Examensarbete

Design of test hardware
for characterization of key parameters
of analog gas sensors

Examensarbete utfört i Elektroniska komponenter
vid Tekniska högskolan i Linköping
av

Watchanun Tanacharoenwat

LiTH-ISY-EX--11/4414--SE
Linköping 2011
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Controller area network (CAN) protocol for data communication is used in the project work. With the benefit of CAN over multiple device communication, the test hardware is designed for multichannel testing. Graphical LabVIEW software is developed and programmed basically for instrumental control and sensor response acquisition. Finally, a few experiments have been conducted to estimate some key parameters of the gas sensors such as a sensor noise level and sensor responses over different hydrogen concentrations.

Keywords: key1, key2
Abstract

Hydrogen sensors are essential to facilitate the detection of accidental hydrogen releases wherever hydrogen will be produced, distributed, stored, and used. Compared to the helium detection: hydrogen is cheaper than helium, no need for a vacuum and the lower cost of producing the instruments. Thus, hydrogen leak detectors are used in variety of applications such as localization of telephony cable damages, finding leaks in fuel tanks and quality control in heating, ventilating, and air conditioning (HVAC) and refrigeration systems. This thesis work combines the design and implementation of test hardware, software programming and the characterization of critical parameter of analog hydrogen sensor for leak detection system development.

Controller area network (CAN) protocol for data communication is used in the project work. With the benefit of CAN over multiple device communication, the test hardware is designed for multichannel testing. Graphical LabVIEW software is developed and programmed basically for instrumental control and sensor response acquisition. Finally, a few experiments have been conducted to estimate some key parameters of the gas sensors such as a sensor noise level and sensor responses over different hydrogen concentrations.
Acknowledgments

First of all, I would like to thank all the helpful people at Adixen Scandinavia especially Fredrik Enquist and Patrik Kaliff for giving the opportunity to do this thesis and providing me supports and valuable guidance.

I would also like to thank Professor Atila Alvandpour who is my examiner and despite a very full schedule of him, he always finds time for me when I have questions regarding the thesis work.

I would like to express my gratitude to my parents and my sister for their encouragement and support to my studies at Linköpings University.

Last but not least, I would like to say a big thank to the wonderful person who meant the most to me and my work, Kristina Schelander, for her love and support which gave me strength to complete the thesis.
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</tbody>
</table>
Chapter 1

Introduction

In this diploma work, identification and evaluation of key parameters for gas sensor application in leakage analysis will be performed. The introduction covers the project background, the presentation of problem, delimitations of the project and the outline description of thesis report.

1.1 Background

Nowadays hydrogen has grown to be one of the most useful gases for a leak detection considered by various industries involved with the manufacture of air conditioners, refrigerators and automotive components. As the hydrogen molecule is the smallest and lightest of elements, it is quickly transported to the leaks and dissipates much faster than other gases. On the otherhand, hydrogen leaks must be avoided as the gas is highly flammable in concentrations ranging from the lower explosive limit (LEL) of 4% in air to 75% by volum, which is the upper explosive limit (UEL) [7], therefore, the hydrogen leak detection is done with an extremely safe gas mix of 5% hydrogen in 95% nitrogen. The inherent characteristics of Hydrogen enable fast, precise and safe leak location and qualification. Hydrogen is also a renewable gas, environmentally sound, certified as food additive and much cheaper than other gases for example Helium. Moreover, the present shortage of Helium opens a good opportunity for the Hydrogen Technology.

Adixen Scandinavia, which will be called Adixen later in the report, was founded in the early 80s and was driven initially by a number of researchers at Applied Physics at IFM in Linköping University. The invention that was exploited was the hydrogen-sensitive transistor and the business idea came to be that of the sensor as a key component to develop and sell leak detectors for various applications. The company pioneered the use of hydrogen gas mixtures as a tracer for industrial leak testing. The most recent detector model developped by Adixen is called ASH2000, see in Figure 1.1. This instrument combines the use of digital signal processing together with a catalytic gate metal-oxide-semiconductor field effect transistor (MOSFET) sensor and Controller Area Network (CAN) interface for data communication.
1.2 Problem Statement

As the demand for hydrogen gas grows, the accurate hydrogen detection is critical in several industries for safety and process improvement. Real-time and sensitive hydrogen sensors are in immediate need for the process industry as replacements to slow-response and noisy sensors. However, a high risk of increasing the false signals will be produced as the higher sensitivity is developed.

To improve the sensitivity of hydrogen leak detectors, it is essential to know the average noise level in the developed system. Some previous studies of the system noise done by Adixen were proven that roughly 90% of the noise in the signal bandwidth originates from the sensor. Therefore, the study to measure an average noise level in the analog gas sensors, by the development of synthesized signal mixer to quantify the low-frequency noise in the sensors, is introduced in the thesis project.

In addition, Adixen aims the thesis to help validate the new approach of multichannel product with the use of CAN protocol from ASH2000 leak detector which allows 63 devices at maximum to handle the communication within the same network. Thus, the CAN based multichannel system development for sensor characterization is also a part of the thesis project.

1.3 Delimitations

For the project to be carried out reasonably within the limited time frame, some delimitations have been made. First of all, there will be no algorithm modification in the project work which means that the studies of sensor noise and characterization will be done with the existing analysis algorithm developed by Adixen. Also the main electronic part for the CAN-based multichannel system will be similar to one used for the selling product, ASH2000, which is a single-channel model. The schematic level of the product hardware is classified and there will be no
redesigning of this electronic part.

1.4 Outline

The main topics in the report are listed as follows.

- **Chapter 2** describes the hydrogen sensing mechanism.
- **Chapter 3** introduces the basics of CAN protocol.
- **Chapter 4** explains the implemented CAN based multichannel control system.
- **Chapter 5** shows the evaluation of sensor noise.
- **Chapter 6** presents the experiment for gas sensor characterization using the multichannel control unit.
- **Chapter 7** sums up the diploma work with conclusions and suggestions for future work.
Chapter 2

Hydrogen Sensing Operation

In this chapter, the basic of MOS sensor as well as the hydrogen sensing mechanism are briefly described based on the hydrogen sensors developed by Adixen.

2.1 Background

In recent years, plenty of researches and developments have been done in the field of gas microsensors. A gas microsensor is a small transducer which detects gas molecules and generates an electrical signal with a proportional to the gas concentration. The hydrogen microsensor is designed to detect hydrogen molecules but insensitive to other gases. Hydrogen microsensors have advantages over conventional gas-detecting devices as they are low cost, compact, reliable and durable, and easy to maintain. The microsensors are thus more suitable for portable applications and multi-sensor systems.

2.2 Metal-Oxide-Semiconductor (MOS) Sensors

There are many different technologies currently available for hydrogen detection, each with advantages and disadvantages. The hydrogen sensors based on MOS structure share the longest history of research and development. Over years, many different types of MOS sensors with catalytic metal gates have been produced and tested [2]. They can be categorized into three main types: metal-oxide-semiconductor field effect transistor (MOSFET), metal-oxide-semiconductor capacitors, and Schottky barrier diodes. As the hydrogen leak detectors developed by Adixen are based on catalytic gate MOSFET sensors, the MOSFET sensors will be discussed further in the following section.

2.2.1 MOSFET Sensors

A MOSFET hydrogen sensor is a specific type of chemical field-effect transistors (ChemFETs) which are sensitive to the presence of chemicals (gases, liquids, etc.).
Typically, a MOS field effect transistor is a device in which the conductivity between a source terminal and a drain terminal is controlled by a potential on a gate electrode. The drain current \((I_D)\) through the channel of MOS transistor is given by

\[
I_D = \mu C_{ox} \frac{W}{L} \left( (V_{GS} - V_{th})V_{DS} - \frac{V_{DS}^2}{2} \right)
\]

for triode mode or linear region, when \(V_{GS} > V_{th}\) and \(V_{DS} < V_{GS} - V_{th}\), and

\[
I_D = \frac{\mu C_{ox}}{2} \frac{W}{L} (V_{GS} - V_{th})^2 (1 + \lambda V_{DS})
\]

for saturation or active mode, when \(V_{GS} > V_{th}\) and \(V_{DS} > V_{GS} - V_{th}\),

where \(\mu\) is the charge-carrier effective mobility, \(C_{ox}\) is the gate oxide capacitance per unit area, \(W\) is the channel width, \(L\) is the channel length, \(\lambda\) is the channel-length modulation parameter, and \(V_{GS}, V_{DS}, \) and \(V_{th}\) are gate, drain, and threshold voltages respectively [8].

In a sensor configuration, the gate and drain terminals are connected together, which gives \(V_{GS} = V_{DS}\). Thus, the transistor is assumed to operate at the boundary between linear and saturation regions, as shown in Figure 2.1. Note that the voltage at the gate and drain constitutes the sensor signal \((V_{GD})\). The boundary between linear and saturation modes is indicated by the upward curving parabola.

Gas-sensitive field effect devices have been studied for over decades, since the original discovery of the large sensitivity of palladium (Pd) gate metal-oxide-semiconductor structures to hydrogen. Figure 2.2 shows a schematic illustration of a n-type Pd-MOSFET sensor structure.

2.2.2 Hydrogen Sensing Mechanism

The hydrogen sensor substrate wafers are produced in a metal gate complementary metal-oxide-semiconductor (CMOS) process leaving the gate oxide naked for subsequent deposition of the catalytic metal layer. The hydrogen sensitive part of the sensor is the catalytic gate metal which is capable of absorbing hydrogen by forming metal hydride. The effect of an increased hydrogen content of the gate film is an effective increase in the work function of the gate metal which can then easily be detected as a shift in the effective gate voltage. The insulating layer (white) is the original gate oxide grown in the CMOS process. On top of the oxide, you can see the Pd-gate metal (purple), as shown in Figure 2.3.

When exposed to the surface of catalytic metal, hydrogen gas molecules are dissociated and subsequently adsorbed by the palladium surface as hydrogen atoms, shown in Figure 2.4.

Inside the metal layer the hydrogen atoms, one electron and one proton, can be considered as positives charges in a Fermi gas (the hydrogen electrons being screened by the conduction electrons of the metal) [6]. As depicted in Figure 2.5, there are absorption sites for protons at the metal oxide interface. When hydrogen
2.2 Metal-Oxide-Semiconductor (MOS) Sensors

Figure 2.1. MOSFET drain current ($I_D$) vs. drain-to-source voltage ($V_{GS}$) for several values of $V_{GS}-V_{th}$.

Figure 2.2. Schematic representation of a Pd-MOS transistor.
Figure 2.3. The sensor chip.

Figure 2.4. Hydrogen adsorption and dissociation and proton adsorption.
gas is disappear, the process will be reversed. Hydrogen atoms will be diffused to the gate metal surface where they are able to combine with oxygen to form water (H₂O) or with another hydrogen atom to form hydrogen molecule (H₂). These two processes are in balance with the hydrogen concentration in the ambient, therefore, the effective voltage of the gate is a measurement of the hydrogen concentration.

**Figure 2.5.** Cross section of the sensor showing proton adsorption at metal oxide interface.

The voltage drop, ΔV_{th} which appears at the interface, will be added to the external sensor voltage (V_{GD}). ΔV_{th} gives a shift in the I-V curve towards lower voltages, shown in Figure 2.6. The voltage drop (ΔV_{th}) is proportional to the number of hydrogen atoms absorbed per unit area at the metal-oxide interface, and is used to monitor the hydrogen concentration in the ambient environment.

**Figure 2.6.** Current-voltage characteristics demonstrating the effect of hydrogen on a MOSFET sensor.
This chapter introduces the basics of controller area network (CAN) includes layered architecture, two-wire CAN bus and different types of message frames. The CAN basics have been studied mainly for software implementation purposes. Therefore, the reader could just skim through this chapter without going into details.

The CAN protocol basics presented in this chapter are basically the summaries from references [1], [3], [4]and [10].

3.1 Background

The data communication of the hydrogen leak detector, ASH2000, is based on controller area network (CAN), which is a bus standard designed to allow microcontrollers and devices to communicate with each other within a network without a host computer. CAN is a serial communications protocol which supports real-time control with high security. The high level CAN protocol implemented by Adixen is called Phoenix CAN Protocol or PCP while the low level CAN protocol implemented by the hardware subsystem handles physical transfer of messages across the bus line, with built in error handling, such as collision detection and data verification.

3.2 CAN Protocol Basics

3.2.1 Layered Architecture

The CAN protocol architecture is structured according to the layered approach of the International Organization for Standardization (ISO)/ Open System Interface (OSI) reference model. However, based on most of the currently existing networks in the automated manufacturing environments, only few layers have been considered in the protocol stack in order to make the cost of implementation lower with higher efficient.
Figure 3.1 shows the comparison between the seven-layer ISO/OSI reference model and the CAN protocol stack as the architecture of CAN corresponds to the two lower layers of the ISO reference model. An embedded CAN controller corresponds to both the data-link layer and physical signaling at the physical layer. In comparison, the CAN transceiver, which attaches to the CAN bus, represents the physical medium attachment (PMA) and physical dependent interface (PDI) specifications of the physical layer. Therefore, the CAN transceiver specifications include the manner by which pulses are formed as well as connectors and the cable used for the bus, which is a two-wire bus. This two-wire bus has a multimaster capability where multiple devices connected to the bus can communicate with one another.

![Figure 3.1. Comparison between the layered structure of CAN and the ISO reference model [3].](image)

### 3.2.2 CAN Bus

The two-wire CAN bus, which enables differential signal transmissions and ensures reliable communications, represents the most popular implementation of CAN. The non-return-to-zero (NRZ) bit encoding with bit stuffing is used in two-wire CAN bus. The NRZ signaling features a high efficiency as the synchronization information is not encoded separately from data.

Figure 3.2 shows the connection of a CAN controller to a two-wire CAN bus and signal on the CAN bus. The first connection, CANh, is used for a differential signal transmission, while the second connection, CANl, is used to monitor the CAN bus and is also provided for the receipt of the receiver signal by the CAN controller. The CAN controller is usually integrated on a digital signal processor (DSP) chip, which is respectively built into an electronic control unit (ECU). An ECU can communicate with another to check its status or exchange information by the mechanism provided by the CAN controller.
In CAN, the electrical interface of a node to the bus is based on an open-collector-like scheme. Therefore, the level on the bus can assume two complementary values denoted as dominant and recessive. The dominant level corresponds to the logical value 0 while the recessive level denotes the logical value 1.

![Figure 3.2. CAN two-wire physical layer and signal on CAN bus [3].](image)

According to one characteristic of NRZ code which the signal provides no edges that can be used for resynchronization if transmitting a large number of consecutive bits with the same polarity, the bit-stuffing technique is used to ensure the synchronization of all bus nodes. Thus, during the transmission of a message (either dominant or recessive), a maximum of five consecutive bits may have the same polarity. In practice, whenever five consecutive bits of the same value appear in the bit stream, the transmitting node inserts one additional stuff bit at the complementary value, as shown in Figure 3.3. The stuff bits can be easily and safely removed by the receiver, to obtain the original stream of bits back. A bit stuffing violation in which six consecutive bits of the same type are received is considered as an error.

![Figure 3.3. Bit stuffing technique [10].](image)

The encoding efficiency of bit-stuffing technique can be as low as 80% as the maximum number of stuff bits added is one every four bits in the original frame. Although the bit stuffing is quite efficient, the main disadvantage of this technique is that the code rate is unpredictable; it depends on the data being transmitted. This might cause annoying jitters. Not all fields in a CAN frame are encoded applying the bit stuffing mechanism, it applies only to the initial part of the frames; the start-of-frame (SOF), arbitration field, control field, data field and
cyclic redundancy check (CRC) field. The remaining fields are of fixed form and are not stuffed.

Furthermore, CAN applies a modified carrier sense multiple access with collision detection (CSMA/CD) method for nodes to gain access to the bus, besides an arbitration process. In CAN each device listens to the bus in order to determine whether the message flowing on the bus is the same as what the device is trying to transmit. The device will immediately release the bus when the message is different. This process ensures that only one master always wins and results in no messages lost due to a collision. Figure 3.4 illustrates the arbitration process on the CAN bus, at bit 5 nodes 1 and 3 send a dominant identifier bit while node 2 looses bus arbitration and switches to listening mode which is transmitting recessive bits. At bit 2 node 1 looses arbitration against node 3. This means that the message identifier of node 3 has a higher priority than the messages of nodes 1 and 2. Thus, node 3 with the highest priority message wins the arbitration without loosing time to repeat the message. Nodes 1 and 2 will send their messages after node 3 finishes the transmission.

![Figure 3.4. CAN bus arbitration method [1].](image)

### 3.2.3 Message Frames

There are four different kinds of message frame being transmitted or broadcasted on the CAN bus include:

- Data frame
- Remote frame
- Error frame
- Overload frame
3.2 CAN Protocol Basics

Data Frame

The CAN specification according to ISO1 defines both a standard and an extended frame format. These formats mainly differ for the size of the identifier field and for some other bits in the arbitration field. The standard CAN uses an 11-bit identifier while the extended CAN uses a 29-bit identifier formed by separate 11-bit and 18-bit identifier fields as illustrated in Figure 3.5.

![Figure 3.5. CAN bus Data Frame [10].](Image)

A data frame is produced by a CAN bus node when the node wishes to transmit data or is requested by another node. One frame can transport up to 8 byte data. Each data frame in CAN begins with a start-of-frame (SOF) bit at the dominant level. The SOF bit is used to mark the beginning of the frame for hard synchronization of receiving nodes. Immediately after the SOF bit there is the arbitration field, which includes both the identifier and the remote transmission request (RTR) bit. As mentioned before in this report, the identifier is used to detect and manage the priority of the frame (the lower the numerical value of the identifier, the higher the priority of the frame).

The identifier is transmitted starting from the most significant bit (MSB) up to the least significant bit (LSB). The length of a standard identifier is 11 bit which corresponds to the first 11-bit identifier in extended format. Under the extended CAN, the arbitration field consists of a 29-bit identifier divided into two parts, base identifier with 11 bits and extended identifier with 18 bits. The base and extended identifier are separated by two recessive bits, substitute remote request (SRR) and identifier extension (IDE) bits, to preserve the structure of the frames.

The RTR bit is used to define between data and remote frames. A dominant value of RTR represents a data frame while a recessive value denotes a remote frame. Note that a data frame has a higher priority than a remote frame with the same identifier.

The next field is the control field which specifies mainly the number of bytes of data contained in the message. In standard format, the control field begins with

---

IDE bit, used to identify between standard and extended frames, followed by a reserved bit r0 then the data length code (DLC) which is 4-bit wide. In the case of extended frames, IDE bit is a part of an arbitration field with SRR bit, thus, the control fields begins with two reserved bits r1 and r0 then DLC.

Cyclic redundancy check (CRC) field is used to detect possible transmission errors. It consists of a 15-bit CRC sequence completed by one recessive CRC delimiter bit.

In the acknowledgement (ACK) field, there are two bits containing the ACK slot and the ACK delimiter. The transmitting node sends both bits of the ACK Field recessive. Any receiving node, which received a valid message correctly, reports back by sending a dominant bit during the ACK Slot.

At the end of the frame there is the end-of-frame (EOF) field. Each data and remote frame is delimited by a flag sequence of seven recessive bits, which notifies all the nodes of the end of an error-free transmission.

To provide a better understanding on each field and bit setting in a data frame, the overall pictures for both standard and extended frame formats are given in Table 3.1 and Table 3.2.

<table>
<thead>
<tr>
<th>Field name</th>
<th>Length (bits)</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start-of-frame (SOF)</td>
<td>1</td>
<td>Denotes the start of frame transmission</td>
</tr>
<tr>
<td>Identifier</td>
<td>11</td>
<td>An identifier for the data</td>
</tr>
<tr>
<td>Remote transmission request (RTR)</td>
<td>1</td>
<td>Dominant (0)</td>
</tr>
<tr>
<td>Identifier extension (IDE)</td>
<td>1</td>
<td>Dominant (0)</td>
</tr>
<tr>
<td>Reserved bit (r0)</td>
<td>1</td>
<td>Have to be sent dominant (0), but receivers accept either dominant or recessive</td>
</tr>
<tr>
<td>Data length code (DLC)</td>
<td>1</td>
<td>Number of bytes of the data (0-8 bytes)</td>
</tr>
<tr>
<td>Data field</td>
<td>0-8 bytes</td>
<td>Data to be transmitted with length corresponded to DLC</td>
</tr>
<tr>
<td>Cyclic Redundancy Check (CRC)</td>
<td>15</td>
<td>Based on division in the ring of polynomials over the smallest finite field</td>
</tr>
<tr>
<td>CRC delimiter</td>
<td>1</td>
<td>Recessive (1)</td>
</tr>
<tr>
<td>ACK slot</td>
<td>1</td>
<td>Transmitter sends recessive (1) and any receiver reply a dominant (0)</td>
</tr>
<tr>
<td>ACK delimiter</td>
<td>1</td>
<td>Recessive (1)</td>
</tr>
<tr>
<td>End-of-frame (EOF)</td>
<td>7</td>
<td>Recessive (1)</td>
</tr>
</tbody>
</table>

Table 3.1. Standard frame format.
Table 3.2. Extended frame format.

<table>
<thead>
<tr>
<th>Field name</th>
<th>Length (bits)</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start-of-frame (SOF)</td>
<td>1</td>
<td>Denotes the start of frame transmission</td>
</tr>
<tr>
<td>Base identifier</td>
<td>11</td>
<td>First part of the identifier for the data</td>
</tr>
<tr>
<td>Substitute remote request (SRR)</td>
<td>1</td>
<td>Recessive (1)</td>
</tr>
<tr>
<td>Identifier extension (IDE)</td>
<td>1</td>
<td>Recessive (1)</td>
</tr>
<tr>
<td>Extended identifier</td>
<td>18</td>
<td>Second part of the identifier for the data</td>
</tr>
<tr>
<td>Remote transmission request (RTR)</td>
<td>1</td>
<td>Dominant (0)</td>
</tr>
<tr>
<td>Reserved bit (r0, r1)</td>
<td>1</td>
<td>Have to be sent dominant (0), but receivers accept either dominant or recessive</td>
</tr>
<tr>
<td>Data length code (DLC)</td>
<td>1</td>
<td>Number of bytes of the data (0-8 bytes)</td>
</tr>
<tr>
<td>Data field</td>
<td>0-8</td>
<td>Data to be transmitted with length corresponded to DLC</td>
</tr>
<tr>
<td>Cyclic Redundancy Check (CRC)</td>
<td>15</td>
<td>Based on division in the ring of polynomials over the smallest finite field</td>
</tr>
<tr>
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<td>ACK slot</td>
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</tr>
<tr>
<td>End-of-frame (EOF)</td>
<td>7</td>
<td>Recessive (1)</td>
</tr>
</tbody>
</table>

Remote Frame

Remote frames are quite similar to data frames. However, there are two main differences between the remote frame and the data frame. Firstly, there is no data field in the remote frame. Secondly, the RTR bit, which is sent as dominant in the data frame, is marked recessive in the remote frame. In general data transmission is done with a data source node sending out data by a data frame. On the other hand, a destination node can also request data from the source by sending a remote frame with the same identifier as one of required data frame. The requested data source node will then reply with a data frame asked by the destination. As mentioned earlier in the report, in the event of a data frame and a remote frame with the same identifier being transmitted at the same time, the data frame wins arbitration due
to the dominant RTR bit following the identifier.\footnote{In this case, the node that transmitted the remote frame receives the desired data immediately.}

**Error Frame**

Error frames represent special messages which violate rules of CAN messages. The error frame is generated by any node in the network that detects a bus error. There are two fields including an error flag and an error delimiter in the error frame. The error flag field is created by the superposition of error flags contributed by different nodes on the bus. There are two kinds of error flags: active and passive. An active error flag is sent by a node that detects an error on the network. In comparison, a passive error flag is transmitted by a node that detects an active error frame on the network. The active error flag is made up of six dominant bits, while the passive error flag consists of six recessive bits. The error delimiter consists of eight recessive bits and allows the bus nodes to restart bus communications cleanly after an error.

**Overload Frame**

Overload frames can be transmitted by nodes which become too busy to process additional data to slow down operations on the network. This is done by adding an extra delay between consecutive data and remote frames. The format of overload frames is very similar to that of error frames. In particular, it is made up of an overload flag followed by an overload delimiter. Note that every node may transmit consecutively only two overload frames. However, the CAN controllers nowadays are very fast, thus, they make the overload frame almost useless.
Chapter 4

Multichannel System Identification

The CAN based multichannel control system is described in this chapter includes the system design and characterization. The system design discusses hardware and software implementations while the system characterization identifies the implemented system noise and capability.

4.1 Original System

The original system of hydrogen leak detector, ASH2000, from Adixen Sensistor can be divided into two main parts regarding the hydrogen sensor; the hand probe and the instrument. As shown in Figure 4.1, a hydrogen sensor provides two output signals, a sensor signal and a heater signal. An analog sensor signal is converted to a digital form by 24-bit analog-to-digital converter (ADC) then is processed by the microcontroller unit (MCU) inside the hand probe. By the algorithm inside an MCU, the sensor signal is compensated and computed into two outputs, analysis and detection results. The raw output represents the unprocessed voltage level of the hydrogen sensor.

On the other side of Figure 4.1, the heater signal inputs a temperature control part which communicates with MCU through a voltage signal. The current through a heating element is controlled by the feedback control signal from MCU with 10-bit digital-to-analog converter (DAC). The diode output is a temperature control value for a heating diode in the hydrogen sensor. A lower output voltage from temperature control unit means a higher temperature on the heating element. Finally, The MCU sends data and communicates with the instrument via the CAN-bus with 29-bit extended frame format.

In this thesis work only two output parameters, raw and analysis, have been used for the experimental measurements and analysis in this project. The real-time output response of test sensor is presented in the raw data. The analysis data represents the level of hydrogen leak regarding the maximum negative deviation
Figure 4.1. Overall system of hydrogen leak detector from Adixen Sensistor.
or slope of raw data in specific time window.

4.2 Multichannel System Design

As mentioned in the previous chapter, ASH2000 hydrogen leak detector is developed using CAN-interface for data communication between hand probes and instruments. With the advantage of the CAN interface over the multiple device communication, one key requirement of the thesis project is the implementation of a multichannel system for measurements and evaluations of hydrogen sensors. The multichannel control system can be categorized into two main parts, the hardware and the software parts.

4.2.1 Hardware Implementation

As mentioned in chapter one, the hand probe printed circuit boards (PCBs) used in the multichannel control box were designed and prepared by Adixen, see Figure 4.2. Figure 4.3 shows the implemented multichannel control unit included 20 probe PCBs. The hardware implementation of the control box can be depicted roughly in Figure 4.4. Five boards of hand probe PCBs are integrated in a panel called Probe panel in Figure 4.4.

The requirement specification states that a dc power supply of 24 volts is required to be used as an input power supply for the multichannel control unit but the hand probes PCBs require 12V input power supply. Thus, a dc voltage conversion is required to step down 24V power supply to 12V input for the probe PCBs. Figure 4.5 shows a schematic of the 12V regulating circuit using a step-down switching regulator.

Since a probe panel with five sensors connected requires approximately 1A load current, one individual set of voltage regulating board which guarantees 2A output load current as specified in the datasheet of the switching regulator [9], LM2592HVAdj, is needed for each probe panel.

4.2.2 Software Implementation

The control software for the multichannel system has been done in LabVIEW program which is basically a graphical programming language for data acquisition,
Figure 4.3. The implemented multichannel control unit.
Figure 4.4. An overview of the hardware implementation.

Figure 4.5. A schematic level of 12V regulating circuit.
instrument control, and industrial automation. A fundamental Queued State Machine (QSM) architecture based on a ‘While loop’, a ‘Case statement’ and a shift register, which is a LabVIEW programming method often used to implement complex decision-making algorithms from one or more parallel processes, has been introduced for the control software approach.

Figure 4.6 illustrates an example of simple QSM architecture. The commands processor handles commands and data produced by the parallel SubVI processes, such as instrument control, CAN communication and data acquisition, regarding the queue reference [5]. Figure 4.7 shows the LabVIEW front panel of the implemented multichannel control software.

![Simple block diagram of Queued State Machine](image)

**Figure 4.6.** Simple block diagram of Queued State Machine [5].

To support various types of test and evaluation of the gas sensors, some basic conceptual requirements for the control software are introduced in the requirement specifications which can be summarized as listed in the followings:

- A control software is able to control and communicate with the designed hardware unit via CAN interface.
- A control software is able to acquire, compute, present and store the signal responses from the test devices.
- A serial communication, RS-232, is required in the control software to control gas selection valves which handle the gas concentration in the test chamber.
- A control software is able to handle an automated input pattern, an excel file, and operate the test system as designed.

### 4.3 System Characterization

System characterization covers both software and hardware validations which assure that the implementeded system works accordingly to the requirements in a
4.3 System Characterization

Figure 4.7. Front panel of LabView software for multichannel test system.

consistent and reproducible manner. The validation process requires several tests and measurements which can be categorized into two main parts, the overall system capabilities and the system noise.

4.3.1 Overall System Capabilities

In order to specify performances of the multichannel system, two key system capabilities are defined:

1. **Sampling rate:** The maximum sampling rate of the multichannel system is limited mainly by the LabVIEW software corresponding to a CPU speed. The data control loop, which handles the received messages from the microcontrollers, takes 50 milliseconds approximately to be finished for all 20 channels. This results in a maximum sampling rate of 20 Hz with 20 input channels.

2. **Ramp detection:** As the negative slope represents a gas concentration detected by hydrogen sensors, the smallest negative ramp which can be detected by the designed system is another key parameter to be measured. The measurement is done by introducing a controlled triangle wave signal from a signal generator to a sensor input of the control box. Therefore, by adjusting the amplitude and frequency of the input triangle wave, the lowest negative ramp which is detectable can be measured as shown in Figure 4.8 and 4.9.

Figure 4.8 depicts the lowest triangle wave that the multichannel system and the analysis algorithm can detect which is 11 $\mu$V/s on the negative slope (n-
As shown in Figure 4.9, there are a few ramps that were misdetected which means that the ramp signal of 10 $\mu$V/s n-slope is on the limit of the multichannel system detectability of sensor response.

Note that the analysis data presents the highest value of negative slope detected by the algorithm implemented inside the hand probe MCU within the specific sampling window. Thus, small differences in the amplitudes of analysis data from the same input ramp could be found due to the synchronization of sampling rate and the timing of each ramp signal.

**Figure 4.8.** Measurement results for the ramp detection with 11 $\mu$V/s n-slope ramp signal.

**Figure 4.9.** Measurement results for the ramp detection with 10 $\mu$V/s n-slope ramp signal.
4.3 System Characterization

4.3.2 System Noise

Even though the majority of the noise in signal bandwidth is generated from the sensor, it is beneficial to measure the level of noise from an electronic part. However, the measurement for a low noise in assembled PCBs is practically not possible without an appropriate instrument, a simple test can be performed by replacing the gas sensing transistor part of the sensor with a fixed resistor, 18-kΩ resistor, see Figure 4.10. Without a noise from an electronic part, the output voltage should ideally remain constant.

Figure 4.10. Replacement of sensing transistor with fixed resistor in schematic of gas sensor.

Figure 4.11 represents the measurement for system noise estimation. The top graph shows that the output response from the fixed resistor is not completely clean but looks quite noisy with peak-to-peak amplitude fluctuation around 10 µV. However, when converting to the frequency domain, the Fourier transform of the noisy signal finds only the frequency components closed to a dc level with very little noise at very low frequencies, see bottom graph in Figure 4.11. The analysis algorithm is also not able to detect the very low noise from the system hardware. Thus the multichannel system noise can be considered to be unharm to measurements of sensor reponses.
Figure 4.11. Experimental results for the system noise estimation.
Chapter 5

Sensor Noise Evaluation

In this chapter, the evaluation of a noisy behavior of the analog gas sensor, comprises the experimental setup and results, is defined. Furthermore, a conclusion of the experimental studies is included.

5.1 Background

The CAN-base multichannel control system is developed for the evaluation of nanostructured metal oxide semiconductor based gas sensors in order to improve sensitivity and reliability of the hydrogen leak detectors. The key parameter to begin for the system improvement is to understand an unpredicted noisy sensor behavior, will be called a sensor noise later in the report.

According to earlier studies by Adixen, the noise density has been measured by Fourier transform and it has shown that such analysis is practically impossible. Even with the reliable measurement of the noise in the specific frequency region, it is still difficult to evaluate how the noise impacts the actual analysis algorithm. Figure 5.1 shows an example of a noisy output signal obtained from a hydrogen sensor.

Thus, the first approach to estimate the noise in hydrogen sensors is to emulate gas exposure by applying a known triangle wave to the sensor output.

5.2 Experiment Setup

The basic test setup of the sensor noise measurement, see Figure 5.2, comprises of the ramp controlled mixing system, the multichannel control box and the computer-based LabVIEW software for sensor response acquisition. The ramp controlled mixing part, shown in Figure 5.3, can be devided into two parts includes a sensor output current control part and a voltage adder part.

The sensor output current source, as shown in Figure 5.4, is developed from the operational amplifier (op-amp) and transistor current source circuit, which supplies an output current to a gas sensing transistor (T) inside the sensor. An
Figure 5.1. Example of noisy signal from hydrogen sensor.

Figure 5.2. The test setup of sensor noise measurement.

Figure 5.3. The implemented ramp controlled mixing circuit board.
op-amp buffer circuit is applied between the sensing transistor and the sensor voltage. Figure 5.5 shows the schematic level of the implemented voltage adder which is developed from a basic non-inverting summing amplifier using a rail-to-rail op-amp for the maximum output voltage swing. With the limitation of the signal generator used for a triangle wave generator, an addition voltage divider using a precision potentiometer has been added to adjust and control the slope of the input ramp signal.

Figure 5.4. The schematic level of a sensor output current control part.

5.3 Measurement Results

With the possibility to vary the size of the ramp signal added to the sensor signal, the experimental results of sensor noise quantification are presented in Figures 5.6, 5.7, 5.8 and 5.9 respectively. RawData graph represents the output signal response which in this case is a sensor signal mixed with a ramp signal. AnalysisData graph shows the level of gas detection from the algorithm computation. Reference graph identifies the detection level of the input ramp signal applied to each case, it will be used to compare with the detection of the mixed signal. Errors or differences between two detection graphs, AnalysisData and Reference, are considered as noise from the gas sensor.

Figure 5.6 shows the experimental results of a noisy sensor signal added with a non-ideal triangle wave of a 40 nV/s negative slope (n-slope). Note that the low frequency triangle wave, generated by the signal generator used in the experiment,
is not quite symmetrical with a twice higher slope on positive side (p-slope) than n-slope. The detection level of the mixed signal shown in Figure 5.6 maps the reference graph quite perfectly, all the gas exposures are detectable. This can be assumed that the sensor noise impact is not as great compared to the level of the ramp signal.

A 38 µV/s n-slope ramp signal has been applied to the second experiment, see Figure 5.7. The sensor noise causes a few misdetected response from the algorithm but the majority of the gas exposures sequences are detected which means that the ramp level is close to the noise level.

Shown in Figure 5.8, the sensor signal has been mixed with a 35 µV/s n-slope ramp signal. Although the measurement results show both misdetected and false detected signals, the amplitude of the false alarm is still lower that the gas detection level and the size of misdetection reponse is still acceptable. In this case,
5.4 Summary

Figure 5.7. Sensor noise quantification: measured with 38 $\mu$V/s n-slope ramp signal added to hydrogen sensor.

the level of controlled triangle wave is right at the margin of sensor noise level.

Figure 5.8. Sensor noise quantification: measured with 35 $\mu$V/s n-slope ramp signal added to hydrogen sensor.

From the experimental results shown in Figure 5.9, the average noise level from the gas sensor can be assumed to be above the level of the input ramp signal, which is 30 $\mu$V/s n-slope. Since the sensor noise causes a big false detection and also contains wider area of misdetection compared to the previous case.

5.4 Summary

Since the sensor responses causes negative slopes behave similar to the signal responses when detecting hydrogen exposures which could cause false alarms to the
hydrogen detecting system, it is beneficial for the leak detecting system developer to know the average noise level generated by the gas sensors.

Respecting an introduction of the known ramp signal added with the gas sensing signal and the advantage of the analysis algorithm from Adixen, the measurement data should considerably reflect the average level of the sensor noise. According the experimental results, the average limit of sensor noise was found to be approximately $35 \, \mu V/s$ on the negative slope.
Chapter 6

Gas Sensor Characterization

Recognizing the need for the CAN based multichannel control system verification, this chapter describes the characterization of gas sensors developed by Adixen includes experimental setup, measurements and discussion.

6.1 Experimental Setup

This section discusses the test setup for the characterization of catalytic gate MOSFET based gas sensors using the test bench. The change in the threshold voltage of the sensing transistor when the sensor is exposed to varying concentration of test gas can be measured. Figure 6.1 depicts the experimental setup for the characterization of hydrogen sensors.

![Sensor test bench for characterization of analog hydrogen sensors.](image)

Figure 6.1. Sensor test bench for characterization of analog hydrogen sensors.

The test bench comprises of the gas selection system, sensor test chamber,
multichannel control unit and the LabVIEW based computer software for sensor response acquisition. The gas selection system includes programmable logic controller (PLC), switching relays and pressure regulators to control the flow of gas through the test chamber. In this experiment, 10 parts per million (ppm), 400 ppm and 50,000 ppm or 5% hydrogen concentrations are used to simulate different hydrogen leaks. Two different sets of hydrogen sensors developed by Adixen, called HS-85 and HS-04, are used to be tested in the sensor test chamber, see Figure 6.2. Three HS-85 sensors are marked as sensor group 1 while the others, HS-04, are marked as sensor group 2. The membrane filter is added inside the test chamber to prevent an effect of any gas flows to the test sensors.

![Figure 6.2. Two different types of hydrogen sensors inside the sensor test chamber.](image)

### 6.2 Test Results

Different gas leaks have been exposed to the sensor test chamber for a period of 10 seconds as depicted as the marked green area in the following graphs.

#### 10 ppm leak

Figure 6.3 shows the sensor responses and the analysis algorithm results of the test sensors in group 1 with 10 ppm gas exposure. The output responses of test sensors show similar behaviors with different levels of detection depending on the sensitivity of each sensor. Sensor number three, in the bottom graph, tends to have the highest sensitivity for 10 ppm leak. An approximately delay of 0.5 seconds is found to be an average reaction time of the analysis algorithm. Delay time between 1 to 2 seconds after the removal of gas exposure are needed to clear the algorithm responses.

The measurement of the test sensors group 2, see Figure 6.4, shows much lower level of analysis responses compared with the results from sensors group 1. The average reaction time is about 1 seconds which is twice longer than the reaction time of group 1. Also the algorithm with group 2 sensors needs 4 to 6 seconds for the removal of the detection signal since the sensors recovered very slowly after the gas leak was removed compared with the sensors in group 1.
Figure 6.3. Measurement results of gas sensors in group 1 with 10 ppm hydrogen exposure.
Figure 6.4. Measurement results of gas sensors in group 2 with 10 ppm hydrogen exposure.
400 ppm leak

The comparisons of sensors responses to medium concentration hydrogen exposure between the sensors in group 1 and the sensor in group 2 are presented in Figure 6.5 and Figure 6.6. Similarly to the 10 ppm leak test, the results of group 1 sensors show that overall respond to 400 ppm leak quicker with higher analysis levels and much better recovery time than sensors of group 2.

5% leak

Finally, with the high concentration range of gas leak, as shown in Figure 6.7 and Figure 6.8, the measurements of group 2 sensors show that the average reaction time after the gas exposure is as quick as sensors in group 1 with similar level of analysis detection. However, the sensor responses after the removal of gas leak are much slower than the recovery responses of group 1 sensors.

6.3 Summary

The test sensors in group 1, HS-85, overall perform better in all range of leak detection than the sensors in group 2, HS-04. In all concentration ranges of gas leak, the measurement results of HS-85 sensor show higher sensitivity, faster reaction time and better recovery of sensor response after the removal of gas exposure than the results from HS-04 sensors.
Figure 6.5. Measurement results of gas sensors in group 1 with 400 ppm hydrogen exposure.
Figure 6.6. Measurement results of gas sensors in group 2 with 400 ppm hydrogen exposure.
Figure 6.7. Measurement results of gas sensors in group 1 with 5% hydrogen exposure.
Figure 6.8. Measurement results of gas sensors in group 2 with 5% hydrogen exposure.
Chapter 7

Conclusion and Future Work

7.1 Conclusion

The aim of the diploma work was to design and develop a CAN based multichannel test system for the evaluation of different sensors performances. The synthesized signal mixer for quantitative in-circuit analysis of the ultra low frequency noise in gas sensor has also been developed as a part of the thesis.

Firstly, experiments were made to quantify the average level of the ultra low frequency sensor noise. With the use of the synthesized signal mixer and the analysis algorithm developed by Adixen, the average limit of sensor noise was found to be approximately $35 \, \mu V/s$ on the negative slope side of the ramp signal.

Secondly, the CAN based multichannel system has been implemented to evaluate two different types of gas sensors. The measurement results show that one type of test sensors has significantly better performance in key parameters, such as sensitivity, response time and recovery time, than the other type of sensor. However, all sensor of the same type tend to behave similarly in all concentration ranges of gas exposure.

Finally, implementation-wise, the CAN based multichannel control box, LabVIEW control software for CAN master and the synthesized signal mixer considerably fulfilled the goal of the thesis work.

7.2 Future Work

In order to evaluate different sensors performances in wider range of key parameters, more test systems can be added to the current test bench using the CAN based multichannel control box, such as an automatic controlled arm for a movable gas leak test. Also additional tests can be performed with an option to control the temperature of the sensor chip through CAN messages, thus, sensor performances in different temperature set points can be evaluated. Finally, it is interesting to do a real measurement outside the laboratory which might contain interferences affecting sensor signals.
Bibliography


