENG 4111 – S1, D. 2004;
ENG 4112 – S2, D. 2004

PROJECT AIM:
This project aims to identify the frequency and temperature response characteristics of low cost piezoresistive pressure transducers and provide accurate calibration to allow these pressure sensors to be used in fast-response thermofluids experiments.

PROGRAMME: Issue B, 18 October 2004

1. Review existing techniques for temperature measurement and compensation in piezoresistive pressure measurement devices.

2. Devise appropriate electrical circuits to implement such techniques.

3. Devise suitable apparatus for quasi-static calibration of pressure transducers for both pressure and temperature sensitivity

4. Perform calibrations on selected transducers.

5. Investigate the dynamic response of sensors of various configurations (added grease, modified cases etc.) using a shock tube calibration.


7. Analyse the measurements from the Gun Tunnel and compare with data obtained from a piezoelectric sensor.

8. Obtain pressure measurements in an IC engine.

9. Analyse the measurements from the IC engine and compare with data obtained from a piezoelectric sensor.
As time permits:

10. Compare the measurements from the Gun Tunnel with predictions based on a computational model (Lagrangian quasi one dimensional).

11. Compare the measurements from the IC engine with predictions based on a computational model (thermodynamic engine simulation).

AGREED: __________________________ (Student) __________________________ (Supervisor)

(dated) ___/___/___
Appendix B

Specification and Data Sheets

Appendix B Contents

Specifications for 13U0500 and 13U3000 Piezoresistive Sensors 95
Specifications for SX150AH0 Piezoresistive Sensor 101
Specifications for INA114 Instrumental Amplifier 105
Specifications for PCB 112B11 Piezoelectric Sensor 117
Specifications for Encoder Optical Sensor 118
B.1 Specifications for 13U0500 and 13U3000 Piezoresistive Sensors

13mm Series

Low Cost, Stainless Steel Isolated Pressure Sensors

Applications
- Industrial Controls
- Hydraulic Controls
- Tank/Pressure
- Transmitter

Features
- 133 and 13U
- Rugged - Isolated Stainless Steel Package
- In-Line Semiconductor Technology
- 133 Compensated Series
  - Calibrated and Temperature Compensated
  - Voltage or Current
  - Supply Options
  - Absolute & Gauge
  - Gauge/Pressures
- 13U Uncompensated Series
  - Low Cost Cell Package
  - Absolute Pressure

Equivalent Basic Circuit

0 to 500, 1,000, 2,000, 3,000, and 5,000 psi Pressure Sensors

These SenSym ICT 13mm stainless steel devices are designed for high pressure applications that involve measurement of hostile media in harsh environments. This series uses SenSym ICT's proven piezoresistive semiconductor sensor chip in an all isolated housing with or without an integral ceramic for temperature compensation and calibration. This design has proven to be highly reliable, stable, and accurate.

These sensors feature a weld ring collar and special back support ring for high cycle life capability as they are designed for further package integration in OEM applications. Parts are available with pressure ranges from 500 through 5,000 psi and can be used with voltage or current supplies.

Contact your local SenSym ICT representative, the factory, or go to SenSym ICT's Web site at www.sensym-ict.com for additional details.
### 13mm Compensated Series

#### PRESSURE SENSOR CHARACTERISTICS (all devices)

**Environmental Specifications (all devices)**

- **Temperature Ranges**
  - Compensated: -40°C to +125°C
  - Humidity: 10% at -20°C to 90% at 25°C
- **Operating**: -40°C to +125°C
- **Shock**: 100G for 11 msec
- **Storage**: -40°C to +125°C

**Maximum Ratings (all devices)**

- **Voltage Range**: 5V
- **Supply Voltage**: 4.5 to 5.5V
- **Current Range**: 100μA to 1.5mA
- **Insulation Resistance**: 100MΩ at 50V

#### PRESSURE RANGE SPECIFICATIONS

<table>
<thead>
<tr>
<th>KenSym Part No.</th>
<th>Pressure Range</th>
<th>Full Scale Span</th>
<th>Proof Pressure</th>
<th>Breakdown Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>13C 1000F (55)</td>
<td>0-100 psi</td>
<td>96psi to 100psi</td>
<td>500psi</td>
<td>2500psi</td>
</tr>
<tr>
<td>13C 2000F (55)</td>
<td>0-200 psi</td>
<td>96psi to 200psi</td>
<td>500psi</td>
<td>5000psi</td>
</tr>
<tr>
<td>13C 3000F (55)</td>
<td>0-300 psi</td>
<td>96psi to 300psi</td>
<td>500psi</td>
<td>10000psi</td>
</tr>
<tr>
<td>13C 5000F (55)</td>
<td>0-500 psi</td>
<td>146psi to 500psi</td>
<td>500psi</td>
<td>10000psi</td>
</tr>
</tbody>
</table>

#### PERFORMANCE CHARACTERISTICS

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Min</th>
<th>Typical</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero Pressure Offset</td>
<td>-2</td>
<td>0</td>
<td>+2</td>
<td>mV</td>
</tr>
<tr>
<td>Pressure Non-Linearity</td>
<td>±0.1</td>
<td>±0.15</td>
<td>±0.25</td>
<td>%FSFS</td>
</tr>
<tr>
<td>Pressure Hysteresis</td>
<td>±0.01</td>
<td>±0.015</td>
<td>±0.02</td>
<td>%FSFS</td>
</tr>
<tr>
<td>Repeatability</td>
<td>±0.5</td>
<td>±0.5</td>
<td>±1.0</td>
<td>%FSFS</td>
</tr>
<tr>
<td>Temp. Effect on Span</td>
<td>±0.5</td>
<td>±0.5</td>
<td>±1.0</td>
<td>%FSFS</td>
</tr>
<tr>
<td>Temp. Effect on Offset</td>
<td>±0.2</td>
<td>±0.3</td>
<td>±1.5</td>
<td>%FSFS</td>
</tr>
<tr>
<td>Thermal Hysteresis 60°C to 80°C</td>
<td>±0.01</td>
<td>±0.3</td>
<td>±1.5</td>
<td>%FSFS</td>
</tr>
<tr>
<td>Long-Term Stability of Offset &amp; Span</td>
<td>±0.1</td>
<td>±0.3</td>
<td>±1.5</td>
<td>%FSFS</td>
</tr>
<tr>
<td>Response Time</td>
<td>±0.1</td>
<td>±0.1</td>
<td>±0.1</td>
<td>ms</td>
</tr>
</tbody>
</table>

Note 1: Reference Conditions: Unless otherwise noted: 
- Ta = 25°C ±5°C
- Voltage = 5V ±10%
- Maximum error is for 1 minute at 25°C

Note 2: Full Scale Span is the algebraic difference between the output voltage at full scale pressure and the output at zero pressure. Full Scale Span is referenced to the supply voltage.

Note 3: Pressure Non-Linearity is based on a best straight line from the zero to the maximum pressure.

Note 4: Pressure Hysteresis is the maximum output difference at any point within the operating pressure range for increasing and decreasing pressure.

Note 5: The maximum error band of the offset and span over the compensated temperature range, relative to the 25°C reading.

Note 6: Long-term stability over 1 month period.

Note 7: Response time for a 1 psi to full-scale span pressure step change, 10% to 90% rise time.

Note 8: The maximum pressure that can be applied without changing the transmitter's performance or accuracy.

Note 9: The maximum pressure that can be applied to the transmitter without rupture of either the measurement or transducer case.

Note 10: Common Mode Voltage is measured from output to ground.
B.1 Specifications for 13U0500 and 13U3000 Piezoresistive Sensors

13mm Series

PHYSICAL DIMENSIONS

Dimensions in inches (mm)

PACKAGE 1 (See Note)
RING WITH BACK SUPPORT

Note: Non-concentricity effects at the diaphragm weld area may cause runout of up to ±0.0006" between the upper and lower portion of the sensor body. It is recommended to use a counter bore to mate with this device to allow for this non-concentricity.

PACKAGE 4
1/8-27 NPT
B.1 Specifications for 13U0500 and 13U3000 Piezoresistive Sensors

13 mm Series

PHYSICAL DIMENSIONS (cont'd)

Dimensions in inches (mm)

PACKAGE 5
1/4-18 NPT

PACKAGE 6
7/16-20 UNF
### 13mm Uncompensated Series

#### PRESSURE RANGE SPECIFICATIONS

<table>
<thead>
<tr>
<th>Sensor Part No.</th>
<th>Pressure Range</th>
<th>Full-Scale Span$^a$</th>
<th>Proof Pressure$^b$</th>
<th>Burst Pressure$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>13U 0500 A 0 R</td>
<td>0-500 psi</td>
<td>175mV to 300mV</td>
<td>1200 psi</td>
<td>2400 psi</td>
</tr>
<tr>
<td>13U 1000 A 0 R</td>
<td>0-1000 psi</td>
<td>350mV to 600mV</td>
<td>2400 psi</td>
<td>4800 psi</td>
</tr>
<tr>
<td>13U 2000 A 0 R</td>
<td>0-2000 psi</td>
<td>700mV to 1200mV</td>
<td>4800 psi</td>
<td>9600 psi</td>
</tr>
<tr>
<td>13U 3000 A 0 R</td>
<td>0-3000 psi</td>
<td>1400mV to 2400mV</td>
<td>9600 psi</td>
<td>19200 psi</td>
</tr>
<tr>
<td>13U 5000 A 0 R</td>
<td>0-5000 psi</td>
<td>2800mV to 4800mV</td>
<td>19200 psi</td>
<td>38400 psi</td>
</tr>
</tbody>
</table>

#### PERFORMANCE CHARACTERISTICS$^c$

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Min</th>
<th>Typical</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero Pressure Offset</td>
<td>0</td>
<td>±7.5</td>
<td>±7.5</td>
<td>mV/V</td>
</tr>
<tr>
<td>Pressure Non-Linearity$^c$</td>
<td>–</td>
<td>±0.1</td>
<td>±0.25</td>
<td>%FS</td>
</tr>
<tr>
<td>Pressure Hysteresis$^c$</td>
<td>–</td>
<td>±0.015</td>
<td>±0.025</td>
<td>%FS</td>
</tr>
<tr>
<td>Repeatability</td>
<td>–</td>
<td>±0.010</td>
<td>±0.015</td>
<td>%FS</td>
</tr>
<tr>
<td>Temp. Coefficient of Span$^c$ (0 to 82°C)</td>
<td>300</td>
<td>720</td>
<td>1200</td>
<td>ppm/°C</td>
</tr>
<tr>
<td>Temp. Coefficient of Resistance$^c$ (0 to 82°C)</td>
<td>0</td>
<td>370</td>
<td>420</td>
<td>ppm/°C</td>
</tr>
<tr>
<td>Temp. Coefficient of Offset$^c$ (0 to 82°C)</td>
<td>0</td>
<td>30</td>
<td>450</td>
<td>ppm/°C</td>
</tr>
<tr>
<td>Thermal Hysteresis (0 to 82°C)</td>
<td>–</td>
<td>±0.1</td>
<td>±0.3</td>
<td>%FS</td>
</tr>
<tr>
<td>Long Term Stability of Offset &amp; Span$^c$</td>
<td>–</td>
<td>±0.1</td>
<td>±0.2</td>
<td>%FS</td>
</tr>
<tr>
<td>Response Time$^c$</td>
<td>–</td>
<td>0.1</td>
<td></td>
<td>ms</td>
</tr>
<tr>
<td>Input Resistance</td>
<td>4.0</td>
<td>4.75</td>
<td>6.0</td>
<td>kΩ</td>
</tr>
<tr>
<td>Output Resistance</td>
<td>4.0</td>
<td>4.75</td>
<td>6.0</td>
<td>kΩ</td>
</tr>
</tbody>
</table>

#### PHYSICAL DIMENSIONS

Dimensions in inches (mm)

**PACKAGE 0 (See Note)**

**RING AND CELL**

**Note:** Non-concentric effects at the diaphragm void shall not cause output shifts of up to ±0.005% of the span and input reference of the sensor body. It is recommended to use a circular hole to test with this device to allow for this non-concentricity.

#### 13mm Uncompensated Series Specification Notes

- **Note 1:** Reference Condition: same as specified above. Tolerance: ±0.25%.
- **Note 2:** Full-Scale Span is the minimum span without the effects of any other temperature or sensor bias. Tolerance: ±0.25%.
- **Note 3:** Pressure Non-Linearity is the maximum output difference at any point on the pressure range.
- **Note 4:** The output is specified to have a linear characteristic within ±0.005% of the rated span. Tolerance: ±0.005%.
- **Note 5:** The sensor is rated 100% for use with a single output source and is guaranteed to operate within the specified range.
- **Note 6:** Temperature coefficient of output is ±0.005% per °C, determined using a constant current source.
- **Note 7:** The sensor is specified to have a response time of 0.1 ms under the conditions specified by the manufacturer.
- **Note 8:** The maximum pressure that can be applied to the sensor without damage or loss of accuracy is 100% of the rated span.
B.1 Specifications for 13U0500 and 13U3000 Piezoresistive Sensors

__13mm Series__

Low Cost, Stainless Steel Isolated Pressure Sensors

**ORDERING INFORMATION - PART # DESCRIPTION**

13mm Compensated Series

<table>
<thead>
<tr>
<th>T1</th>
<th>C</th>
<th>X000P</th>
<th>A5</th>
<th>T</th>
<th>A</th>
<th>S</th>
<th>K</th>
<th>I1</th>
</tr>
</thead>
<tbody>
<tr>
<td>13m cell</td>
<td>Compensation</td>
<td>C = Compensated</td>
<td>Pressure Range in (PSI)</td>
<td>K = 11 Vdc Isolation</td>
<td>L = 1.5 kΩ Isolation</td>
<td>Pressure Connections</td>
<td>1 = Ring with biax support</td>
<td>4 = 1/8-27 BSWT</td>
</tr>
<tr>
<td>A = Absolute Pressure</td>
<td>5 = Sealed gauge pressure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For example: Part #13C060F5K = 13 mm Cell, Compensated, 3000 psi, Sealed Gauge, 11VDC Port with 15 Vdc excitation.

13mm Uncompensated Series

<table>
<thead>
<tr>
<th>T1</th>
<th>U</th>
<th>X000P</th>
<th>A</th>
<th>S</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>13m cell</td>
<td>Compensation</td>
<td>U = Uncompensated</td>
<td>Pressure Range in (PSI)</td>
<td>5 VDC Isolation</td>
<td>0 VDC excitation</td>
</tr>
<tr>
<td>Pressure Connection</td>
<td>0 = Ring and Cell</td>
<td>A = Absolute Pressure</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For example: Part #13U3004A4K = 13 mm Cell, Uncompensated, 3000 psi, Absolute, Ring pressure connection with 5 Vdc excitation.
B.2 Specifications for SX150AHO Piezoresistive Sensor

SX Series
Low Cost Pressure Sensors

The SX Series of pressure sensors provide the lowest cost components for measuring pressures up to 150 psi. These sensors were specifically designed for use with non-corrosive, non-abrasive media such as air, dry gases, and the like. Convenient pressure ranges are available to measure differential, gauge, and absolute pressures from 0 to 1 psi (0010) up to 0 to 150 psi (SX150).

The absolute die devices have an internal vacuum reference and an output voltage proportional to absolute pressure. The Differential (D) die does not allow application of pressure to either side of the diaphragm and can be used for gauge or differential pressure measurements.

This product is packaged either in Century ICT's standard low-cost step-center "hamburger" package, a plastic point "M" package, or a metal TO5 package with or without gel. All packages are designed for applications where the sensing element is to be integral to the OEM equipment. These packages can be epoxy sealed and/or clamped onto a pressure fitting. A standard bridge type SP configuration is provided for electrical connection to the "Button" or "M" package. The TO5 Package offers a 5-pin open-bridge configuration. A DIP Package is also available, which mounts on a PC board like a standard K with through-hole pin. This extremely small-size package enables the use of multiple sensors in a limited available space application.

Because of its high impedance bridge, the SX Series is ideal for portable and low power or battery operated systems. Due to its low noise, the SX is an excellent choice for medical and other low pressure applications.

Contact your local Sensys ICT representative, the factory, or see Sensys ICT's Web site at www.sensys-ict.com for additional details.
### SX Pressure Series

**SenSym ICT**

#### B.2 Specifications for SX150AHO Piezoresistive Sensor

**Ordering Information**

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Pressure Range (psi)</th>
<th>Temp. Range (deg C)</th>
<th>Mounting Style</th>
</tr>
</thead>
<tbody>
<tr>
<td>SX150AHO</td>
<td>-15 to 15</td>
<td>-40 to 125</td>
<td>Surface Mount</td>
</tr>
</tbody>
</table>

**SX Performance Characteristics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual Error</td>
<td>±1%</td>
<td>±2%</td>
</tr>
<tr>
<td>Temp Coefficient</td>
<td>±0.1%/°C</td>
<td>±0.2%/°C</td>
</tr>
</tbody>
</table>

**Notes:**

- Operating conditions: 0°C to 60°C
- Storage conditions: -40°C to 125°C
- Humidity: 0% to 95% non-condensing

---

**Table:**

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>Temp (°C)</th>
<th>Resistance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-40</td>
<td>1000</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>950</td>
</tr>
<tr>
<td>30</td>
<td>60</td>
<td>850</td>
</tr>
</tbody>
</table>

**Graph:**

- Linear pressure response
- S-shape temperature characteristic
B.2 Specifications for SX150AHO Piezoresistive Sensor

**ELECTRICAL CONNECTIONS**

**PACKAGE OUTLINES**

- Button Package
- Nipple Package
- N Housing Package
- D2 Dip Package
Sx Series

Low Cost Pressure Sensors

PACKAGE OUTLINES (cont’d)

DD4 Dip Package

AD4 Dip Package

TO5 Package

TO39 Package
B.3 Specifications for INA114 Instrumental Amplifier

**INA114**

**Precision INSTRUMENTATION AMPLIFIER**

**FEATURES**
- LOW OFFSET VOLTAGE: 50μV max
- LOW DRIFT: 9.2μV/°C max
- LOW INPUT BIAS CURRENT: 2nA max
- HIGH COMMON-MODE REJECTION: 115dB min
- INPUT OVER-VOLTAGE PROTECTION: ±40V
- WIDE SUPPLY RANGE: ±2.25 to ±18V
- LOW QUIESCENT CURRENT: 5mA max
- 8-PIN PLASTIC AND SOIC-16

**APPLICATIONS**
- BRIDGE AMPLIFIER
- THERMOCOUPLE AMPLIFIER
- RTD SENSOR AMPLIFIER
- MEDICAL INSTRUMENTATION
- DATA ACQUISITION

**DESCRIPTION**

The INA114 is a low-cost, general-purpose instrumentation amplifier offering excellent accuracy. Its versatile 8-pin amplified small size makes it ideal for a wide range of applications.

A single external resistor sets any gain from 1 to 10,000. Internal input protection can withstand up to ±40V without damage.

The INA14 is designed for very low offset voltage (50μV), drift (8μV/°C) and high common-mode rejection (115dB at G = 1000). It operates with power supplies as low as ±2.25V, allowing use in battery-operated and single-supply systems. Quiescent current is 5mA maximum.

The INA114 is available in 8-pin plastic and SOIC-16 surface-mount packages. Both are specified for the -40°C to +105°C temperature range.
### SPECIFICATIONS

#### ELECTRICAL

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>CONDITIONS</th>
<th>MIN</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offset Voltage</td>
<td>$V_{OS} = 0$</td>
<td>$1 \mu V$</td>
<td>$100 \mu V$</td>
</tr>
<tr>
<td>Bias Current</td>
<td>$I_{B}$</td>
<td>$100 \mu A$</td>
<td>$1 \ mA$</td>
</tr>
<tr>
<td>Common Mode Rejection</td>
<td>$K_{CM}$</td>
<td>$1000$</td>
<td>$10$</td>
</tr>
<tr>
<td>Power Supply</td>
<td>$V_{CC}$</td>
<td>$5$</td>
<td>$5$</td>
</tr>
<tr>
<td>Input Resistance</td>
<td>$R_{IN}$</td>
<td>$100$</td>
<td>$100$</td>
</tr>
</tbody>
</table>

#### NOTES

- Specifications are subject to change without notice.
- The specifications in this document are not intended for use in life support devices or systems where failure of a device could reasonably be expected to result in significant injury to the user.

### INA114

2
B.3 Specifications for INA114 Instrumental Amplifier

**ELECTROSTATIC DISCHARGE SENSITIVITY**

This integrated circuit can be damaged by ESD. Fairchild recommends that all integrated circuits be handled with appropriate precautions. Failure to observe proper handling and installation procedures can cause damage.

ESD damage can range from subtle performance degradation to complete device failure. Precision integrated circuits may be more susceptible to damage because very small parametric changes could cause the device not to meet its published specifications.

**PACKAGE/ORDERING INFORMATION**

<table>
<thead>
<tr>
<th>PRODUCT</th>
<th>PACKAGE</th>
<th>TEMPERATURE RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1004</td>
<td>SOT-23-5</td>
<td>-40°C to +85°C</td>
</tr>
<tr>
<td>1004D</td>
<td>SOT-23-5</td>
<td>-40°C to +85°C</td>
</tr>
<tr>
<td>1008</td>
<td>SOT-89-5</td>
<td>-40°C to +85°C</td>
</tr>
</tbody>
</table>

**ABSOLUTE MAXIMUM RATINGS**

- Input Voltage: ±15 V
- Output Voltage: ±15 V
- Output Short-Circuit Duration: Continuous
- Operating Temperature: -40°C to +85°C
- Storage Temperature: -65°C to +150°C
- Relative Humidity: 10% to 90%
- Lead Temperature (Soldering, 10s): 260°C

NOTE: All voltage limits are absolute maximum ratings. These limits may cause permanent damage.
TYPICAL PERFORMANCE CURVES (CONT)

Input Signal Response, G = 1

Small Signal Response, G = 1

Large Signal Response, G = 100

Small Signal Response, G = 1000

Input Distortion: Noise, G = 1000

Gain

Distortion

Error

INA114
APPLICATION INFORMATION

Figure 1 shows the basic connections required for operation of the INA114. Applications with noisy or high impedance power supplies may require decoupling capacitors close to the device pins as shown.

The output referred to the output reference (Ref) terminal which is normally grounded. There must be a low-impedance connection to assure good common-mode rejection. A resistance of 3kΩ in series with the Ref pin will cause a typical offset to degrade to approximately 300μV CMR (G = 1).

SETTING THE GAIN

Gain of the INA114 is set by connecting a single external resistor, RG:

$$ G = 1 + \frac{50 \text{kΩ}}{R_G} $$

Commonly used gains and resistor values are shown in Table 1.

The fixed term in equation (1) comes from the sum of the two internal feedback resistors. These are on-chip metal film resistors which are laser trimmed to accurate absolute values. The accuracy and temperature coefficient of these resistors are included in the gain accuracy and drift specifications of the INA114.

The stability and temperature drift of the external gain setting resistor, RG, also affects gain. RG's contribution to gain accuracy and drift can be directly inferred from the gain equation (1). Low resistor values required for high gain can make winding resistance important. Addition of a fixed termination resistor across the winding can minimize additional gain error (possibly an unstable gain error) in gains of approximately 100 or greater.

NOISE PERFORMANCE

The INA114 provides very low noise in most applications. For differential source impedances less than 100Ω, the INA114 may provide lower noise. For source impedances greater than 500Ω, the INA114 FET input instrumentation amplifier may provide lower noise.

Low frequency noise of the INA114 is approximately 0.1μV RMS from 0 Hz to 100 Hz. This is approximately one tenth the noise of "low noise" shaper-stabilized amplifiers.

![Diagram of INA114 connections](image)
B.3 Specifications for INA114 Instrumental Amplifier

OFFSET TRIMMING

The INA114 has been trimmed for very low offset voltages and drift. Most applications require no external offset adjustment. Figure 2 shows an optional circuit for trimming the output offset voltage. The voltage applied to Ref terminal is summed at the output. Low impedance must be maintained at this node to ensure good common-mode rejection. This is achieved by buffering the voltage with an op amp as shown.

![Offset Trimming Circuit](image)

FIGURE 2. Optional Trimming of Output Offset Voltage.

INPUT BIAS CURRENT RETURN PATH

The input impedance of the INA114 is extremely high—approximately 60E9. However, a path must be provided for the input bias current of both inputs. This input bias current is typically less than 20nA (it can be either polarity due to cancellation circuitry). High input impedance routes that this input bias current changes very little with varying input voltage.

Input common-mode bias must provide a path for the input bias current if the INA114 is to operate properly. Figure 3 shows various provisions for an input bias current path. Without a bias current return path, the input will have no potential which exceeds the common-mode range of the INA114 and the input amplifiers will saturate if the differential source resistance is low. Bias current return path can be connected to one input (see thermocouple example in Figure 3). With higher source impedance, using two resistors provides a balanced input with possible advantages of lower input offset voltage due to bias current and better common-mode rejection.

![Input Bias Current Return Path](image)


A combination of common-mode and differential input signals can cause the output of A1 or A2 to saturate. Figure 4 shows the output voltage swing of A1 and A2, examined in terms of a common-mode and differential input voltages. Output swing capability of these internal amplifiers is the same as the output amplifiers, A4. For applications where input common-mode range must be maximized, limit the output voltage swing by connecting the INA14 in a lower gain (for performance curve “Input Common-Mode Voltage Range vs Output Voltage”)

![Output Voltage Swing](image)

INPUT COMMON-MODE RANGE

The linear common-mode range of the input op amp of the INA114 is approximately ±1.35V (or 1.25V from the power supplies). As the output voltage increases, however, the linear input range will be limited by the output voltage swing of the input amplifiers, A4 and A5. The common-mode range is related to the output voltage of the complete amplifier—see performance curve “Input Common-Mode Range vs Output Voltage.”

![Input Common-Mode Range](image)

INPUT PROTECTION

The inputs of the INA114 are individually protected for voltages up to ±60V. For example, a condition of ±60V on one input and ±15V on the other input will not cause damage. Internal diodes on each input provide low source impedance under normal signal conditions. To provide equivalent protection, series input resistors would contribute excessive noise. If the input is over-scaled, the protection diodes limits the input current to a safe value approximately 1.5mA. The typical performance curve “Input Bias Current vs Common-Mode Input Voltage” shows the input
B.3 Specifications for INA114 Instrumental Amplifier

Current limit behavior. The inputs are protected even if no power supply voltage is present.

**OUTPUT VOLTAGE SENSE (SOL-16 package only)**

The surface-mount version of the INA114 has a separate output sense feedback connection (pin 12). Pin 12 must be connected to the output terminal (pin 11) for proper operation. This connection is made internally on the DIP version of the INA114.

The output sense connection can be used to sense the output voltage directly at the load for best accuracy. Figure 5 shows how to drive a load through sense interconnection resistance. Remotely located feedback paths may cause instability. This can be generally be eliminated with a high frequency feedback path through $R_1$. Heavy loads or long lines can be driven by connecting a buffer inside the feedback path (Figure 6).

**FIGURE 4. Voltage Swing of $A_1$ and $A_2$.**

**FIGURE 5. Remote Load and Ground Sensing.**

**FIGURE 6. Buffered Output for Heavy Loads.**

**FIGURE 7. Shield Driver Circuit.**
B.3 Specifications for INA114 Instrumental Amplifier

FIGURE 8. RTD Temperature Measurement Circuit.

B.3 Specifications for INA114 Instrumental Amplifier

**FIGURE B.** ECG Amplifier With Right-Leg Drive.

**FIGURE 11.** Bridge Transducer Amplifier.

**FIGURE 12.** AC-Coupled Instrumentation Amplifier.

**FIGURE 13.** Differential Voltage-to-Current Converter.
B.4 Specifications for PCB 112B11 Piezoelectric Sensor

Model 112B11

Product Type: Pressure Transducer, Pressure Sensor

Engine combustion pressure sensor, 3000 psi, 1 pC/psi, cylinder head, flush mount

<table>
<thead>
<tr>
<th>PERFORMANCE</th>
<th>ENGLISH</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity (±25%-10%)</td>
<td>1.0 pC/psi</td>
<td>0.0145 pC/MPa</td>
</tr>
<tr>
<td>Measurement Range</td>
<td>3 kpsi</td>
<td>20,685 kPa</td>
</tr>
<tr>
<td>Maximum Pressure (static)</td>
<td>5 kpsi</td>
<td>34,475 kPa</td>
</tr>
<tr>
<td>Resolution</td>
<td>10 mps/</td>
<td>0.009 kPa</td>
</tr>
<tr>
<td>Resonant Frequency</td>
<td>≥ 200 kHz</td>
<td>2100 kHz</td>
</tr>
<tr>
<td>Rise Time (Reflected)</td>
<td>≤ 3.0 μsec</td>
<td>≤ 3.0 μsec</td>
</tr>
<tr>
<td>Non-Linearity</td>
<td>≤ 2.0% FS</td>
<td>≤ 2.0% FS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ENVIRONMENTAL</th>
<th>ENGLISH</th>
<th>SI</th>
</tr>
</thead>
</table>
| Acceleration Sensitivity | 0.002 psig | 0.0014 kPa (ms²)
| Temperature Range (Operating) | -100 to +600 °F | -73 to +315 °C |
| Temperature Coefficient of Sensitivity | ≤ 0.35%/°F | ≤ 0.03%/°C |
| Maximum Flange Temperature | 4500 °F | 2480 °C |
| Maximum Shock | 10,000 g pk | 98,100 m/s² pk |

<table>
<thead>
<tr>
<th>ELECTRICAL</th>
<th>ENGLISH</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Polarity (Positive Pressure)</td>
<td>Negative</td>
<td>Negative</td>
</tr>
<tr>
<td>Capacitance</td>
<td>20 pF</td>
<td>20 pF</td>
</tr>
<tr>
<td>Insulation Resistance (at room temp)</td>
<td>10⁸ ohm</td>
<td>10⁸ ohm</td>
</tr>
<tr>
<td>(600°F/316°C)</td>
<td>10⁷ ohm</td>
<td>10⁷ ohm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PHYSICAL</th>
<th>ENGLISH</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensing Element</td>
<td>Quartz</td>
<td>Quartz</td>
</tr>
<tr>
<td>Housing Material</td>
<td>Invar</td>
<td>Invar</td>
</tr>
<tr>
<td>Diaphragm</td>
<td>Invar</td>
<td>Invar</td>
</tr>
<tr>
<td>Sealing</td>
<td>Welded Hermetic</td>
<td>Welded Hermetic</td>
</tr>
<tr>
<td>Electrical Connector</td>
<td>10-32 Coaxial Jack</td>
<td>10-32 Coaxial Jack</td>
</tr>
<tr>
<td>Weight (with clamp nut)</td>
<td>0.2 oz</td>
<td>0.0 gm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SUPPLIED ACCESSORIES:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model OECAS5 Clamp nut, 5/16-24 A thd, 1/4&quot; hex, stainless steel (1)</td>
</tr>
<tr>
<td>Model OEGAS5 Seal sleeve sensor recess mount 0.240&quot; OD x 0.221&quot; ID x 0.240&quot; thick (1)</td>
</tr>
<tr>
<td>Model OEGAS5 Seal, 250° OD x 216° ID x 0.015°, 316L (3)</td>
</tr>
<tr>
<td>Model UCSAS3 Spacer, 240&quot; OD x 0.221&quot; ID x 0.25&quot; thick, 17-4PH (1)</td>
</tr>
<tr>
<td>Model UCSAS3 Spacer, 240&quot; OD x 0.221&quot; ID, 17-4PH (1)</td>
</tr>
<tr>
<td>Model UCSAS4 Spacer, 240&quot; OD x 0.221&quot; ID, ST 31L (1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OPTIONAL VERSIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>M - Metric Mount</td>
</tr>
<tr>
<td>P - Positive Output Polarity</td>
</tr>
</tbody>
</table>

All specifications are at room temperature unless otherwise specified.

NOTES:
(1) Resolution dependent on range setting and cable length used in charge system.
(2) Zero-based, least-squares, straight line method.
B.5 Specifications for Encoder Optical Sensor

A slotted opto-switch comprising an infra-red source and integrated photodetector. The i.c. photodetector consists of a photodiode, amplifier, voltage regulator, Schmitt trigger and output stage. An important feature is its wide supply voltage range, +4.5 V to 16 V, which allows the output to interface directly to TTL, LS/TTL and C-MOS. The detector can sink 10 TTL loads when the infra-red beam is interrupted. The output rise and fall times are independent of object speed and the integrated voltage regulator ensures high noise immunity. Applications include position detection, paper sensing, counting, optical encoding and level sensing. Operating temperature range: -40°C to +100°C.

<table>
<thead>
<tr>
<th>Technical Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>diode</strong></td>
</tr>
<tr>
<td>( V_{ph} ) max. (at ( I_p = 29 \text{mA} ))</td>
</tr>
<tr>
<td>( V_{ph} ) max.</td>
</tr>
<tr>
<td>( I_p ) max. (cont.)</td>
</tr>
<tr>
<td><strong>photodetector</strong></td>
</tr>
<tr>
<td>Operating supply voltage range</td>
</tr>
<tr>
<td>Max. dissipation</td>
</tr>
<tr>
<td>Output sink current</td>
</tr>
<tr>
<td>Operating current</td>
</tr>
<tr>
<td><strong>coupled</strong></td>
</tr>
<tr>
<td>Propagation delay times</td>
</tr>
<tr>
<td>(high to low, or low to high)</td>
</tr>
<tr>
<td>Output rise times</td>
</tr>
<tr>
<td>Output fall time</td>
</tr>
<tr>
<td>Max. operating frequency</td>
</tr>
</tbody>
</table>

RS Data Sheet No. 232-2447, Mar 97 is available.

<table>
<thead>
<tr>
<th>Stock no.</th>
<th>price each ( A $ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-24</td>
<td>18.10</td>
</tr>
<tr>
<td>25-99</td>
<td>13.60</td>
</tr>
</tbody>
</table>

**opto-switch**

394-560
Appendix C

MATLAB Scripts and Functions

Appendix C Contents

Load_cal2.m 120
Temp_cal2.m 122
Shock_analysis2.m 126
P_T_reflected.m 132
Fill_Time.m 133
Psd_display.m 134
Gt28_analysis2.m 135
Engine_1.m 137
Engine_2.m 142
C.1 MATLAB Scripts and Functions

The following MATLAB (version 6) programs are scripts and functions that were used to analyse the experimental data.

Listing C.1: Load_cal2.m

```matlab
function [span, offset] = load_cal2(file_name, nrows, ncolumns, Vs, p1, doplots)....
    load_cal2.m
    % Function for determining the Span and Offset
    % from a set of calibration data (from the Dead Weight tester)
    % INPUTS –
    % file_name – file name of calibration data (eg cal.txt)
    % nrow – numbers of rows of calibration (number of pressures tested)
    % ncolumn – number of columns of data (usually 2 or 3)
    % Vs – supply voltage to calibration
    % p1 – atmospheric pressure during calibration
    % doplots – 1 if plots required, 0 if not
    % OUTPUTS
    % span – matrix of span values
    % offset – matrix of offset values
    %
    % Data layout in calibration file as follows –
    % column 1, pressure in PSI
    % column 2, Vout
    % column 3 (optional), Vout (decreasing pressure)
    N = 1; %linear fit
    
    % Remove text from data file (data column headings)
    fid=fopen(file_name);
    fscanf(fid, '%s', ncolumns);
    for i = 1:nrows,
        for j = 1:ncolumns,
            num(i,j)=fscanf(fid, '%f', 1);
        end
    end
    
    % Convert calibration pressures from psi to Pa
    x = num(:,1).*6894.8 + p1; %convert pressure to Pa (absolute)
    
    % Linear regression for 1st set of data (increasing pressure)
    y1 = num(:,2);
    [P1] = POLYFIT(x, y1, N);
    offset1 = P1(2)/Vs; %mV/V
    span1 = P1(1)/Vs; %mV/V
    span(1,1) = span1; %span of first set of data (up)
    offset(1,1) = offset1; %offset of first set of data (up)
    
    % Linear regression if 2nd set of data (decreasing pressure)
    if ncolumns>2,
        y2 = num(:,3);
        [P2] = POLYFIT(x, y2, N);
        offset2 = P2(2)/Vs; %mV/V
        span2 = P2(1)/Vs; %mV/V
        span(1,2) = span2; %span of second set of data (down)
        offset(1,2) = offset2; %offset of second set of data (down)
    end
    % Average Span and Offset
```
C.1 MATLAB Scripts and Functions

\[
y_3 = [y_1; y_2]; \\
x_3 = [x; x]; \\
\{P_3\} = \text{POLYFIT}(x_3, y_3, N); \\
\text{offset}_3 = P_3(2)/V_s; \% \text{mV/V} \\
\text{span}_3 = P_3(1)/V_s; \% \text{mV/V-\text{pa}} \\
\text{span}(1,3) = \text{span}_3; \% \text{average span (up and down)} \\
\text{offset}(1,3) = \text{offset}_3; \% \text{average offset (up and down)}
\]

end

\% Give calibration plots if required
if doplots
  figure(1)
  \text{plot}(x, y_1, 'o', x, \text{polyval}(P_1, x))
  \text{title}('Calibration with increasing pressure')
  \text{xlabel}('Pressure (\text{Pa})')
  \text{ylabel}('Sensor Output (mV)')
  \%text(1e5, -150, \{\text{num2str}(P_1(1)), 'mV/\text{Pa}'\});
  if ncolumns>2
    figure(2)
    \text{plot}(x, y_2, 'o', x, \text{polyval}(P_2, x))
    \text{title}('Calibration with decreasing pressure')
    \text{xlabel}('Pressure (\text{Pa})')
    \text{ylabel}('Sensor Output (mV)')
    \%text(1e5, -150, \{\text{num2str}(P_2(1)), 'mV/\text{Pa}'\});
    figure(5)
    \text{plot}(x_3, y_3, 'o', x_3, \text{polyval}(P_3, x_3), 'm');
    hold on
  end
end
% Script to determine the temperature effects on the 13U0500 piezoresistive pressure sensor

% Data on previous sensor calibrations:
% 13U0500_1.txt @ approx 22.0 deg C av. Vsense = 91.8mv
% 13U0500_2.txt @ approx 53.0 deg C av. Vsense = 856mv
% 13U0500_3.txt @ approx 100.5 deg C av. Vsense = 1957mv
% 13U0500_4.txt @ approx 138.5 deg C av. Vsense = 2885mv

% Allocate test temperatures
temp1 = 273 + 22;
temp2 = 273 + 53;
temp3 = 273 + 100.5;
temp4 = 273 + 138.5;
TEMP = [temp1 temp2 temp3 temp4];  % K

% Allocate average values for Vsense for each test
Vsense = [91.8 856 1957 2885];  % mv

% Average atm pressure
p1 = 9.38e4;  % Pa

% Determine the actual sensor supply voltage
Vs1 = 15 - Vsense(1)/1000;
Vs2 = 15 - Vsense(2)/1000;
Vs3 = 15 - Vsense(3)/1000;
Vs4 = 15 - Vsense(4)/1000;

% Correct Vsense for circuit supply voltage (total 30V)
Vsense_new = [Vsense(1)/30 Vsense(2)/30 Vsense(3)/30 ....
Vsense(4)/30];

% Load Span and Offset for each calibration
[span1, offset1] = load_cal2('13U0500_1.txt', 8, 3, Vs1, p1, 0);
[span2, offset2] = load_cal2('13U0500_2.txt', 8, 3, Vs2, p1, 0);
[span3, offset3] = load_cal2('13U0500_3.txt', 8, 3, Vs3, p1, 0);
[span4, offset4] = load_cal2('13U0500_4.txt', 8, 3, Vs4, p1, 0);

% Plot Span against temperature
temp_span = [span1(3) span2(3) span3(3) span4(3)];
figure(1);
plot(TEMP, temp_span, 'b', TEMP, temp_span, 'r*');
hold on

% Plot Offset against temperature
temp_offset = [offset1(3) offset2(3) offset3(3) offset4(3)];
figure(2);
plot(TEMP, temp_offset, 'b', TEMP, temp_offset, 'r*');
hold on

figure(4)
plot(TEMP, temp_offset, 'b', TEMP, temp_offset, 'r*');
hold on

% Determine Span temperature sensitivity (linear)
N = 1;
[Pspan] = POLYFIT(TEMP, temp_span, N);
dspan = Pspan(1);  % (mV/V.Pa)/C

% Plot linear regression of Span against data points
figure(1);
plot(TEMP, Pspan(1)+Pspan(2)*TEMP, 'r')
ttitle('Relationship between Span and Temperature')
ylabel('Span (mV/V.Pa)')
xlabel('Temperature (K)')
hold off

% Determine Offset temperature sensitivity
[Poffset] = POLYFIT(TEMP,temp_offset,2);
doffsetdt = Poffset(1); % (mV/V)/C
figure(2);
% plot(TMP,Poffset(3)+Poffset(2)*TMP+Poffset(1)*TMP.^2,'r')
title('Relationship between Offset and Temperature')
ylabel('Offset (mV/V)')
xlabel('Temperature (K)')
hold off

% Determine Offset temperature sensitivity (linear) – up to approx 370K
[Poffset2] = POLYFIT(TEMP(1:3),temp_offset(1:3),1);
doffsetdt2 = Poffset2(1);
% Plot linear regression of Offset against data points
figure(4);
plot(TEMP(1:3),Poffset2(2)+Poffset2(1)*TEMP(1:3),'r')
hold off

% Plot Vsense and temperature
figure(3)
plot(TEMP,Vsense_temp_new,'b',TEMP,Vsense_temp_new,'r')
hold on
% Determine Vsense temperature sensitivity (linear)
[PVsense] = POLYFIT(TEMP,Vsense_temp_new,N);
% Plot linear regression of Vsense against data points
% plot(TEMP,PVsense(2)+PVsense(1)*TEMP,'r')
title('Relationship between Vsense and Temperature')
ylabel('Vsense(mV/V)')
xlabel('Temperature (K)')
hold off
dVsensedt = PVsense(1); % mV/V

%==========================================================================
% Calculate the errors associated with
temperature compensation
% Initialize the Vout matrix
Vout = zeros(8,1);
% Step through the calibration data for each temperature
for i=1:4

% Load calibration data
eval(['file_name=' '13U0500_z',int2str(i),'.txt'';'])
 fid=fopen(file_name);
 fscanf(fid,'%s',3);
 for i=1:8,
   for j=1:3,
     num(i,j)=fscanf(fid,'%f',1);
   end
 end
% Convert calibration pressures from psi to Pa
num(:,1) = num(:,1).*6894.8 + p1; % Pa

% Define pressures and related Vout
% Test Pressures
x = num(:,1); % Pa
% Vout - increasing pressure
y1 = num(:,2);
% Vout - decreasing pressure
y2 = num(:,3);
% Vout - average
y3 = (y1+y2)/2;
% Record values of Vout
Vout = [Vout y3];
end
% Trim zeros from Vout matrix
Vout = Vout(:,(2:5));
% Calculate uncompensated pressure values (Pa abs)
% use approximate Span and Offset from 25 deg C
span25 = span1(3) + Ps from (1)*3 \( \text{mV/V, Pa} \)
offset25 = interp1([273 TEMP],[1.56897 temp_offset],[(273+25), 'linear'])

% Supply voltage for each test is different (due to Vsense)
pressures_uncomp(1) = (Vout(:,1) - offset25*V) / (span25 * Vs1); \( \% \text{Pa} \)
pressures_uncomp(2) = (Vout(:,2) - offset25*V) / (span25 * Vs2); \( \% \text{Pa} \)
pressures_uncomp(3) = (Vout(:,3) - offset25*V) / (span25 * Vs3); \( \% \text{Pa} \)
pressures_uncomp(4) = (Vout(:,4) - offset25*V) / (span25 * Vs4); \( \% \text{Pa} \)

Vsense25 = Psense2 + Psense1 * 298
Vsense_temp = [91.8 856 1957 2885]
temp1 = ((91.8/30) - Vsense25) / dVse end + 25
temp2 = ((856/30) - Vsense25) / dVse end + 25
temp3 = ((1957/30) - Vsense25) / dVse end + 25
temp4 = ((2885/30) - Vsense25) / dVse end + 25

span1 = span25 + Ps from (1)*temp1 - 25
span2 = span25 + Ps from (1)*temp2 - 25
span3 = span25 + Ps from (1)*temp3 - 25
span4 = span25 + Ps from (1)*temp4 - 25

offset1 = interp1([273 TEMP],[0.5155 temp_offset],[(temp1+273), 'linear'])
offset2 = interp1([273 TEMP],[0.5155 temp_offset],[(temp2+273), 'linear'])
offset3 = interp1([273 TEMP],[0.5155 temp_offset],[(temp3+273), 'linear'])
offset4 = interp1([273 TEMP 420],[0.5155 temp_offset 1.0875],[(temp4+273), 'linear'])

% Calculate compensated pressure values (Pa abs)
pressures_comp(1) = (Vout(:,1) - offset1*V) / (span1*Vs1); \( \% \text{Pa} \)
pressures_comp(2) = (Vout(:,2) - offset2*V) / (span2*Vs2); \( \% \text{Pa} \)
pressures_comp(3) = (Vout(:,3) - offset3*V) / (span3*Vs3); \( \% \text{Pa} \)
pressures_comp(4) = (Vout(:,4) - offset4*V) / (span4*Vs4); \( \% \text{Pa} \)

% Determine difference between predicted and actual pressure
% (uncompensated) - percentage FS
error_uncomp1 = ((x) - pressures_uncomp(:,1)) / (500*6894.8 + p1) * 100;
error_uncomp2 = ((x) - pressures_uncomp(:,2)) / (500*6894.8 + p1) * 100;
error_uncomp3 = ((x) - pressures_uncomp(:,3)) / (500*6894.8 + p1) * 100;
error_uncomp4 = ((x) - pressures_uncomp(:,4)) / (500*6894.8 + p1) * 100;

% Determine difference between predicted and actual pressure
% (compensated) - percentage FS
error_comp1 = ((x) - pressures_comp(:,1)) / (500*6894.8 + p1) * 100;
error_comp2 = ((x) - pressures_comp(:,2)) / (500*6894.8 + p1) * 100;
error_comp3 = ((x) - pressures_comp(:,3)) / (500*6894.8 + p1) * 100;
error_comp4 = ((x) - pressures_comp(:,4)) / (500*6894.8 + p1) * 100;

% Convert pressures to percentage FS
pressures = (x) / (500*6894.8 + p1) * 100;

% Plot uncompensated errors
figure(5)
plot(x, error_uncomp1, 's', x, error_uncomp2, 's', pressures,...
     error_uncomp3, 'd', pressures, error_uncomp4, 'd')
axis([0 100 -15 5]);
grid on
legend('22.0 C', '53.0 C', '100.5 C', '138.5 C', '3');
title('Errors Before Temperature Compensation');
ylabel('Pressure Error (%FS)');
xlabel('Pressure (%FS)');

% Plot compensated errors
figure(6)
plot(x, error_comp1, 's', x, error_comp2, 's', pressures,...
     error_comp3, 'd', pressures, error_comp4, 'd')
axis([0 100 -5 5]);
GRID on
Legend('22.0 C', '53.0 C', '100.5 C', '138.5 C', 3);
Title('Errors After Temperature Compensation');
ylabel('Pressure Error (%FS)');
xlabel('Pressure (%FS)');
Listing C.3: Shock_analysis2.m

% shock_analysis2.m
% Script for analysis of Shock Tube data using the piezoresistive SX150AHO pressure sensor

% Summary of Shock Tube Tests -
% 9 10 11 12 13 14 15 16 ....
% Pburst= [430 570 565 395 555 505 568 545 ....
% 485 460 560 440 460 430 475 595 ....
% 420]; % gauge kPa

Patm= [700.30 700.30 709.45 709.45 705.45 705.45 705.45 ....
% 706.10 706.10 706.10 701.05 701.05 701.05 701.05 ....
% 701.05 701.05]*133.22368 % atm. pressure in Pa

Tamb= [21.2 21.2 22.8 22.8 18.5 18.5 18.5 18.3 ....
% 20.0]; % degC best estimate of st lab temperature

Cal= [1 2 3 3 4 5 6 7 7 7 8 8 9 ....
% 9 ]; % number corresponding to calibration number (eg 1 = calibration sx150_1)

% pz_st_9 tested with medium grease – calibration for thin grease used
% pz_st_12 tested with thin grease – calibration for no grease used (cal 7)
% pz_st_13 tested with thin grease – calibration for no grease used (cal 7)

% Temp and Pressure (atm) for 16 and 17 were assumed from previous tests – no data taken during testing

% 1 = unmodified pressure transducer
% 2 = stock sensor with top cut off (physically a different sensor to case 1 ?)
% 3 = top off, epoxy added, but wires still exposed (physically .... different to 1 and 2)
% 4 = top off, epoxy added, wires covered (physically different sensor ....
% to 1, 2, and 3)
% 5 = sensor 4 with thin layer grease (about 1mm thick)
% 6 = sensor 5 with thickest layer of grease (filling up to sensor lip)
% 7 = sensor from 2 with thin layer of latex added
% 8 = sensor 7 with grease filling up to sensor lip
% 9 = sensor with margarine (made thinner with additional canola oil) ....
% filled to top

% Voltage drop across bridge

Vexcite=ones(1,17)*12; Vexcite(1)=12.4; % V

% No. cellophane diaphragms

Ndiaphragms=ones(1,17)*4; Ndiaphragms(1)=3;

% Arrangement of data in text files from wavestar

numrows=2500; ncolumns=12;

% Distances between pressure sensors

dx1,2=0.6935; % m

dx2,3=0.1735+0.003; % m (taking into account the distance from the front.... of the plate to the silicon chip)

% If shock speeds need to be redetermined let findshockspeeds = 1

findshockspeeds=1;

% All data in files pz_st_x where x=1:15 consists of 12 columns of the .... following variables
% columns 1 to 8 long time base
% columns 9 to 12 short time base
% 1 = time (long)
% 2 = piezoelectric 1
if findshockspeeds
    % Step through each shock tube test (1 to 17)
    for i = 1:17,
        % Load shock tube test data
        data = load_wavestar_2(file_name, nRows, nColumns);
        % Locate shock arrival times at each pressure sensor
        % Piezoelectric 1
        figure(1);
        plot(data(:,2));
        title('heading=' 'pz_st_' int2str(i) 'A'; ');
        zoom on;
        pause
        % Shock time at piezoelectric 1
        nt1 = round(nt1);
        % Piezoelectric 2
        plot(data(:,4));
        title('heading=' 'pz_st_' int2str(i) 'B'; ');
        zoom on;
        pause
        % Shock time at piezoelectric 2
        nt2 = round(nt2);
        % Piezo resistive (long time scale)
        plot(data(:,6));
        title('heading=' 'pz_st_' int2str(i) 'C'; ');
        zoom on;
        pause
        % Shock time at piezo resistive long time scale
        nt3 = round(nt3);
        % Piezo resistive (short time scale)
        plot(data(:,10));
        title('heading=' 'pz_st_' int2str(i) 'D'; ');
        zoom on;
        pause
        % Shock time at piezo resistive short time base
        nt3s = round(nt3s);
        % Time of flight for shock
        dt1 = data(nt2,1)-data(nt1,1);
        % Find velocities
        us1 = dx1_2/dt1;
        us2 = dx2_3/dt2;
        % Determine approximate shock speed at piezo resistive sensor
        us_coeff = polyfit ([data(nt1,1) data(nt2,1) data(nt3,1)],...(dx1_2+...
            dx2_3 -dx2_3 0],2);
        usp = 2*us_coeff(1)*data(nt3,1)+us_coeff(2); %m/s
        % Ambient temperature
        T1 = Tamb(i)+273; %K
    end
end
% Determine shock pressures, temperatures and mach numbers
% for each possible shock speed
\[\begin{align*}
[p_{5\text{us1}}, T_{5\text{us1}}, M_{5\text{us1}}, M_{r\text{us1}}] &= p_{\text{T reflected}}(\text{Patm}(i), T_{1\text{us1}}); \\
[p_{5\text{us2}}, T_{5\text{us2}}, M_{5\text{us2}}, M_{r\text{us2}}] &= p_{\text{T reflected}}(\text{Patm}(i), T_{1\text{us2}}); \\
[p_{5\text{usp}}, T_{5\text{usp}}, M_{5\text{usp}}, M_{r\text{usp}}] &= p_{\text{T reflected}}(\text{Patm}(i), T_{1\text{usp}});
\end{align*}\]

% Load calibration data for related pressure sensor
\[
eval({'file_name2=' 'sx150AHO', 'int2str(Cal(i))', '.txt' '});
\]
\[
[\text{Span(Cal(i),:)}, \text{Offset(Cal(i),:)}] = \text{load_cal2(file_name2, 15, 3, ...}
\]
\[
\text{Vexcite(i), Patm(i), 0)};
\]

% Find zero level and apply sensitivity to piezoresistive sensor
sensitivity=(\text{Span(Cal(i),:)}\times \text{Vexcite(i)}+1e-3; \% V/Pa
\]
\[
\text{pz_long}=(\text{data(:,6)}-\text{mean(data(1:nt3,6))})/\text{sensitivity}+\text{Patm(i); \%Pa}
\]
\[
\text{pz_short}=(\text{data(:,10)}-\text{mean(data(1:nt3s,10))})/\text{sensitivity}+\text{Patm(i); ...}
\]

% Create time variables
t_long=data(:,1);
t_short=data(:,9);

% Smooth piezoresistive data (short time scale)
\[
\text{pz_short_smo} = \text{smo(pz_short,20)};
\]

% Graph 1 – short time, compare exp. with theo. results
\[
\text{figure(3)}; \\
\text{plot(t_short-t_short(nt3s), pz_short,'b')};
\]

% Determine average shock pressure according to shock test number
if i<3
\[
\text{p5_av_short} = \text{mean(pz_long((nt3+75):(nt3+100))) \% 4 us steps...}
\]
\[
(500us to 400 us)
\]
end
if i>=2 & i<14
\[
\text{p5_av_short} = \text{mean(pz_short((nt3s+500):(nt3s+1000))) \%0.1 us...}
\]
\[
data steps (50us to 100us)
\]
end
if i>=14
\[
\text{p5_av_short} = \text{mean(pz_short((nt3s+1600):(nt3s+2000))) \%0.1 ....}
\]
\[
us data steps (p2_st_14 & p2_st_15 have a much slower .... response) (160us to 210us)
\]
end

% Compare actual and estimated reflected shock pressures
\[
\text{plot([0 p5_us1 p5_us1]','m--',[0 t_short(ntrows)],}
\]
\[
[0 p5_us2 p5_us2]','r--',[0 t_short(ntrows)],[0 p5_us3],',',
\]
\[
[0 t_short(ntrows)],[p5_av_short p5_av_short],'b--'); \\
\text{plot(t_short-t_short(nt3s),pz_short_smo,'k');}
\]

AXIS tight
if i<3
\[
\text{Legend('Pressure from SX150AHO', 'P5 from US1', 'P5 from US2', ....}
\]
\[
'P5 from USP', 'P5 average(300us to 400us) ', 'Smoothed ....}
\]
\[
ouptut from SX150(AHO)',4);}
end
if i>=2 & i<14
\[
\text{Legend('Pressure from SX150AHO', 'P5 from US1', 'P5 from US2', ....}
\]
\[
'P5 from USP', 'P5 average(50us to 100us) ', 'Smoothed ....}
\]
\[
ouptut from SX150(AHO)',4);}
end
if i>=14
\[
\text{Legend('Pressure from SX150AHO', 'P5 from US1', 'P5 from US2', ....}
\]
\[
'P5 from USP', 'P5 average(160us to 200us) ', 'Smoothed ....}
\]
\[
ouptut from SX150(AHO)',4);}
end
\[
eval(['\text{axistight}'])
\]
\[
\text{Ttitle('heading')}
\]
\[
\text{ylabel('Pressure (Pa)')} \\
\text{xlabel('Time (s)')} \\
\text{eval(['\text{axistight}'])}
\]

C.1 MATLAB Scripts and Functions 128
CD Graphs;
% Save plot image
saveas(3, graphname, 'jpg');
saveas(3, graphname, 'eps');
cd('..');
hold off;
pause

% Graph 2 - short time, find rise time from
% 10% (green) to 90% (red) of average pressure (blue)
figure(4);
plot(t_short-t_short(nt3s), pz_short, 'b', t_short-t_short(nt3s), ...
    pz_short, smo, 'k');
AXIS tight
Legend('Pressure from SX150AHO', 'Smoothed output from SX150AHO'....
    ', 4)
eval(['heading=' 'Pressure vs Time for pz \_st\_\_' , int2str(i) , ' - ....
    Graph for Determining Rise Time'' ; ']);
Title(heading)
ylabel('Pressure (Pa)')
xlabel('Time (s)')
pause
hold on;
plot([-2.5e-5 t_short(nrows)], [p5_av_short p5_av_short], 'b--'....
    ; [-2.5e-5 t_short(nrows)], [0.9*(p5_av_short-Patm(i))+Patm(i)....
    0.9*(p5_av_short-Patm(i))+Patm(i)], 'r--');
if i<3
    Legend('Pressure from SX150AHO', 'Smoothed output from ....
    SX150AHO', 'P5 average(300us to 400us)', '90% of P5 ....
    average', '4');
end
if i>2 & i<14
    Legend('Pressure from SX150AHO', 'Smoothed output from ....
    SX150AHO', 'P5 average(50us to 100us)', '90% of P5 average....
    ', 4);
end
if i>=14
    Legend('Pressure from SX150AHO', 'Smoothed output from ....
    SX150AHO', 'P5 average(160us to 200us)', '90% of P5 ....
    average', '4');
end
zoom on;
pause

% Select point where Blue line first crosses Red
[rise_upper, dummy]=ginput(1);
plot([-2.5e-5 t_short(nrows)], [0.1*(p5_av_short-Patm(i))+Patm(i)....
    0.1*(p5_av_short-Patm(i))+Patm(i)], 'g--');
if i<3
    Legend('Pressure from SX150AHO', 'Smoothed output from ....
    SX150AHO', 'P5 average(300us to 400us)', '90% of P5 ....
    average', '10% of P5 average', '4');
end
if i>2 & i<14
    Legend('Pressure from SX150AHO', 'Smoothed output from ....
    SX150AHO', 'P5 average(50us to 100us)', '90% of P5 average....
    ', '10% of P5 average', '4');
end
if i>=14
    Legend('Pressure from SX150AHO', 'Smoothed output from ....
    SX150AHO', 'P5 average(160us to 200us)', '90% of P5 ....
    average', '10% of P5 average', '4');
end
zoom on;
pause

% Select point where Blue line first crosses Green
[rise_lower, dummy]=ginput(1);
rise_time=rise_upper-rise_lower;
eval(['graphname=' 'pz\_st\_\_' , int2str(i) , ' 2' '; ']);
AXIS tight
CD Graphs;
% Save plot image
% Graph 3 — long time, compare exp. with theo results
% for P5 (P5 average from 0.5 to 1.5 ms)
figure (5);
plot(t_long-t_long(nrows),pz_long,'b');
p5_av_long = mean(pz_long((nt3+125):(nt3+375)));
hold on;
plot([0 t_long(nrows)],[p5_us1 p5_us1],'y--',[0 t_long(nrows)],[p5_us2 p5_us2],'r--',
    [0 t_long(nrows)],[p5_usp p5_usp],'g--',
    [0 t_long(nrows)],[p5_av_long p5_av_long],'b--');

AXIS tight
Legend('Pressure from SX150AHO','P5 from US1','P5 from US2',
      'P5 from USP','P5 average (0.5 ms to 1.5 ms)');
Title(heading);
ylabel('Pressure (Pa)');
xlabel('Time (s)');
eval(['graphname=','pz_st_','int2str(i)','_3'';''']);
AXIS tight

% Save data for shock tube test
eval(['save pz_st_','int2str(i)',';''']);
pause
% Save specific variable in 'test_data' matrix
if num2str(i) == num2str(15)
    test_data(i,1) = p5_us1; %Pa
    test_data(i,2) = p5_us2; %Pa
    test_data(i,3) = p5_usp; %Pa
    test_data(i,4) = p5_av_short; %Pa
    test_data(i,5) = p5_av_long; %Pa
    test_data(i,6) = rise_time; %s
end

% Save 'test_data' matrix
save test_data test_data -ascii -tabs;
save test_data test_data;
end

% In saved files (pz_st_x where x=1:15) the following values are ....
% included —
% us1 — shock speed from piezoelectric 1 to piezoelectric 2
% us2 — shock speed from piezoelectric 2 to piezoresistive sensor
% usp — Polynomial fit (second order) to displacement and time — speed =....
% slope at time of shock impact
% p5_us1 — pressure after reflected shock wave (based on us1)
% p5_us2 — pressure after reflected shock wave (based on us2)
% p5_usp — pressure after reflected shock wave (based on usp)
% T5_us1 — temperature after reflected shock wave (based on us1)
% T5_us2 — temperature after reflected shock wave (based on us2)
% T5_usp — temperature after reflected shock wave (based on usp)
% Ms_us1 — Mach number of incident shock wave (based on us1)
% Ms_us2 — Mach number of incident shock wave (based on us2)
% Ms_usp — Mach number of incident shock wave (based on usp)
% Mr_us1 — Mach number of reflected shock wave (based on us1)
% Mr_us2 — Mach number of reflected shock wave (based on us2)
% Mr_usp — Mach number of reflected shock wave (based on usp)
% p5_av_short — average pressure from sensor from 0.5 to 1.5 ms
% p5_av_long — average pressure from sensor from 0.5 to 1.5 ms
rise_time - time for signal (short) to rise from 10% to 90% of ....
p5_av_short
function [p5, T5, Ms, Mr] = p_T_reflected(p1, T1, us)

% The function is used in conjunction with functions developed by Dr. David Buttsworth

% INPUTS –
% p1 – atmospheric pressure, Pa
% T1 – testing temperature (air), K
% us – inbound shock speed, m/s

% OUTPUTS
% p5 – reflected shock pressure, Pa
% T5 – reflected shock temperature, K
% Ms – inbound shock Mach number
% Mr – reflected shock Mach number

% Determine gas properties within shock tube

g = 1.4;
R = 287;
a1 = sqrt(g*R*T1);
Ms = us/a1;
p2p1 = p2onp1s(Ms, g);
T2T1 = T2onT1(p2p1, g);
Mr = mreflect(Ms, g);
p5p2 = p2onp1s(Mr, g);
T5T2 = T2onT1(p5p2, g);
p5 = p5p2 + p2p1 + p1
T2 = T2T1 + T1
T5 = T5T2 + T2T1 + T1

% u2 = vel2(p2p1, a1, g)
% Fill_Time.m

% Script for calculating and plotting the filling time of a stock SX150AHO sensor

%===========================================================

% Determine filling characteristics of unmodified sensors
% (pz_st_1 and pz_st_2)

% Step through shock tube tests 1 and 2
for i = 1:2
    cd('./')
eval(['load pz_st_', int2str(i), ';']);
cd FillTime

    % Due to the limits of the interpolation tables, % T5_usp must not exceed 433 K
    if i == 2
        T5_usp = 433
    end

    % Run filling routine 'sx150_fill.m' -- originally created by Dr. David Buttsworth. Certain values within this script
    % (e.g. inlet area) were changed to match the sensor
    % dimensions

    % To simulate possible effects of the shock wave, the value of % 'pTube0' (initial pressure) in 'sx150_fill.m' was altered

    sx150_fill;
    R = 297;
    Vol = (0.0074^2*pi/4)*0.0041 - 0.0016*0.00317^2;

    % Plot fill time and compare with recorded sensor pressures
    figure(6);
    plot(t_short-t_short(nt3s),pz_short,'b');
    hold on;
    p5_av_short = mean(pz_long((nt3+75):((nt3+100))) % (300us to 400us)
    plot([0 t_short(nrows)],[p5_us1 p5_us1], 'm--', [0 t_short(nrows)],[p5_us2 p5_us2], 'r--', [0 t_short(nrows)],[p5_av_short p5_av_short], 'b--');
    plot(t_short-t_short(nt3s),pz_short_smo,'k');
    AXIS tight
    plot(T,X(:,1)*R.*X(:,2)/Vol,'r');
xlabel('Time (s)');
ylabel('Pressure (Pa)');
eval(['heading=':''Pressure vs Time for px\_st\_' int2str(i) ',''']);
Comparison of Experimental and Theoretical Results'';'']);
Title(heading)
eval(['graphname=':''pz_st_' int2str(i) ',''6''']);
Legend('Pressure from SX150AHO','P5 from US1','P5 from US2','P5 from....
        USP','P5 average (300us to 400us))','Smoothed output from ....
        SX150AHO','Theoretical Filling Pressure''',4);
cd('...');
cd Graphs;
% Save plot images
saveas(6,graphname,'jpg');
saveas(6,graphname,'eps');
cd('...');
cd FillTime;
hold off;
pause

clear

end
C.1 MATLAB Scripts and Functions

Listing C.6: Psd_display.m

% psd_display.m
% Script for analysis of resonant frequencies of shock tube data
% Performs a power spectrum density analysis of data

%%
% Step through each shock tube test (1 to 17)
for i=1:17
  % Load shock tube test data
  eval(['load pz_st_'.int2str(i).';']);
  % Smooth piezoresisitive sensor response (to eliminate high frequency ....
  % signal noise)
  smoothed = smo(pz_short(nt3s:(length(pz_short))),5);
  % Switch directory to preform PSD analysis
  cd external;
  % Plot PSD (psd.m is a MATLAB produced script)
  figure(6); psd(smoothed,3000,1e7);
  eval(['heading='Power Spectrum Density for pz\_st\_'.int2str(i).',(...
      smoothing = 5 points)'';']);
  Title(heading);
  zoom on;
  pause;
  hold on;
  % Select obvious peak of PSD
  % If no obvious frequency present - input 0 Hz
  [freq1,dummy]=input(1); freq1=round(freq1);
  plot(freq1,dummy,'go')
  zoom out;
  hold off;
  % Save PSD Plot
  eval(['graphname='''pz_st_'.int2str(i).'_4'';']);
  cd ('..');
  saveas(6,graphname,'jpg');
  saveas(6,graphname,'eps');
  % Save PSD plot with more appropriate axes
  axis([0 5e5 60 150]);
  eval(['graphname='''pz_st_'.int2str(i).'_5'';']);
  saveas(6,graphname,'jpg');
  saveas(6,graphname,'eps');
  cd ('..');
  % Record resonant frequency
  frequencies(i)=freq1
end
% save set of resonant frequencies
save frequencies frequencies -ascii -tabs;
save frequencies frequencies;
Listing C.7: Gt28_analysis2.m

% g28_analysis2.m
% Script for comparing the Gun Tunnel pressures
% recorded with the piezoelectric (112B11) and
% piezoresistive (13U3000) sensors

% Load Gun Tunnel Data
data = load_wavestar_2('gt28.txt',2500,10);

% Piezoelectric recorded as column 2, column 10
% Piezoresistive recorded as column 4 (pressure) column 6 (temperature) ....
column 8

% Average atmospheric pressure:
p1 = 9.38e4;

% Assign times from experimental data
tim1 = data(:,1);
tim2 = data(:,7);
pze1 = data(:,2)*10;
pze2 = data(:,10)*10; % factor of 10 because:
  % Kistler charge amp set up with 149.7pC/MPa (deadweight tested 29/4/04)....
  % and 10MPa/V output
  
% But note that manufacturer's calibration data for this transducer is:
% 1.058pC/psi (for 0~300psi) = 157.8 pC/MPa and
% 1.107pC/psi (for 0~3000psi) = 160.6 pC/MPa

% For a given pressure, the transducer produces a given charge (in pC),
% but if we have specified a sensitivity in pC/MPa that is less than the....
% real value,
% we will overestimate the pressure proportionately.

% If the manufacturer's value is actually correct, we should make this ....
% adjustment:
pze1 = pze1*149.7/157.8 + p1/1e6;
pze2 = pze2*149.7/157.8 + p1/1e6;

% calculate pressure from piezoresistive sensor
pzr = -(data(:,8)-mean(data(1:200,8)))/(1.786e-3*15)+p1/1e6; % Pa (abs)

% Smooth data for Vsense
pzrT = smo((data(:,6).*1000),100);

% Plot piezoelectric and raw piezoresistive pressure data
figure(1)
plot(tim2,pzr,'r',tim1,pze1,'g')
xlabel('time (s)')
ylabel('Abs. Pressure (MPa)')
title('Gun Tunnel (Test 28), Barrel pressure with closed end')
legend('Piezoresistive Reading','Piezoelectric Reading')

% Plot piezoelectric and smoothed piezoresistive data
figure(2)
plot(tim1,pze1,'g',tim2,pzrT,'r')
xlabel('time (s)')
ylabel('Abs. Pressure (MPa)')
title('Gun Tunnel (Test 28), Barrel pressure with closed end')
legend('Piezoelectric Reading','Smoothed Piezoresistive Reading (3 pts)....')

% Plot close-up on raw data to show differences between results
figure(3)
plot(tim2,pzr,'r',tim1,pze1,'g')
xlabel('time (s)')
ylabel('Abs. Pressure (MPa)')
title('Gun Tunnel (Test 28), Barrel pressure with closed end')
legend('Piezoresistive Reading','Piezoelectric Reading')

AXIS([4e-3 28e-3 0 4])
%% Plot close-up on smoothed data to show differences between results
figure(5)
plot(tim1, pzr1, 'g', tim2, smo(pzr, 3), 'r')
xlabel('time (s)')
ylabel('Abs. Pressure (MPa)')
title('Gun Tunnel (Test 28), Barrel pressure with closed end')
legend('Piezoelectric Reading', 'Smoothed Piezoresistive Reading (3 pts)')
AXIS([1e-3 28e-3 0 4])
Listing C.8: Engine_1.m

% engine_1.m
%
% Script for analysis of engine data.
% This script provides an analysis of engine pressures
% recorded by a piezoelectric (13U0500) and a
% piezoresistive (112B11) sensor
%
% 4 different engine data sets collected,
% step through each data set -
% for k=5
% Run temperature calibration to load values
% for dspan/dt, doffset/dt etc.
temp_cal2

% Load relevant engine data
eval(['file_name=' 'pz_en_1',int2str(k),' .txt ' ' ']);
data=load_wavestart2(file_name,2500,8);

% Layout of information in engine data files -
% column 1 - time for piezoelectric
% column 2 - readings for piezoelectric
% column 3 - time for piezoresistive
% column 4 - Vout
% column 5 - time for piezoresistive
% column 6 - Vsense
% column 7 - time for encoder
% column 8 - Output for encoder

% Determine the position of the piston relative to the pressure data
% Plot encoder data
figure(1)
plot(data(:,8),'g');
zoom on;
pause
[enc1,dummy]=ginput(1); % input value anywhere between end of ....
long slot and start or short slot
enc1=round(enc1);

% Determine points of encoder signals
% (these points are the edges of the encoder slots)
enc_new = [0];
enc_new2 = [0];
trigger_A = 0;
for i=1:1500
point = enc1 + i;
if data(point,8)<1
enddummy = point;
if trigger_A == 1
if enddummy - enc1+i-1
enc_new2 = [enc_new2 enddummy];
end
end
trigger_A = 0;
end
if data(point,8)>1
enddummy = point;
trigger_B = 0;
if trigger_A == 0
if enddummy - enc1+i-1
enc_new = [enc_new enddummy];
trigger_A = 1;
end
end
end
C.1 MATLAB Scripts and Functions

```matlab
% Allocate times to encoder signal points
enc_time1 = data(enc_new(2),7);
enc_time2 = data(enc_new(5),7);
enc_time3 = data(enc_new(8),7);
enc_time4 = data(enc_new(11),7);
enc_time5 = data(enc_new(14),7);
enc_time6 = data(enc_new(17),7);
enc_time1 = data(enc_new2(2),7);
enc_time2 = data(enc_new2(5),7);
enc_time3 = data(enc_new2(8),7);
enc_time4 = data(enc_new2(11),7);
enc_time5 = data(enc_new2(14),7);
enc_time6 = data(enc_new2(17),7);

% Determine period of engine revolution
period = ((enc_time2 - enc_time1) + (enc_time3 - enc_time2) + (enc_time4 - enc_time3) + (enc_time5 - enc_time4) + (enc_time6 - enc_time5))/5;

% Fit encoder data to function for cylinder volume

% Determine the length of time for each slot

time_slot1_b = ((data(enc_new2(2),7) - data(enc_new(2),7)) + (data(enc_new2(5),7) - data(enc_new(5),7)) + (data(enc_new2(8),7) - data(enc_new(8),7)) + (data(enc_new2(11),7) - data(enc_new(11),7)) + (data(enc_new(14),7) - data(enc_new2(14),7)) + (data(enc_new(17),7) - data(enc_new2(17),7)))/6;
time_slot2_a = ((data(enc_new(3),7) - data(enc_new(2),7)) + (data(enc_new(6),7) - data(enc_new(5),7)) + (data(enc_new(9),7) - data(enc_new(8),7)) + (data(enc_new(12),7) - data(enc_new(11),7)) + (data(enc_new(15),7) - data(enc_new(14),7)) + (data(enc_new(18),7) - data(enc_new(17),7)))/6;
time_slot2_b = ((data(enc_new2(3),7) - data(enc_new(2),7)) + (data(enc_new2(6),7) - data(enc_new(5),7)) + (data(enc_new2(9),7) - data(enc_new(8),7)) + (data(enc_new2(12),7) - data(enc_new(11),7)) + (data(enc_new2(15),7) - data(enc_new(14),7)) + (data(enc_new2(18),7) - data(enc_new(17),7)))/6;
time_slot3_a = ((data(enc_new(4),7) - data(enc_new(2),7)) + (data(enc_new(7),7) - data(enc_new(5),7)) + (data(enc_new(10),7) - data(enc_new(8),7)) + (data(enc_new(13),7) - data(enc_new(11),7)) + (data(enc_new(16),7) - data(enc_new(14),7)) + (data(enc_new(19),7) - data(enc_new(17),7)))/6;
time_slot3_b = ((data(enc_new2(4),7) - data(enc_new(2),7)) + (data(enc_new2(7),7) - data(enc_new(5),7)) + (data(enc_new2(10),7) - data(enc_new(8),7)) + (data(enc_new2(13),7) - data(enc_new(11),7)) + (data(enc_new2(16),7) - data(enc_new(14),7)) + (data(enc_new2(19),7) - data(enc_new(17),7)))/6;
slot_time = [0 time_slot1_b time_slot2_a time_slot2_b ...
time_slot3_a time_slot3_b];

% Determine precise slot angles

slot_angle = slot_time/period+2*pi;

% Slot position is the measured cylinder position (from TDC) for each encoder slot

slot_position = [48.1 45.3 1.2 0 36.4 47.2];/1000; %m

plot(slot_angle, slot_position);

% Engine Data (adapted from enginedata.m created by Dr. David Buttsworth)

 % engine geometry

b=0.069; % engine bore (m)
stroke=0.054; % engine stroke (m)
esps=0.287693; % half stroke to rod ratio, s/2l
r=6.1; % compression ratio
Vtdc=pi/4*b^2*stroke/(r-1); % volume at TDC
```
Vbdc=pi/4*b^2*stroke+Vdc; % volume at BDC

% Calculate engine parameters related to encoder slots
slot_volume = slot_position*(b^2*pi/4)+Vdc;
theta = 0:0.01:2*pi;
V=Vdc*(1+(r-1)/2*(1-cos(theta)+1/eps*(1-(1-eps^2*sin(theta))^2).^0.5));
figure(8);
plot(theta,V,'b');
hold on;
plot(slot_angle,slot_volume,'r*');
X = ones(1,6);

% Match volume function with encoder slots and piston positions
for i = 1:6
  angle_solve = slot_angle(i);
  volume_solve = slot_volume(i);
  x = 4; % move function close to expected point
  j = 1;
  while j == 1
    V=Vdc*(1+(r-1)/2*(1-cos(angle_solve+x)+1/eps*(1-(1-eps^2*sin(angle_solve+x).^2).^0.5)));
    if abs(V-volume_solve)>1e-7
      x = x - abs(V-volume_solve)*10;
    end
    if abs(V-volume_solve)<=1e-7
      j = 0;
    end
  end
  X(i) = x;
  V=Vdc*(1+(r-1)/2*(1-cos(theta+X(i))+1/eps*(1-(1-eps^2*sin(theta+X(i)).^2).^0.5)));
  plot(theta,V,'g');
end
x_avg = mean(X);
% This value for x_avg can be used in the following volume calculation —
% V=Vdc*(1+(r-1)/2*(1-cos(theta+x_avg)+1/eps*(1-(1-eps^2*sin(theta+x_avg)).^2).^0.5))

% Plot Data — Compare pressures between Piezoelectric and ....
Piezoresistive

% determine operational temperature
Vsense_mean = mean(data(:,6))*1000; %mv
Vsupply_test = 15 - Vsense_mean/1000; %V
test_temp = ((Vsense_mean/30) - PVsense(2))/PVsense(1); %K

% Apply temperature compensation
% Determine span & offset for temperature (corrected for Vsupply)
span = span_25 + Pspan(1)*((test_temp - 273) - 25); %mV/V-pa
span = span*Vsupply_test; %mV/pa
% Linear Extrapolation used to insert lowest data point for ....
% interpolation
offset = interp1([273 TEMP],[0.5155 temp_offset],test_temp,'linear');
offset = offset*Vsupply_test; %mV/V

% compare pressures
piezoelectric = data(:,2)*1e6+9.38e4; %piezoelectric pressure (Pa abs)
piezores1 = (data(:,4)*1000-offset)/span; % piezoresistive ....
pizeores2 = (data(:,4)*1000-offset)/span;

% Smooth data according to pressure level to preserve peak pressures....

% Low pressure levels — high smoothing
% High pressure levels (above cutoff) — low smoothing
if k == 2
cutoff = 2e5;
end
if k == 3
cutoff = 3e5;
end
if k == 4
cutoff = 3e5;
end
if k == 5
cutoff = 5e5;
end
for num = 21:2480
if (mean((data((num-10:num+10),4)*1000-offset)/span) <= cutoff
piezo2(num)=mean((data((num-10:num+10),4)*1000-offset)/span);
end
if (mean((data((num-10:num+10),4)*1000-offset)/span) > cutoff
piezo2(num)=mean((data((num-2:num+1),4)*1000-offset)/span);
end
end
% Correct for drift in piezoelectric signal
figure(11);
plot(piezoel);zoom on;pause
% Select point in middle of exhaust stroke of piezoelectric (....
time taken 0.01 s either side of point), 400us steps
[time_average,dummy]=ginput(1);
time_average=round(time_average);
difference1 = mean((piezoel((time_average-25):(time_average+25))....
)+25));
difference2 = mean((piezo1((time_average-25):(time_average....
+25))));
total_diff = difference2 — difference1;
piezoel = piezoel + total_diff;
% Compare corrected pressures (time based)
figure(12)
plot(data(:,1),piezoel);
hold on
plot(data(:,3),piezo1,'g',data(:,3),piezo2,'m');
AXIS([0.3 0.6 -0.2e6 2.2e6]);
xlabel('Time (s)');
ylabel('Pressure (Pa)');
if k == 2
Title('Cylinder pressures — motored, closed throttle (1419.1 rpm....
'));
end
if k == 3
Title('Cylinder pressures — fired, no loaded, closed throttle ....
(2868.1 rpm)');
end
if k == 4
Title('Cylinder pressures — fired, loaded, closed throttle ....
(1373.6 rpm)');
end
if k == 5
Title('Cylinder pressures — fired, loaded, open throttle (2673.8....
rpm)');
end
Legend('Piezoelectric Pressure Reading','Piezoresistive Pressure....
Reading', 'Smoothed Piezoresistive Pressure Reading');
hold off
% Compare corrected pressures (crank angle based)
figure(13)
plot(((data(:,1)-enc_time1-(period*((2*pi-x_avg)/(2*pi))))/period)*2*pi, piezoel);
hold on
plot(((data(:,3)-enc_time1-(period*((2*pi-x_avg)/(2*pi))))/period)*2*pi, piezeros1, 'g', ((data(:,3)-enc_time1-(period*(2*pi-x_avg)/(2*pi))))/period)*2*pi, piezeros2, 'm');
axis([0.3 0.6 -0.2e6 2.2e6]);
xlabel('Crank Angle (Radians)');
ylabel('Pressure (Pa)');
if k == 2
title('Cylinder pressures - motored, closed throttle (1419.1 rpm...'))
end
if k == 3
title('Cylinder pressures - fired, no loaded, closed throttle .... (2868.1 rpm)')
end
if k == 4
title('Cylinder pressures - fired, loaded, closed throttle .... (1373.6 rpm)')
end
if k == 5
title('Cylinder pressures - fired, loaded, open throttle (2673.8.... rpm)')
end
legend('Piezoelectric Pressure Reading','Piezoresistive Pressure.... Reading', 'Smoothed Piezoresistive Pressure Reading');
hold off

% Save calculated engine data
eval(['save pz_en_','int2str(k),';'])
clear
end
Listing C.9: Engine_2.m

% engine_2.m
% Script for comparing the theoretical and measured cylinder pressures
% This script is run in conjunction with the scripts
% for the thermodynamic engine simulation developed by
% Dr. David Buttsworth

% The following variables were changed in the script
% 'enginedata.m' to match the specifications of the engine used —
% b = 0.069; engine bore (m)
% stroke = 0.054; engine stroke (m)
% eps = 0.287693; half stroke to rod ratio, s/2l
% r = 6.1; compression ratio
% CHANGE FILE 'enginedata.m' TO MATCH ENGINE TEST NUMBER
% Engine Test Calculated Engine Speeds Conditions
% pz_en_2 1419.1 rpm thetas = 179.9*pi/180, ....
% thetab = 0.1*pi/180 p1 = 5.5e4
% pz_en_3 2868.1 rpm thetas = 0*pi/180, ....
% thetab = 70*pi/180 p1 = 4e4
% pz_en_4 1373.6 rpm thetas = -10*pi/180, ....
% thetab = 55*pi/180 p1 = 8e4
% pz_en_5 2673.8 rpm thetas = -10*pi/180, ....
% thetab = 45*pi/180 p1 = 8.5e4
% Experimental Description
% pz_en_2 — motored, closed throttle
% pz_en_3 — fired, closed throttle, no load
% pz_en_4 — fired, closed throttle, loaded
% pz_en_5 — fired, open throttle, loaded

%===================================================================
% Run Ahrind.m
% This script (developed by Dr. David Buttsworth) runs the
% thermodynamic engine simulation Ahrind
% Load results from engine simulation
load ahrind.mat;
% CHANGE 'data_set' NUMBER TO MATCH ENGINE TEST NUMBER (2 to 5)
data_set = 3;
% Load Experimental Engine Data
cd('..')
eval(['load pz_en_','',int2str(data_set),'.'])
cd Engine
e regions
%===================================================================
% Plot cylinder pressures
figure(1);
plot(thetacomp.pTuWQHI(:,1)/1e6); hold on;
plot(thetacomb.pTuWQHI(:,1)/1e6);
plot(thetaexp.pTuWQHI(:,1)/1e6);
xlabel('crank angle (degrees ATC)')
ylabel('pressure (MPa)')
hold off
%===================================================================
% Determine cylinder pressures with respect to time
thetacomp_new = ((thetacomp+pi)/(2*pi))*period;
thetacomb_new = ((thetacomp+pi)/(2*pi))*period;
thetaexp_new = ((thetaexp+pi)/(2*pi))*period;

% the value of 'cycle' will be 1 or 3, according to
% if the theoretical data is 180 deg out of phase
cycle = 3;
%cycle = 1;

% Plot experimental and theoretical data (time scale)
figure(7)
plot(data(:,1)-enc_time1-(period*((2*pi-x_avg)/(2*pi))),piezo1,'g',... 
data(:,3)-enc_time1-(period*((2*pi-x_avg)/(2*pi))),piezo2,'m',... 
data(:,1)-enc_time1-(period*((2*pi-x_avg)/(2*pi))),piezo3,'k');
hold on;
plot(thetacomp_new+cycle*(period/2),pTbWQlHl(:,1));
plot(thetacomb_new+cycle*(period/2),pTbWQlHl(:,1));
xlabel('Time (s)');
ylabel('Pressure (Pa)');

if data_set == 2
    Title('Experimental vs. Theoretical results - motored, closed ...
throttle (1419.1 rpm)');
end
if data_set == 3
    Title('Experimental vs. Theoretical results - fired, no load, closed ...
throttle (2868.1 rpm)');
end
if data_set == 4
    Title('Experimental vs. Theoretical results - fired, loaded, closed ...
throttle (1373.6 rpm)');
end
if data_set == 5
    Title('Experimental vs. Theoretical results - fired, loaded, open ...
throttle (2673.8 rpm)');
end
Legend('Piezoresistive Pressure Reading', 'Smoothed Piezoresistive...
Pressure Reading', 'Piezoelectric Pressure Reading', 'Theoretical...
Pressure');
hold off

% Plot experimental and theoretical data (crank angle scale)
figure(8)
plot((data(:,3)-enc_time1-(period*((2*pi-x_avg)/(2*pi))))/period..., 
+360-(180+180*cycle),piezo1,'g',(data(:,3)-enc_time1-(period*((2*pi-... 
pi-x_avg)/(2*pi))))/period+360-(180+180*cycle),piezo2,'m',(data.... 
(:,1)-enc_time1-(period*((2*pi-x_avg)/(2*pi))))/period+360-(180+180*.... 
cycle),piezo3,'k');
hold on;
plot((thetacomp_new+cycle*(period/2))/period+360-(180+180*cycle),... 
pTbWQlHl(:,1));
plot((thetacomb_new+cycle*(period/2))/period+360-(180+180*cycle),pTbWQlHl..., 
(:,1));
plot((thetacomp_new+cycle*(period/2))/period+360-(180+180*cycle),pTbWQlHl..., 
(:,1));

%plot((data(:,3)-enc_time1-(period*((2*pi-x_avg)/(2*pi))))/period.... 
+360-360*360*360*360*360*360*360*360*360*360*360*360*360*(1e6); 
xlabel('Crank Angle (deg)');
ylabel('Pressure (Pa)');
if data_set == 2
    Title('Experimental vs. Theoretical results - motored, closed ...
throttle (1419.1 rpm)');
    AXIS([-180 180 -0.26e6 1e6]);
end
if data_set == 3
    Title('Experimental vs. Theoretical results - fired, no load, closed....
throttle (2868.1 rpm)');
    AXIS([-180 180 -0.26e6 1e6]);
end
if data_set == 4
    Title('Experimental vs. Theoretical results - fired, loaded, closed ....
throttle (1373.6 rpm)');
    AXIS([-180 180 -0.26e6 2.5e6]);
end
if data_set == 5

Title('Experimental vs. Theoretical results — fired, loaded, open .... throttle (2673.8 rpm)');
AXIS([-180 180 -0.5e6 4e6]);
end
Legend('Piezoresistive Pressure Reading', 'Smoothed Piezoresistive .... Pressure Reading', 'Piezoelectric Pressure Reading', 'Theoretical .... Pressure');
hold off

%===================================================================
% Determine the output power of the motor

pump = 3.8e-6; %m^3/rev
if data_set == 4
    dp = 1100; % psi
    dp = dp*6894.8;
    flow_rate = 1373.6/60*pump;
    Power = flow_rate*dp;
end
if data_set == 5
    dp = 1700; % psi
    dp = dp*6894.8; %pa
    flow_rate = 2673.8/60*pump;
    Power = flow_rate*dp;
end
clear
# Appendix D

## Detail and Assembly Drawings

### Appendix D Contents

<table>
<thead>
<tr>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawings for SX150AHO Pressure Attachment</td>
<td>146</td>
</tr>
<tr>
<td>Drawings for Oven Insulating Tube</td>
<td>147</td>
</tr>
<tr>
<td>Drawings for Shock Tube Sensor Mountings</td>
<td>158</td>
</tr>
<tr>
<td>Drawings for Gun Tunnel Sensor Mountings</td>
<td>160</td>
</tr>
<tr>
<td>Drawings for Engine Shaft Encoder</td>
<td>162</td>
</tr>
</tbody>
</table>
D.1 Detail Drawings for SX150AHO Pressure Attachment
D.2 Detail Drawings for Oven Insulating Tube
D.2 Detail Drawings for Oven Insulating Tube 149
D.2 Detail Drawings for Oven Insulating Tube

Ø 50.8

DIM IN mm
TOLERANCES

AS 1100
REF. ASSEM. 2

MATERIAL
2mm COPPER SHEET

END CAP

PETER HOCKINGS

SIZE A4
PART 478

SCALE 1:1
DRAWN 4/711
NOTE:
PART CONSTRUCTED BY MAKING A SINGLE CUT IN 2" COPPER TUBE, THEN BENDING TO CORRECT DIAMETER

<table>
<thead>
<tr>
<th>DIM IN mm</th>
<th>TOLERANCES:</th>
<th></th>
<th>PETER HOCKINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MATERIAL COPPER TUBE</td>
<td>END RING</td>
<td></td>
</tr>
<tr>
<td>AS 1100</td>
<td>SIZE A4</td>
<td>SCALE 1:1</td>
<td></td>
</tr>
<tr>
<td>REF. ASSY. 2</td>
<td>PART 6/8</td>
<td>ORG. 6/11</td>
<td></td>
</tr>
</tbody>
</table>
D.2 Detail Drawings for Oven Insulating Tube

M4 x 0.5 ISO-H CLEAR 4.3 DRILL (4.30) THRU (14) HOLE

DIM IN mm
TOLERANCES

MATERIAL
2mm COPPER PLATE

PETER HOOKINGS

TUBE OUTER PLATE

AS 1100
SIZE A4

REF. ASSY. 3
SCALE 1:1

PART 6/8
DRAW. 8/11
D.2 Detail Drawings for Oven Insulating Tube
D.3 Detail Drawings for Shock Tube Sensor Mountings
D.4 Detail Drawings for Gun Tunnel Sensor Mountings
3/4 BRASS THREAD 26TP1

45° x 1

DIM IN mm
TOLERANCES
AS 1100
-

MATERIAL
MS

GUN TUNNEL MOUNT SCREW
SIZE A4
PART 1/1
SCALE 2:1
DRAW. 1/1

PETER HICKINGS
D.5 Detail Drawings for Engine Shaft Encoder
D.5 Detail Drawings for Engine Shaft Encoder 164

**Front View**

**Right Side View**

<table>
<thead>
<tr>
<th>DIM IN mm</th>
<th>TOLERANCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS 1100</td>
<td></td>
</tr>
</tbody>
</table>

**Material**

- DESIGNER: DAVID BUTSWORTH
- ENCODER MOUNT PART 2
- SIZE: A4
- SCALE: 1:1

**Notes**

- REF. ASSY. 1
- PART 3/5
- DRW 3/4
D.5 Detail Drawings for Engine Shaft Encoder
## Appendix E

### Shock Tube Experimental Data

<table>
<thead>
<tr>
<th>Shock Tube Test</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>168</td>
</tr>
<tr>
<td>2</td>
<td>170</td>
</tr>
<tr>
<td>3</td>
<td>172</td>
</tr>
<tr>
<td>4</td>
<td>174</td>
</tr>
<tr>
<td>5</td>
<td>176</td>
</tr>
<tr>
<td>6</td>
<td>178</td>
</tr>
<tr>
<td>7</td>
<td>180</td>
</tr>
<tr>
<td>8</td>
<td>182</td>
</tr>
<tr>
<td>9</td>
<td>184</td>
</tr>
<tr>
<td>10</td>
<td>186</td>
</tr>
<tr>
<td>11</td>
<td>188</td>
</tr>
<tr>
<td>12</td>
<td>190</td>
</tr>
<tr>
<td>13</td>
<td>192</td>
</tr>
<tr>
<td>14</td>
<td>194</td>
</tr>
<tr>
<td>15</td>
<td>196</td>
</tr>
<tr>
<td>16</td>
<td>198</td>
</tr>
<tr>
<td>17</td>
<td>200</td>
</tr>
</tbody>
</table>
E.1 Shock Tube Experimental Data

The following plots display the experimental results recorded from each shock tube test. 4 plots were generated for each shock tube test. These plots, in order of display, are as follows,

1. The short time scale response to compare measured and theoretical reflected shock pressures.
2. The short time scale response for determining the rise-time.
3. The long time scale response to compare measured and theoretical reflected shock pressures.
4. The power spectrum density of the short time scale response.

The shock tube test number is also displayed in the plot headings with ‘pz_st_x’ where ‘x’ is the shock tube test number (1 to 17)
E.1 Shock Tube Experimental Data

E.1.1 Shock Tube Test 1

![Graph of Pressure vs Time for pz_sl_1 - Comparison of Experimental and Theoretical Results](image1)

![Graph of Pressure vs Time for pz_sl_1 - Graph for Determining Rise Time](image2)
E.1 Shock Tube Experimental Data

E.1.2 Shock Tube Test 2
E.1.3 Shock Tube Test 3

![Graph of Pressure vs Time for pz_st_3 - Comparison of Experimental and Theoretical Results](image1)

![Graph of Pressure vs Time for pz_st_3 - Graph for Determining Rise Time](image2)
E.1 Shock Tube Experimental Data
E.1.4 Shock Tube Test 4
E.1 Shock Tube Experimental Data
E.1 Shock Tube Experimental Data

E.1.5 Shock Tube Test 5
E.1 Shock Tube Experimental Data

1. Pressure vs Time for pz_st_5 - Comparison of Experimental and Theoretical Results

2. Power Spectrum Density for pz_st_5 (smoothing - 5 points)
E.1.6 Shock Tube Test 6
E.1 Shock Tube Experimental Data

E.1.7 Shock Tube Test 7

[Graph showing pressure vs. time for pz_st_7 with comparison of experimental and theoretical results.]

[Graph showing pressure vs. time for pz_st_7 with graph for determining rise time.]
E.1 Shock Tube Experimental Data

E.1.8 Shock Tube Test 8
E.1 Shock Tube Experimental Data
E.1.9 Shock Tube Test 9

![Comparison of Experimental and Theoretical Results](image1)

![Graph for Determining Rise Time](image2)
E.1 Shock Tube Experimental Data

![Graph 1: Pressure vs Time for pz_st_9 - Comparison of Experimental and Theoretical Results](image1)

![Graph 2: Power Spectrum Density for pz_st_9 (smoothing - 5 points)](image2)
E.1.10 Shock Tube Test 10

Two graphs are shown:

1. **Pressure vs Time for pz_st_10 - Comparison of Experimental and Theoretical Results**
   - The graph compares different pressure measurements over time.
   - Data points include Pressure from SX150AHO, P5 from US1, P5 from US2, P5 from USP, P5 average (50us to 100us), and Smoothed output from SX150AHO.

2. **Pressure vs Time for pz_st_10 - Graph for Determining Rise Time**
   - The graph shows the pressure over time with markers for determining the rise time.
   - The markers indicate 10% of P5 average, 90% of P5 average, P5 average (50us to 100us), Smoothed output from SX150AHO, and Pressure from SX150AHO.
E.1 Shock Tube Experimental Data
E.1 Shock Tube Experimental Data

E.1.11 Shock Tube Test 11

![Graph 1: Pressure vs Time for pz_st_11 - Comparison of Experimental and Theoretical Results](image1)

![Graph 2: Pressure vs Time for pz_st_11 - Graph for Determining Rise Time](image2)
E.1 Shock Tube Experimental Data

![Graph 1: Pressure vs Time for pz_st_11 - Comparison of Experimental and Theoretical Results](image1)

![Graph 2: Power Spectrum Density for pz_st_11 (smoothing - 5 points)](image2)
E.1 Shock Tube Experimental Data

E.1.12 Shock Tube Test 12

![Graph of Pressure vs Time for pz_st_12 - Comparison of Experimental and Theoretical Results](image1)

![Graph of Pressure vs Time for pz_st_12 - Graph for Determining Rise Time](image2)
E.1 Shock Tube Experimental Data

[Graph 1: Pressure vs Time for pz_st_12 - Comparison of Experimental and Theoretical Results]

[Graph 2: Power Spectrum Density for pz_st_12 (smoothing - 5 points)]
E.1.13 Shock Tube Test 13
E.1 Shock Tube Experimental Data
E.1.14 Shock Tube Test 14

![Graph 1: Pressure vs Time for pz_st_14 - Comparison of Experimental and Theoretical Results](image1)

![Graph 2: Pressure vs Time for pz_st_14 - Graph for Determining Rise Time](image2)
E.1 Shock Tube Experimental Data

E.1.15 Shock Tube Test 15

![Graph 1: Pressure vs Time for pz_st_15 - Comparison of Experimental and Theoretical Results](image1)

![Graph 2: Pressure vs Time for pz_st_15 - Graph for Determining Rise Time](image2)
E.1 Shock Tube Experimental Data
E.1.16 Shock Tube Test 16
E.1 Shock Tube Experimental Data
E.1 Shock Tube Experimental Data

E.1.17 Shock Tube Test 17

![Graph of Pressure vs Time for pz_st_17 - Comparison of Experimental and Theoretical Results](image1)

![Graph of Pressure vs Time for pz_st_17 - Graph for Determining Rise Time](image2)
E.1 Shock Tube Experimental Data

![Pressure vs Time for pz_st_17 - Comparison of Experimental and Theoretical Results](image1)

![Power Spectrum Density for pz_st_17 (smoothing - 5 points)](image2)