NTNU
Norwegian University of
Science and Technology

Calibration and uncertainty analysis of pressure sensors used for dynamic measurements

Aase Sørum Melaaen

Master of Science in Engineering and ICT
Submission date: June 2017
Supervisor: Ole Gunnar Dahlhaug, EPT
Co-supervisor: Einar Agnalt, EPT
Bjørn Winther Solemslie, EPT
Carl Bergan, EPT

Norwegian University of Science and Technology
Department of Energy and Process Engineering

NTNU

Norges teknisk-naturvitenskapelige universitet

Institutt for energi- og prosessteknikk

EPT-M-2017- 51

MASTEROPPGAVE

for

Student Aase Melaaen

Våren 2017

Kalibrering og usikkerhetsanalyse av trykksensorer som benyttes til dynamiske målinger

Calibration and uncertainty analysis of pressure sensors used for dynamic measurements

Bakgrunn

Ved Vannkraftlaboratoriet på NTNU benyttes mange trykk sensorer til å måle hurtige oscillasjoner av trykk. Dette er typisk trykkvariasjoner knyttet til sugerør svingninger, rotor-stator interaksjon mellom løpehjuls skovler og ledeskovler, von Karman virvler, etc. Disse trykk oscillasjonene kan variere fra en til mange tusen hertz, og alle trykk sensorene som benyttes til disse er kalibrert med statisk trykk. Det er usikkert om en statisk kalibrering er gyldig for en dynamisk måling og derfor har man besluttet å etablere en kalibrering av sensorer som benyttes til å måle hurtige oscillasjoner av trykk.

Målsetting

Etablere en metode for dynamisk kalibrering av trykksensorer ved Vannkraftlaboratoriet

Oppgaven bearbeides ut fra følgende punkter

1. Litteraturstudie over etablerte metoder for kalibrering av trykksensorer
2. Evaluere eksisterende metoder for dynamisk kalibrering og anbefale et system for Vannkraftlaboratoriet
3. Dersom det er mulig skal studenten designe og bygge et system for dynamisk kalibrering.
4. Det gjennomføres trykkmålinger i tilløpsrør på Pelton turbin test rigg. Trykksensorene kalibreres statisk og dynamisk.
5. Usikkerheten i målingene beregnes basert på tilgjengelige kalibreringer.
6. Dersom det er tid, skal studenten kalibrere trykksensorer som er benyttet i løpehjulet på Francis turbinen som er installert i Vannkraftlaboartoriet. Deretter beregnes en måleusikkerhet basert på statisk og dynamisk kalibrering.

7. Tidligere arbeid fra prosjektet og det videre arbeidet i denne hovedoppgaven vil bli skrevet som en egen publikasjon og presentert på konferansen: *7^{th} International symposium on Current Research in Hydraulic Turbines (CRHT-VII)* ved Kathmandu University i April 2017.

Senest 14 dager etter utlevering av oppgaven skal kandidaten levere/sende instituttet en detaljert fremdrift- og eventuelt forsøksplan for oppgaven til evaluering og eventuelt diskusjon med faglig ansvarlig/veiledere. Detaljer ved eventuell utførelse av dataprogrammer skal avtales nærmere i samråd med faglig ansvarlig.

Besvarelsen redigeres mest mulig som en forskningsrapport med et sammendrag både på norsk og engelsk, konklusjon, litteraturliste, innholdsfortegnelse etc. Ved utarbeidelsen av teksten skal kandidaten legge vekt på å gjøre teksten oversiktlig og velskrevet. Med henblikk på lesning av besvarelsen er det viktig at de nødvendige henvisninger for korresponderende steder i tekst, tabeller og figurer anføres på begge steder. Ved bedømmelsen legges det stor vekt på at resultatene er grundig bearbeidet, at de oppstilles tabellarisk og/eller grafisk på en oversiktlig måte, og at de er diskutert utførlig.

Alle benyttede kilder, også muntlige opplysninger, skal oppgis på fullstendig måte. For tidsskrifter og bøker oppgis forfatter, tittel, årgang, sidetall og eventuelt figurnummer.

Det forutsettes at kandidaten tar initiativ til og holder nødvendig kontakt med faglærer og veileder(e). Kandidaten skal rette seg etter de reglementer og retningslinjer som gjelder ved alle (andre) fagmiljøer som kandidaten har kontakt med gjennom sin utførelse av oppgaven, samt etter eventuelle pålegg fra Institutt for energi- og prosessteknikk.

Risikovurdering av kandidatens arbeid skal gjennomføres i henhold til instituttets prosedyrer. Risikovurderingen skal dokumenteres og inngå som del av besvarelsen. Hendelser relatert til kandidatens arbeid med uheldig innvirkning på helse, miljø eller sikkerhet, skal dokumenteres og inngå som en del av besvarelsen. Hvis dokumentasjonen på risikovurderingen utgjør veldig mange sider, leveres den fulle versjonen elektronisk til veileder og et utdrag inkluderes i besvarelsen.

I henhold til ”Utfyllende regler til studieforskriften for teknologistudiet/sivilingeniørstudiet” ved NTNU § 20, forbeholder instituttet seg retten til å benytte alle resultater og data til undervisnings- og forskningsformål, samt til fremtidige publikasjoner.

Besvarelsen leveres digitalt i DAIM. Et faglig sammendrag med oppgavens tittel, kandidatens navn, veileders navn, årstall, instituttnavn, og NTNUs logo og navn, leveres til instituttet som en separat pdf-fil. Etter avtale leveres besvarelse og evt. annet materiale til veileder i digitalt format.

☒ Arbeid i Vannkraftlaboratoriet
☐ Feltarbeid

NTNU, Institutt for energi- og prosessteknikk, 15. januar 2017

Ole G. Dahlhaug
____
Ole Gunnar Dahlhaug
Faglig ansvarlig/veileder

Medveiledere:
Einar Agnalt
Bjørn Winther Solemslie
Carl Bergan

Preface

This master's thesis is written at NTNU, Faculty of Engineering and Technology, Department of Energy and Process Engineering, Waterpower Laboratory.

My master's thesis presents the first steps in development of a dynamic pressure calibration method from literature search, design, engineering to construction and testing. This assignment has been challenging both theoretically and practically. In connection with the construction of the test equipment, I needed to order several components. Several of the deliveries were delayed, and some of the in-house constructions were impossible to complete according to the technical drawings. This led to further delays in the final date for equipment completion and test start-up. These issues have been beyond my control, but have given me a lot of project experience and scientific knowledge. Even if periods have been frustrating, I have learned a lot.

During the master's thesis working period, my class received a sponsored trip to Nepal where we attended a conference in April on hydropower at the Kathmandu University. I presented my master's thesis publication shown in Appendix A at the conference. Conference participants showed interest for my master's thesis, indicating the usefulness to have a dynamic pressure calibration system when dynamic measurements are needed. In Nepal, we visited different hydropower plants and schools that made a big impression, and this will be an experience I will remember for a long time. It was an informative and nice trip, which I am grateful for having participated in.

I would thank my supervisor Professor Ole Gunnar Dahlhaug for an exciting and challenging task, and for good guidance. A special thanks to Einar Agnalt for providing good ideas, valuable discussions and for always showing interest in my work. He also helped me with simulations in Ansys and 3D printing. Finally, I would thank Helene Syrstad for machining the calibration tool and Carl Bergan who was of great help when I needed guidance with LabVIEW.

Aase Sørum Melaaen

Trondheim, Norway

Summary

Dynamic calibration of pressure sensors is challenging. Often, steady-state calibration is applied on pressure sensors used to measure dynamical measurements. Steady-state calibration does not represent the dynamic behavior of a sensor. With dynamical calibration the quality of a dynamical measurement increases. This is the motivation for my master's thesis, written at the Waterpower Laboratory at NTNU in spring 2017. The master's thesis investigates methods for performing dynamic calibration. The best method is believed to be the use of an aperiodic pressure generator, because of its large range of frequencies and pressures, and in addition, the low cost and simple construction. The dynamic calibration method developed in this master's thesis is based on a step-response method with use of ultra-fast diaphragm valves with response time less than 5 ms.

The target was to build a functional dynamic calibration system, and by use of the system, find the natural frequency of the calibrated sensor. By finding the natural frequency of the calibrated sensor, it is possible to find the uncertainty in dynamic measurements, and therefore increase the quality of the measurements.

To generate a perfect working dynamic calibration system was proven to be difficult. The first problem arose when it was realized that the machining of the calibration system was not done according to the drawings. These inaccuracies resulted in air pockets in the system that was impossible to deflate, and as a consequence, signal noise was observed in the pressure step. The second problem was the behavior of the diaphragm valves. When the valve opened, the open-valve position was not fixed, and the diaphragm piston started to oscillate. This led to slow fluctuations prior to the final state after the step. The slow fluctuations worked as a low pass filter and delayed the entire system. This caused a slow rise time of the step generated.

The closing position of the valves was fixed, and here the slow fluctuations did not occur, and the rise time improved. The calibration system does still not work in a perfect manner, but has a range of application. An almost suitable step was generated, and with use of Fast Fourier Transform it could be indicated that the highest natural frequency achieved by the system was 2246Hz. By knowing this frequency and with use of a reference sensor it can be determined if a calibrated sensor does not need an extra uncertainty term. The dynamic calibration system developed could also be used to verify if a dynamic pressure sensor and amplifier behave in a correct manner. However, these methods need further investigation by experiments. Further work has also been an important part of this master's thesis.

Sammendrag

Dynamisk kalibrering av trykksensorer er utfordrende. Ofte brukes statisk kalibrering på trykksensorer som brukes til å utføre dynamiske målinger. Statisk kalibrering representerer ikke den dynamiske oppførelsen til en sensor. Med dynamisk kalibrering øker kvaliteten på en dynamisk måling. Dette er motivasjonen for masteroppgaven min, skrevet på Vannkraftlaboratoriet ved NTNU våren 2017. Oppgaven undersøker metoder for dynamisk kalibrering. Den beste metoden antas å være bruk av en aperiodisk trykkgenerator på grunn av sitt store frekvens- og trykk område, og i tillegg er konstruksjonen billig og antatt enkel å lage. Den dynamiske kalibreringsmetoden utviklet i denne oppgaven, er basert på en sprangrespons-metode med bruk av ultra-raske membranventiler med responstid under 5ms.

Målet var å bygge et funksjonelt dynamisk kalibreringssystem, og ved bruk av systemet finne den naturlige frekvensen til en sensor som skal kalibreres. Ved å finne den naturlige frekvensen til den kalibrerte sensoren, er det mulig å finne usikkerheten i dynamiske målinger, og dermed øke kvaliteten på målingene.

Et dynamisk kalibreringssystem viste seg å være vanskelig å lage. Det første problemet oppsto da kalibreringssystemet ikke ble maskinert i henhold til arbeidstegningene. Disse unøyaktighetene resulterte i luftlommer i systemet som var umulig å få ut, og som en følge ble signalstøy observert i spranget. Det andre problemet var ventilens oppførsel. Når ventilen åpnet, ble ikke posisjonen til ventilen låst, og membranstemplet begynte å svinge. Dette førte til trege svingninger før den endelige tilstanden etter spranget ble oppnådd. De trege svingningene fungerte som et lavpassfilter og lagde forsinkelser i systemet. Dette forårsaket en langsom stigningstid for det genererte spranget.

Når ventilene ble lukket, kom de i en låst posisjon. De trege svingningene fremkom ikke, og stigningstiden ble forbedret. Kalibreringssystemet fungerer fortsatt ikke på en perfekt måte, men det har et bruksområde. Det er generert brukbare sprang, og ved bruk av Fast Fourier Transform kan det antydes at den høyeste egenfrekvensen oppnådd av systemet var 2246Hz. Ved å kjenne systemets egenfrekvens og ved bruk av en referanse sensor, kan det avgjøres om en kalibrert sensor, ikke trenger et ekstra usikkerhetsledd. Det dynamiske kalibreringssystemet kan også brukes til å verifisere om en dynamisk trykksensor og forsterker oppfører seg på en korrekt måte. Disse metodene trenger ytterligere undersøkelser ved eksperimenter. Forslag til videre arbeid har også vært en viktig del av denne masteroppgaven.

Table of Contents

List of Figures

List of Tables

Nomenclature

Symbol	Description	Unit
a	Speed of sound	*m/s*
c	Viscous damping factor	*N·s/m*
F(t)	Force	*N*
f_{cav}	Helmholtz resonance frequency	*Hz*
$f_{Nyquist}$	Nyquist frequency	*Hz*
f_s	Logging frequency	*Hz*
G(s)	Transfer function	-
H(s)	Transfer function	-
IN(s)	Laplace Transform	-
K	Gain	-
k	Stiffness	*N/m*
L	Length	*m*
L'	Length	*m*
m	Mass	*kg*
OUT(s)	Laplace Transform	-
s	Complex variable	-
S_{neck}	Cross section area	m^2
T	Period	*s*
t	Time	*s*
V_0	Volume	m^3
x	Length	*m*
ω_o	Natural frequency	*rad/s*
ζ	Damping ratio	-

Abbreviations

Abbreviation	Meaning
CFD	Computational fluid dynamics
CompactDAQ	Compact Data Acquisition
FFT	Fast Fourier transform
NTNU	Norwegian University of Science and Technology
PCU	Piston/Cylinder Unit
RSS	Root Sum Square

1 Introduction

1.1 Background

The Waterpower Laboratory at the Norwegian University of Science and Technology calibrates pressure sensors with steady-state pressure, even though the sensors are used for dynamic measurements, i.e., measurements of pressure change with time. Calibrating a pressure sensor dynamically is essential to determine its dynamic behavior. Determining and locating the natural frequency of the pressure sensors will automatically give measurements that are more reliable and accurate.

Dynamic calibration of pressure sensors has been researched and explored throughout the last fifty years. Even though, at this moment no international standard for dynamic pressure calibration exists, and, as this is a wide and advanced topic it still needs more research [3]. Since there is no standard for dynamical pressure calibration, there is no international agreement for how and what to analyze in the calibration. Sensitivity, rise time and the natural frequency of the sensor have typically been analyzed [1].

1.2 Objective

The objective for this master's thesis is to design and establish a dynamic calibration system for pressure sensors at the Waterpower laboratory at NTNU.

1.3 Motivation

The motivation for this master's thesis is to improve the uncertainty in dynamic measurements conducted at the Waterpower Laboratory at NTNU. With use of a dynamic calibration system, it is possible to compensate for the uncertainty caused by the natural frequency, f_n, to a pressure sensor [4]. The useful frequency range of the sensor can therefore be found by knowing its natural frequency. As a guideline, frequencies measured should be less than $0.1 \cdot f_n$, if no correction for the natural frequency is done [5]. Figure 1 illustrates the principle.

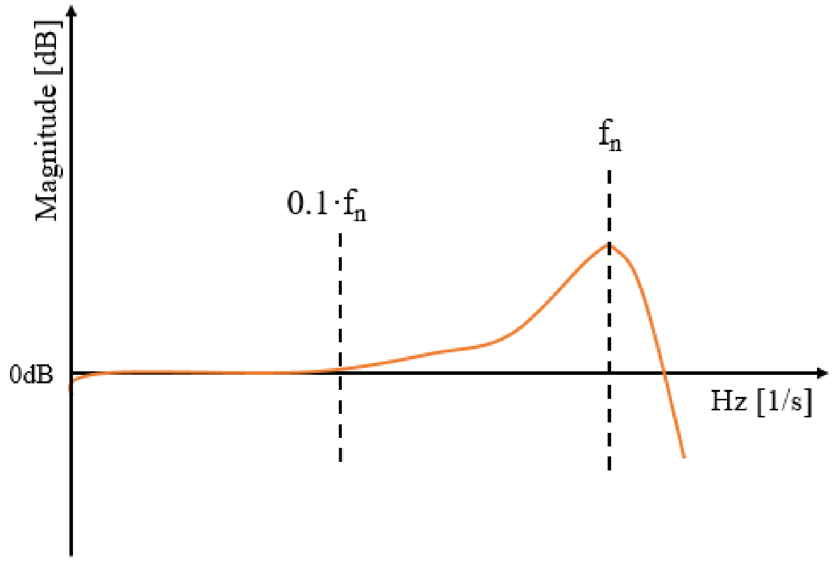


Figure 1 – Behavior caused by the natural frequency of a pressure sensor

If the measurement is within the area between $0.1 \cdot f_n$ and f_n, the measured value will be higher than expected since the measurement is in the range to be affected by the natural frequency of the sensor. With use of steady-state calibration, the natural frequency to the sensor will not be located, and measurements within the area between $0.1 \cdot f_n$ and f_n, could be registered without compensating for the natural frequency.

The frequencies to be measured at the laboratory are usually between 0Hz and 1000Hz, so the motivation is to construct a dynamic calibration system that can ensure that the sensor is capable of measuring correctly within these frequencies.

1.4 Report Structure

Chapter 1 presents the background, objective and motivation which lay the foundation of this thesis.

Chapter 2 provides an overview of the existing research results in this field of study.

Chapter 3 presents the theory used to design the calibration tool, and to log and analyze the measurements.

Chapter 4 presents the 3D drawings of the calibration tool developed, with all its components explained and justified.

Chapter 5 presents the experimental setup in the Waterpower Laboratory for obtaining a calibration system included all external components.

Chapter 6 serves the elements included in uncertainty analyses for dynamic calibration.

Chapter 7 explains the new design of the calibration tool achieved after machining.

Chapter 8 presents and discusses the results achieved with the calibration system developed in current master's thesis.

Chapter 9 gives an overview of the important findings and a conclusion based on the results achieved.

Chapter 10 gives recommendations for improvements of current calibration system, and ideas for further analyzing aspects.

2 Previous work

Many research projects about dynamic pressure measurements have included dynamic calibration of pressure sensors. Determination of the dynamic features of a sensor in a reliable and accurate way is critical to achieve reliable research results. According to Diniz et. al [6] it is insufficient only to measure the exact value of the measured quantity in an accurate manner, the output should also reproduce the time and frequency behavior of the quantity.

There is no international standard method for dynamic calibration and the topic is still under research. Diniz et. al [6], J. P. Damion [7], ISA-37.16.01 standard [8], Hurst et. al [9] and Lally et. al [10] have written scientific articles about dynamic calibration methods, which experimentally characterize the dynamic behavior of pressure sensors. There are two main ways presented, either to generate a periodic or an aperiodic pressure pulsation. These methods are discussed more thoroughly in Sections 2.1 and 2.2.

2.1 Periodic pressure generator

Dynamic calibration performed by using a periodic pressure generator is also denoted as harmonic tests. This calibration is done by generating a sinusoidal pressure input of a given amplitude and frequency to the sensor that is being calibrated. Since the exact amplitude and frequency cannot be determined at input, another pressure sensor with high dynamic sensitivity is needed as a reference sensor, according to ISA-37.16.01 standard [8]. Varying the input frequency point-by-point gives the opportunity to determine the transfer function.

There are different ways to make a periodic pressure generator, but there are three main concepts, which can be read about in the article from J.P. Damion [7]. The first concept is based on pressure in a cavity that changes sinusoidally. The second concept is based on variation in volume or mass inside a cavity. The last concept is based on direct control of the input frequency with use of a modulation motor. According to Diniz et. al [6] the periodic pressure generator can in practice, be difficult to control and build. To avoid a high distortion rate, the input frequency and amplitude must be low. This causes periodic pressure generators to be of limited use since the available range is way below the user's requirements. Thus, J.P. Damion [7] and ISA-37.16.01 standard [8] suggest the solution is an aperiodic pressure generator.

2.2 Aperiodic pressure generator

Dynamic calibration done by an aperiodic pressure generator, also denoted as transient tests, is performed by generating a pressure step to the sensor that is being calibrated. The sensor being calibrated should then reproduce the step. Nascimento et. al [11] presents that usually a reference pressure sensor is also included in the aperiodic pressure generator test, since the pressure step is not perfect. By use of these two sensors, a transfer function can be determined.

There are two main concepts to make an aperiodic pressure generator, according to ISA-37.16.01 standard [8], Nascimento et. al [11], M. Nilsson [1] and Hurst et. al [4]. The first concept is based on generating the pressure step with use of a shock tube. A shock tube is basically made up by two tubes, separated by a thin diaphragm. This is illustrated in the articles written by ISA-37.16.01 standard [8], M. Nilsson [1] and Z. Wang et. al [12]. In the two different sections of the shock tube, different pressure levels are developed. When the thin diaphragm between the two tubes ruptures, the high level pressure flows towards the low level pressure and compresses it. This will form a step, which is registered by both the sensor being calibrated and the reference sensor. The research article written by Diniz et. al [6], emphasizes that the quality of the pressure signal is affected by the deformation of the diaphragm, under pressure.

The other concept of an aperiodic pressure generator is based on using a fast-opening device. This method is easy to implement and can reach a wide area of frequencies and pressures, according to Diniz et. al [6] and Nascimento et. al [11]. The fast-opening device system is made up by two cavities with different pressure levels and volumes. An ultra-fast valve separates the two areas, and when the valve opens, the high level pressure area moves to the low level pressure area, where the sensor being calibrated and the reference sensor is placed. According to Damion [7], the fast opening device does have a lower frequency limit than the shock tube. Furthermore, he states that with a reference sensor that is dynamically calibrated, the highest frequency limit could be almost the same. The highest frequency limit for a shock tube is 100kHz, according to Diniz et. al [6] and Damion [7]. By using the two sensors, a transfer function for the sensor being calibrated can be developed. Figure 2 shows the principle behind a fast-opening device step generator. The calibration system developed in current master's thesis is based on the fast-opening device step generator.

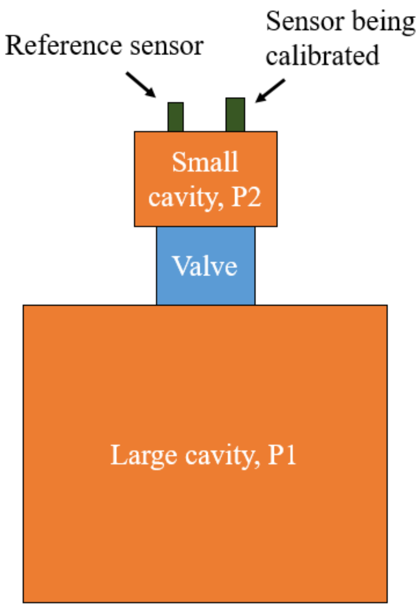


Figure 2 – Principle behind fast-opening device step generator

3 Theoretical background

To be able to create and analyze the calibration system, theory regarding transfer function, Bode diagram, Helmholtz response, discrete signals and Nyquist sampling theorem were used, which is presented in Sections 3.1-3.5.

3.1 Transfer function

Steady-state calibration characterizes pressure sensors by their sensitivity. Characterizing a pressure sensor by its sensitivity is insufficient for dynamic calibration since the input varies with time [7]. Describing a pressure sensor using a differential equation gives a trivial solution. A better way to describe the calibrated sensor is with its transfer function [13]. The transfer function completely quantifies and qualifies the dynamical behavior of the sensor, considering gain and phase as functions of frequency [1, 8, 13].

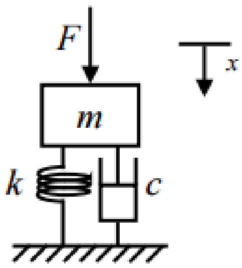


Figure 3 – Mass-damping system [1]

The properties of a pressure sensor are assumed to be represented by a linear second order differential equation [1, 3], with mass *m*, stiffness *k* and viscous damping factor *c*, illustrated in Figure 3. Equation (1) describes the system

$$\frac{d^2x}{dt^2} + \frac{c}{m} \cdot \frac{dx}{dt} + \frac{k \cdot x}{m} = \frac{F(t)}{m} \qquad \left[\frac{m}{s^2}\right] \tag{1}$$

By use of the Laplace Transform, the transfer function which describes the characteristics of a pressure sensor is given by Equation (2)

$$G(s) = \frac{OUT(s)}{IN(s)} = \frac{K \cdot \omega_o^2}{s^2 + 2 \cdot \zeta \cdot \omega_o \cdot s + \omega_o^2} \qquad [-] \tag{2}$$

where abbreviations, constants and variables are shown in Table 1.

Table 1 - Abbreviations, constants and variables used in Equation (2)

Component	**Description**	**Unit**
OUT(s)	Laplace Transform of the output	-
IN(s)	Laplace Transform of the input	-
K	Gain	-
ω_o	Natural frequency of the system	*[rad/sec]*
s	Complex variable	-
ζ	Damping ratio	-

By use of the calibration system to be developed in this master's thesis, an almost perfect pressure step can in theory be created. The transfer function to a perfect step is given in Equation (3), a first order transfer function with no latency [14].

$$H(s) = \frac{K}{T \cdot s + 1} \qquad [-] \tag{3}$$

where K is the gain and T is the time constant.

Equation (3) is used before the calibration system was up and running, for quality measuring frequencies and estimating the expected results from the pressure sensor calibration.

The calibrated sensor is recording its own characteristics, the frequency response to the calibration tool and the pressure step generated. Likewise, the reference sensor is recording its own characteristics, the frequency response to the calibration tool and the pressure step generated. By assuming that the reference sensor used has high dynamic sensitivity, the characteristics of the calibrated sensor can be investigated by dividing the recorded transfer function of the calibrated sensor by the recorded transfer function of the reference sensor. By using this method, it will theoretically only be the properties of the calibrated sensor left. The process is illustrated in Figure 4.

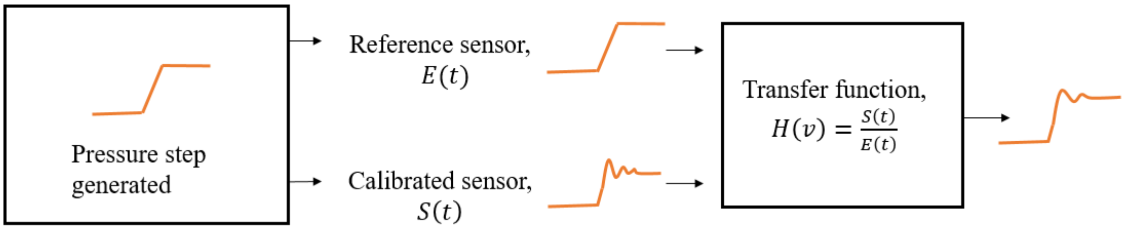


Figure 4 – Generate the transfer function

3.2 Bode diagram

The characteristics of the pressure sensor calibrated will be analyzed by the use of a Bode diagram. A Bode diagram illustrates graphically the natural frequency response of a system.

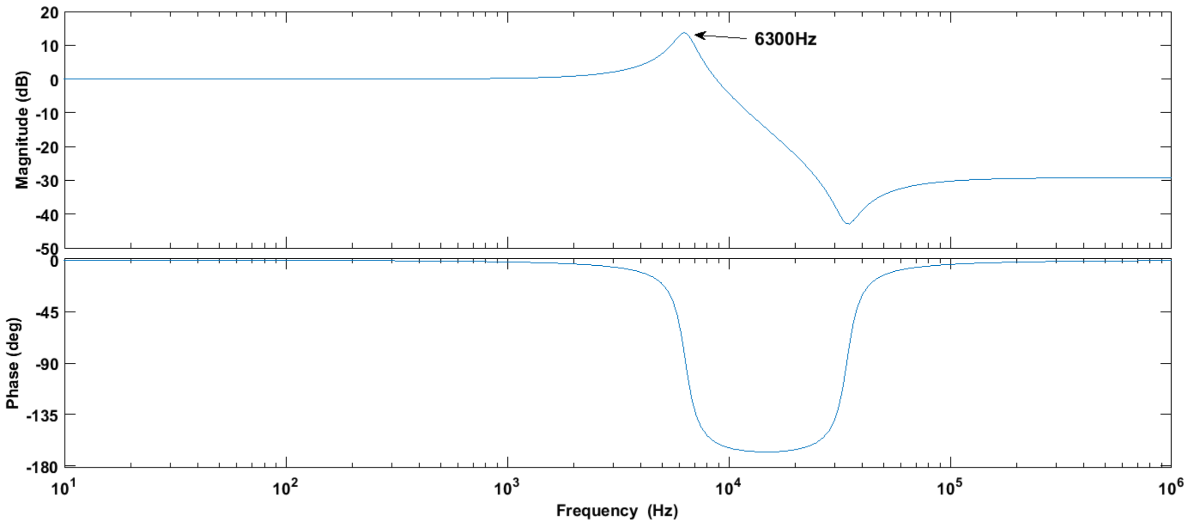


Figure 5 – Bode diagram

Bode diagrams normally illustrate the magnitude in decibels or the phase shift against the logarithm of frequency response [15]. Figure 5 illustrates how a Bode diagram displays the natural frequency response to a pressure sensor with damping factor of 0.1 and a reference sensor with high dynamic sensitivity which has a natural frequency lager than 215kHz [16]. In this illustration, theory from Section 3.1 has been used, while assuming the calibration system developed has the ability to create a perfect step, (see Equation (3)). The peak at 6300Hz illustrates the natural frequency response to the pressure sensor.

The corresponding volt value for the frequencies obtained in the magnitude Bode diagram can be found with Equation (4) [17].

$$decibels\ (dB) = 20 \log_{10} \frac{V_{out}}{V_{in}} \tag{4}$$

The volt value out, V_{out}, is the volt value actually measured for a given frequency, and volt value in, V_{in}, is the value expected to measure.

3.3 Cavities and internal pipelines

When building the calibration tool, connecting lines and cavities cannot be avoided. These elements make frequencies in the calibration tool, which pressure sensors will detect. These frequencies need to be examined, so that the calibrated sensor does not end up getting responses in the same frequency range. If the calibration system has a too low natural frequency, the system will behave as a low pass filter. A low pass filter will register the first physical achieved frequency. This frequency will behave as a cutoff frequency, and damp out the higher frequencies [18].

Theoretically, these frequencies can be determined using Helmholtz resonance theory [19]. This theory defines the resonance frequency developed when a cavity is connected to internal pipelines. The cavity frequency can be expressed by Equation (5)[20]

$$f_{cav} = \frac{a}{2 \cdot \pi} \sqrt{\frac{S_{neck}}{V_0 \cdot L'}} \qquad [Hz] \tag{5}$$

where V_0 is the volume of the cavity, a is the speed of sound, S_{neck} is the cross section area of the passage and L' is the internal pipeline length.

3.4 Discrete signals

When data is logged, the physical signals become converted to discrete data points. When these discrete data points are transformed back into continuous signals, they can give rise to challenges. If the logging rate is too low, signals that are ambiguous relative to the physical signal may occur [21]. These are called alias signals and are illustrated in Figure 6.

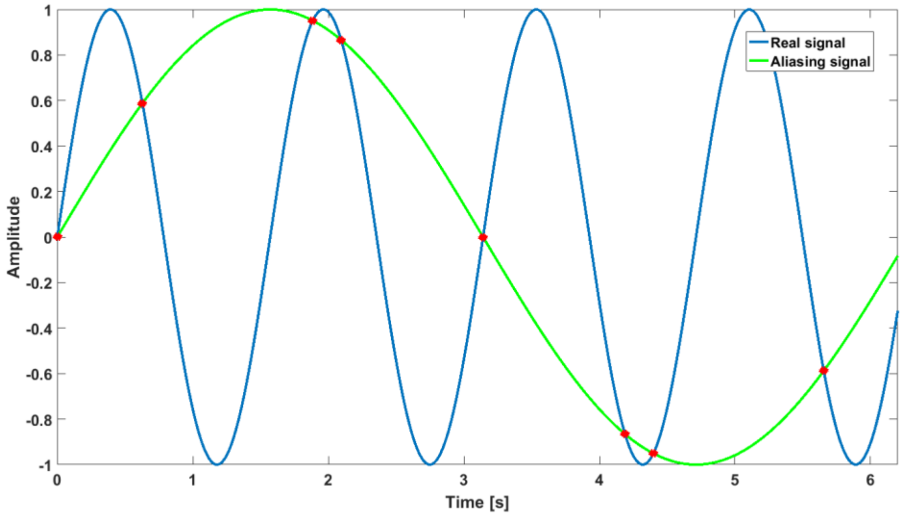


Figure 6 – Example of alias signal using too low logging rate

3.5 Nyquist sampling theorem

To avoid aliasing, *Nyquist sampling theorem* is used. This theorem ensures sufficient logging frequency so that the continuous signal can be recreated using discrete data points. The theorem states that the logging frequency, f_s, should be at least twice as high as the highest frequency in the signal [22]. This can mathematically be written as

$$f_s \geq 2 \cdot f_{Nyquist} \qquad [Hz] \tag{6}$$

where the Nyquist frequency, $f_{Nyquist}$, is the highest frequency capable of being recreated without the emergence of aliasing.

4 The dynamical calibration system

The dynamical calibration system for pressure sensors developed in this master's thesis is based on the concept of an aperiodic pressure generator with use of a fast-opening device. This was explained in Section 2.2. The reason why this method is used, is for its good assumed range of frequencies and pressures, and also the low cost and work for building the dynamical calibration system. In addition to the development of a calibration tool, a logging program used for calibration is modified and adapted to the tool.

4.1 The calibration tool

During the process of constructing the calibration system, the calibration tool was first drawn in a 3D design software program called CREO before it was 3D printed and then machined. CREO gives the opportunity to create precise 3D drawings of the unit to be made, with correct dimension values, and accurate construction work drawings. The construction work drawings of the calibration tool are presented in Appendix D.1.

After the calibration tool was drawn in CREO, it was 3D printed. The 3D print provided an opportunity to quality check that all the parts that should be fastened to the device were suitable. It was also a big help during the machining of the calibration tool, since the tool contains many parts that needed to be milled. The 3D printed calibration tool was made of plastic, and can be seen in Figure 7 below.

The construction is based on a hollowed minor cavity inside the calibration tool, while all the parts required for the calibration system to work were connected. The calibration tool components are described in detail in the next section. It is also made with the least possible internal pipelines which can interfere with the step. The calibration system is constructed for calibrating pressure sensors measuring in the frequency range 0Hz to 1000Hz. The calibration tool is built in the material stainless steel 306. Stainless steel 306 assures a long lifetime for the calibration tool, and is essential to reduce the possibility of rust, since the medium used is water. The final calibration tool in stainless steel 306 is presented in Figure 8. Figure 9 shows the calibration tool in a 3D drawing, with all its components in place. Figure 10 shows the finished calibration tool, with all its components.

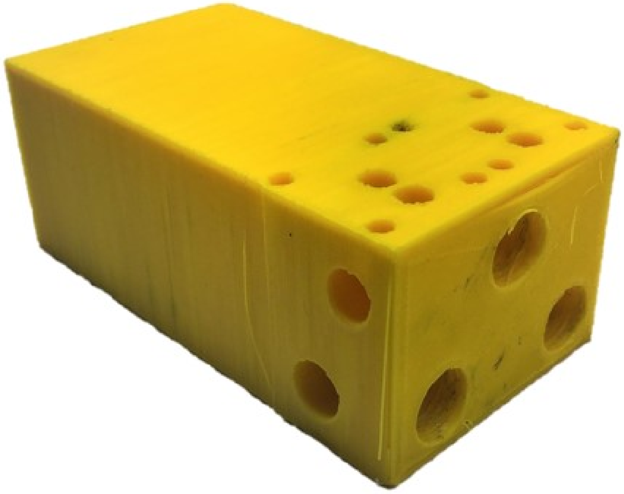


Figure 7 – 3D printed calibration tool

Figure 8 – Finished calibration tool

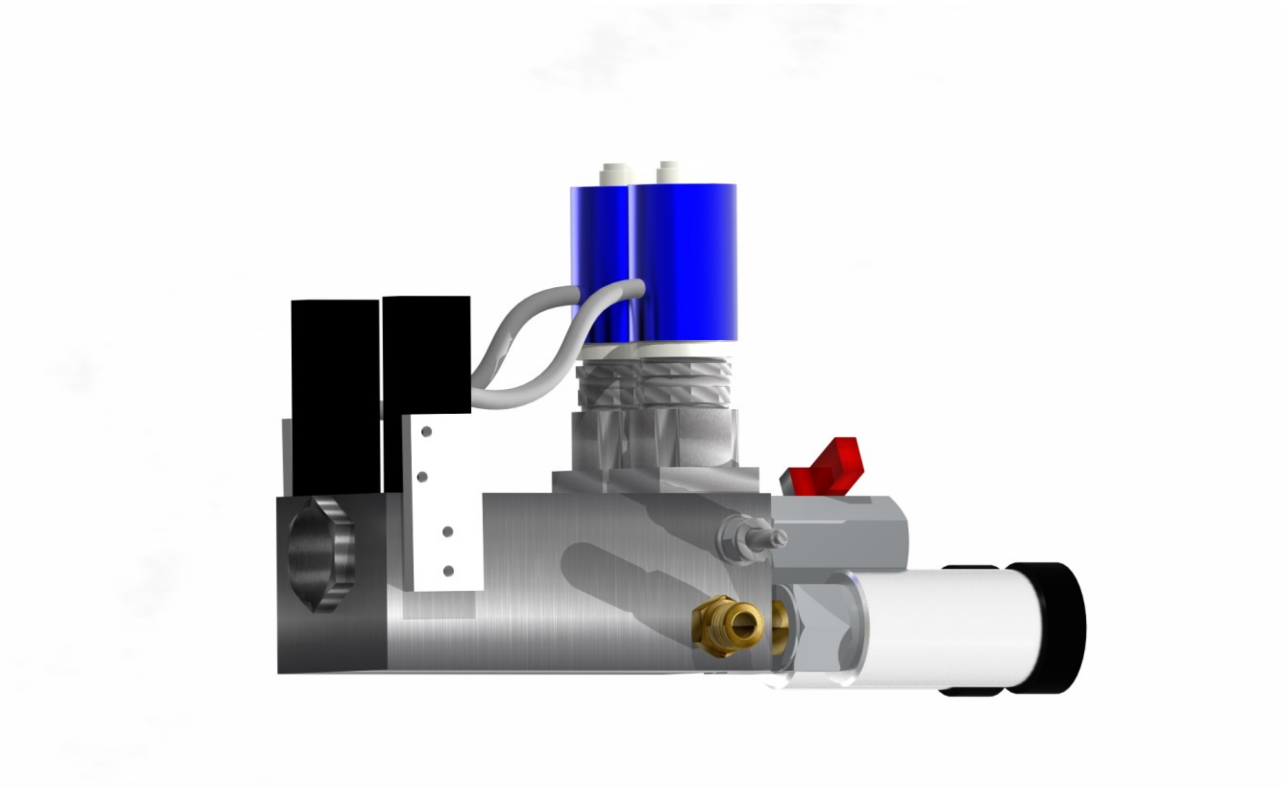


Figure 9 – 3D drawn calibration tool, with components

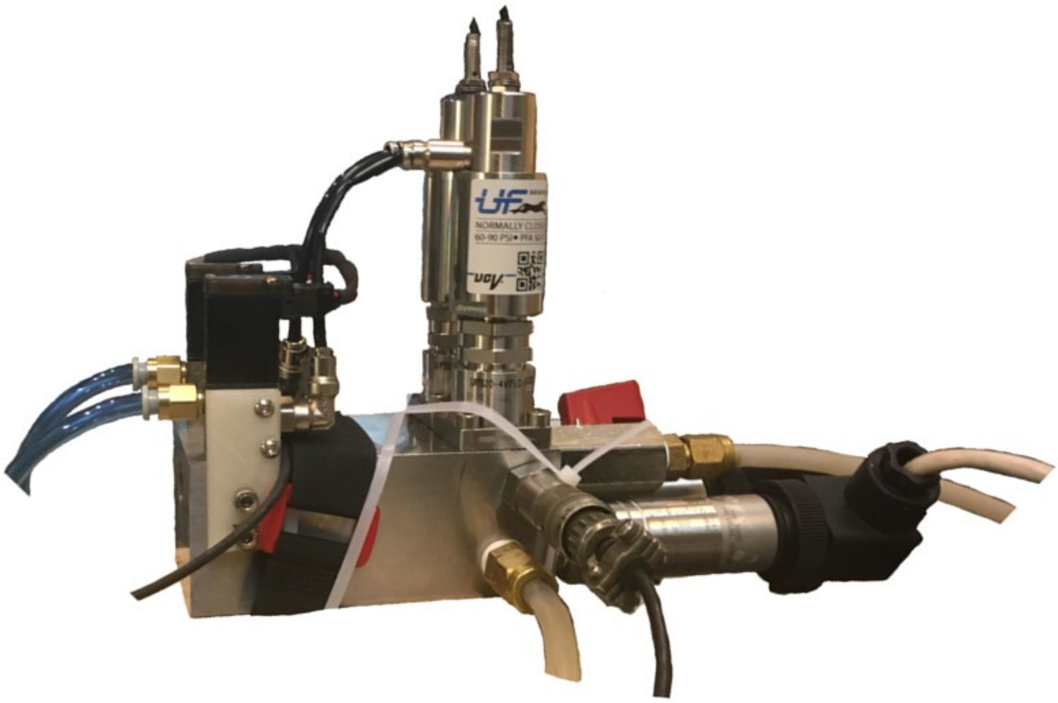


Figure 10 – Finished calibration tool, with components

4.2 Calibration tool components

The calibration tool contains many features, which allows the dynamic calibration in theory to have high reliability, a wide frequency range and several pressure levels. In Subsections 4.2.1 - 4.2.7 the different parts and components included in the calibration tool will be discussed and justified.

4.2.1 Pressure inputs

The calibration tool developed is a compact steel box with a small cavity. The pressure inside this cavity changes rapidly, caused by changes in different inlet-pressure levels. Both high-pressure and low-pressure are supplied to the tool by small pipes connected through the sides. Figure 11 illustrates the calibration tool with the high-pressure and low-pressure inlets.

The high-pressure level is given by opening the valve towards a high-pressure supply and the low-pressure level is given by opening the valve towards the atmospheric pressure. This is further discussed in Subsections 5.1.1 and 5.1.3.

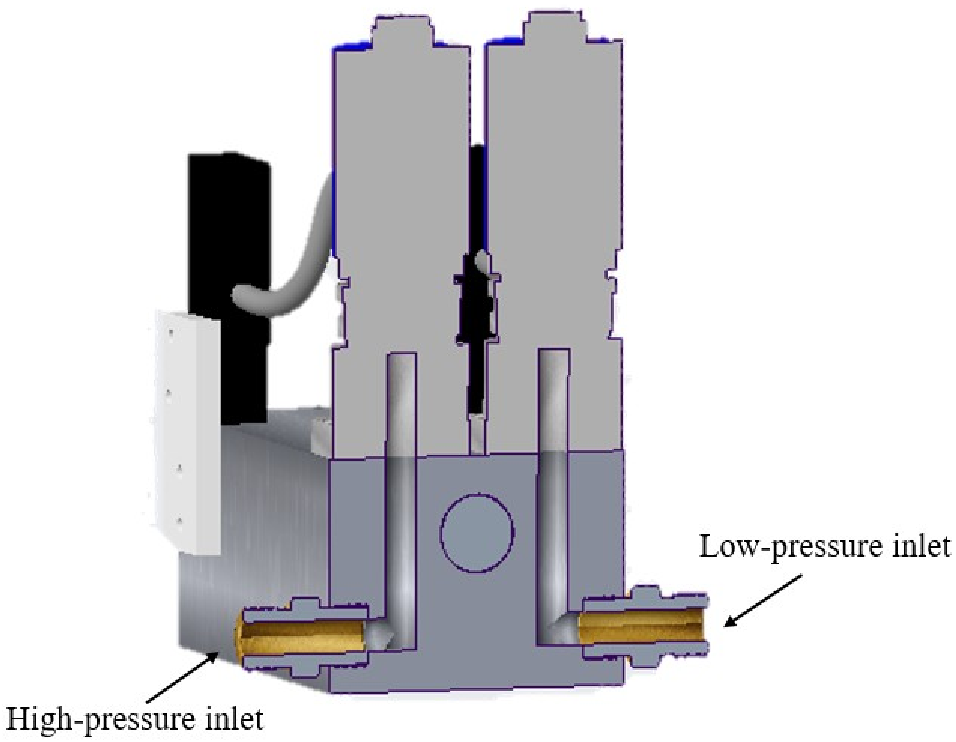


Figure 11 – High-pressure inlet and low-pressure inlet

4.2.2 Ultra-fast diaphragm valves

For obtaining the right behavior of the high-pressure and low-pressure levels, two valves, which control the supply of the different pressure levels inside the cavity, were attached on top of the calibration tool. These valves have a response time less than 5ms, and in theory they will ensure that the alternation between high pressure and low pressure is so fast that it generates an almost perfect pressure step. Figure 12 illustrates the valves on the top of the calibration tool. Two valves are used for better control of the pressure switch during the calibration. They also give the possibility to run multiple pressure steps consecutively in the same run, and change from positive to negative generated steps.

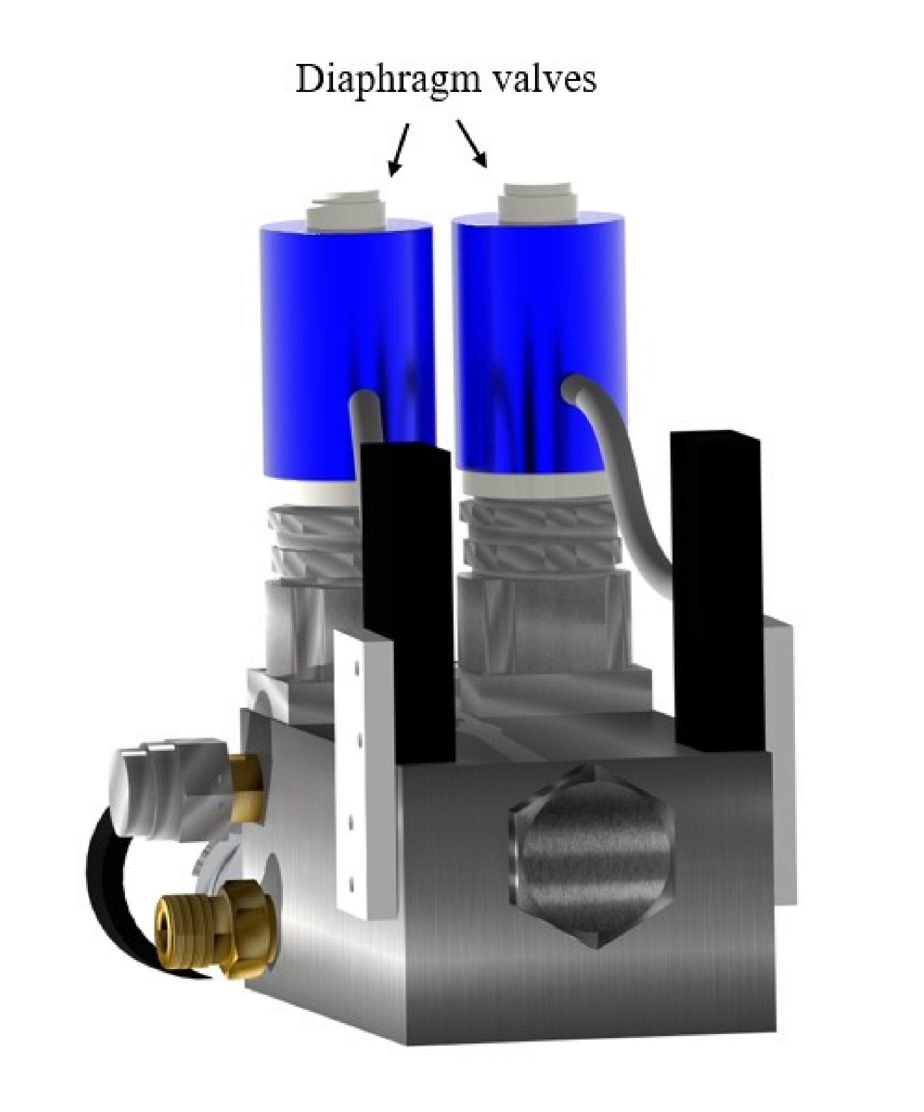


Figure 12 – Fast diaphragm valves

In theory, the input to the calibrated sensor should be a perfect pressure step. A perfect pressure step contains all frequencies. Such a step is impossible to make, since everything will always have some delay. Figure 13 shows a perfect step in blue compared with a realistic step in red.

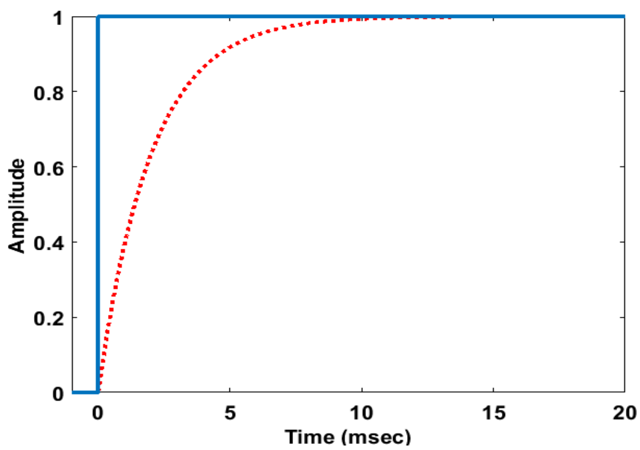


Figure 13 – Perfect and realistic steps

Figure 14 shows a picture of the ultra-fast diaphragm valve being used in the calibration system made in this master's thesis. This is a diaphragm valve from the UF-series delivered from Ham-let. For more information about the valves see Appendix C.

Figure 14 – Picture of the ultra-fast diaphragm valve [2]

4.2.3 Valve controllers

The behavior of the valves is controlled by high-pressure air at 5 bar. The high-pressure air makes the valves switch from closed to open and from open to closed position. The high-pressure air is sent to a valve controller fastened on the top of the calibration tool, assembled with 3D printed blocks. If the valve should be open, the controller sends the air pressure further to the valves, and the controller starts to lighten red. The controllers are further controlled by a manual button, see Subsection 4.3.1. The valve controllers can be seen in Figure 15 below.

Figure 15 – Valve-controllers

4.2.4 Steady-state calibrated pressure sensors

In Figure 16, two steady-state calibrated pressure sensors are indicated. These are used for quality measurement of the high-pressure and low-pressure inputs. One of the pressure sensors used in this master's thesis is illustrated in Figure 17. These are UNIK 5000 PTX5072 pressure sensors. One has the working pressure range from 0 to 10 bar absolute, while the other has a working range from 0 to 5 bar absolute. For further information about the pressure sensors used, see Appendix B.1.

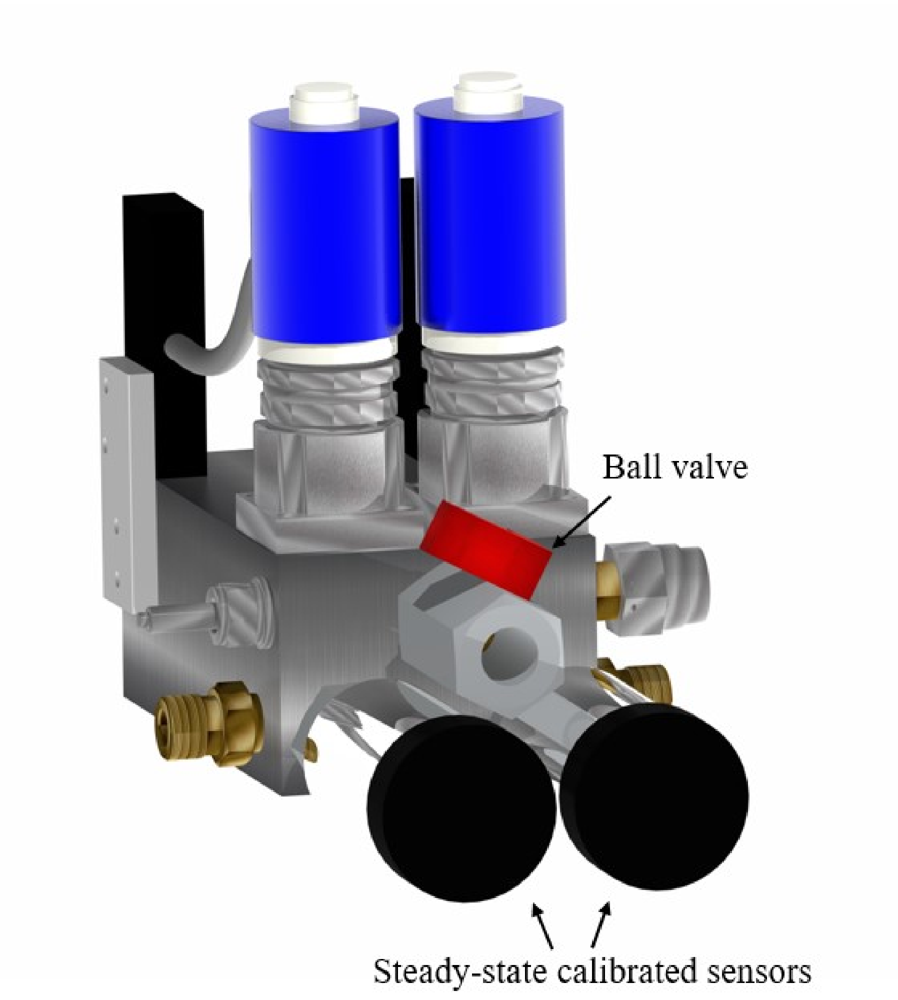


Figure 16 – Steady-state calibrated sensors

Figure 17 – UNIK 5000 PTX5072 pressure sensor

4.2.5 Ball valve

A ball valve is also mounted on the calibration tool, which is illustrated in Figure 16. This ball valve is applied to deflate before calibration begins. Air in the cavity will cause the frequency to be lower than desired and should be avoided. The ball valve used can be seen in Figure 18.

Figure 18 – Ball valve

4.2.6 Reference sensor and calibrated sensor

The calibration tool contains a reference sensor and the calibrated sensor. Since it is impossible to generate a perfect step, the reference sensor is used for measuring the input. In Figure 19, the locations of the reference sensor and the calibrated sensor are shown.

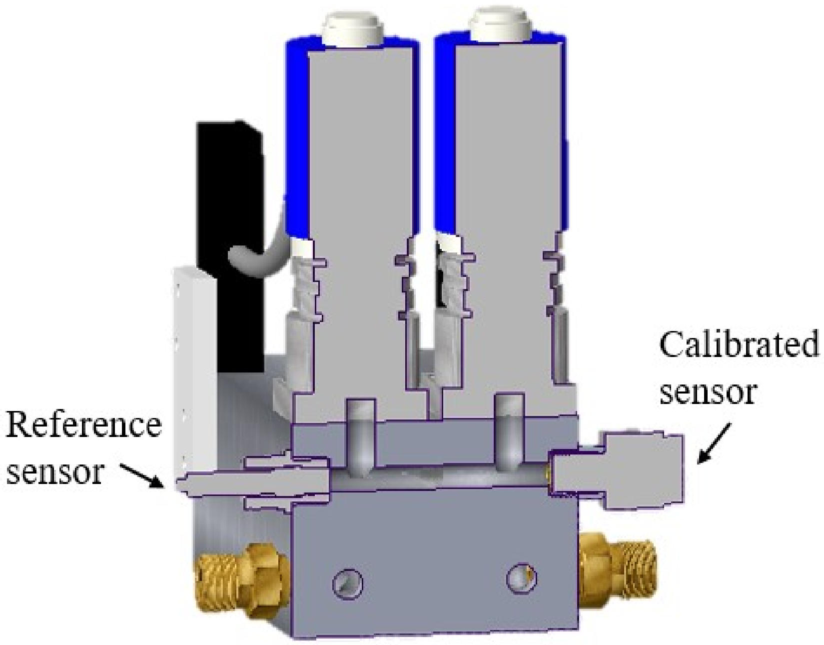


Figure 19 – Reference sensor and calibrated sensor

The reference sensor used in the calibration tool is a Klister Piezoelectric 601C pressure sensor, which can be seen in Figure 20. This pressure sensor has high dynamic sensitivity with a natural frequency lager than 215kHz [16]. For more information about the sensor, see Appendix B.3. The reference sensor used is calibrated from the supplier. The calibration report for this sensor can be seen in Appendix F. Even though the calibration system created in this master's thesis is designed to calibrate many types of sensors, the calibration system testing will use one sensor to calibrate. The calibrated sensor is a Kulite HKM – 375 pressure sensor and can be seen in Figure 21. For more information about the sensor see Appendix B.2.

Figure 20 – Reference sensor

Figure 21 – Calibrated sensor

4.2.7 Adjustable cavity

Figure 22 illustrates the adjustable cavity inside the calibration tool. It is important to have a conscious awareness of the frequency response this cavity will create. The frequency response will behave as a low pass filter, which dampens frequencies higher than its own. To improve frequency response control, water is used as medium during calibration. Water is also used since the dynamical measurements at the Waterpower Laboratory are performed in this medium. The calibration tool is also equipped with an adjustable bolt which can be seen in Figure 22. The bolt makes it possible to adjust the cavity volume, so different frequency responses can be achieved. A completely sealed system is important for avoiding frequencies to be lower than desired, caused by air. Frequency response will be further discussed in Subsection 4.2.8. To get a completely sealed system, a thread sealants solution could be used as gasket at the bolt.

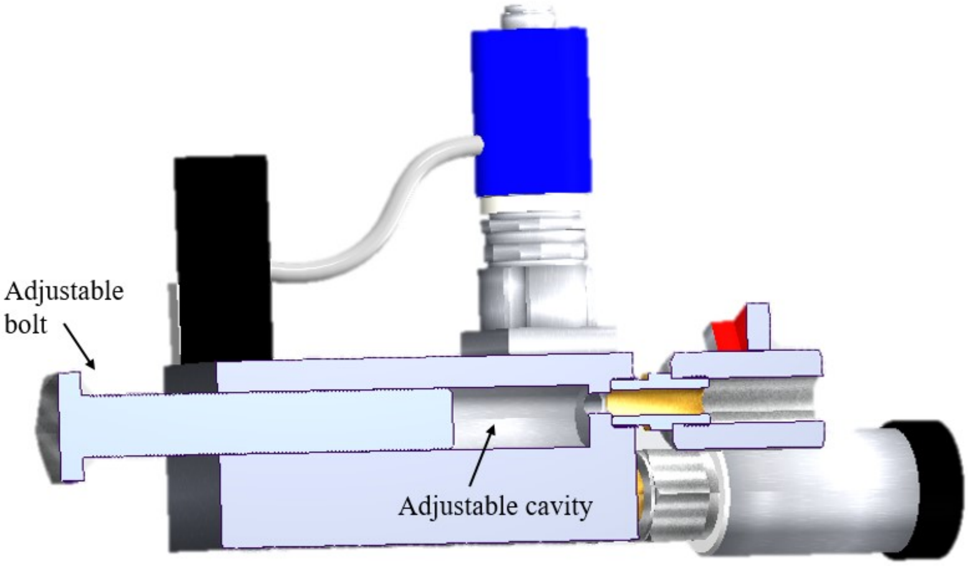


Figure 22 – Adjustable bolt and cavity

4.2.8 Theoretical test of the designed calibration tool

To ensure that the designed calibration tool had sufficiently high natural frequency, computational fluid dynamics (CFD) simulations of the drawn calibration tool were conducted before it was constructed. The CFD analyses where performed with Ansys software. The natural frequency test was done by introducing a unit step at 100Pa at the high-pressure output of the valve on the calibration tool. Furthermore, the natural frequency performed from the tool was simulated. The pressure step applied to the tool is illustrated in Figure 23, with a red arrow.

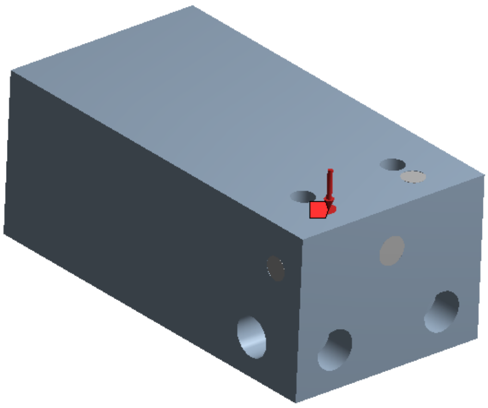


Figure 23 – Applied pressure step

The test was accomplished with different mesh qualities, and the simulations gave the same results for medium and fine mesh. The medium mesh had 67,638 nodes, while the fine mesh had 117,758 nodes. The mesh independency test indicates that the simulated results achieved are reliable, but need to be verified with experiments. Figure 24 shows the medium mesh used in the calibration tool.

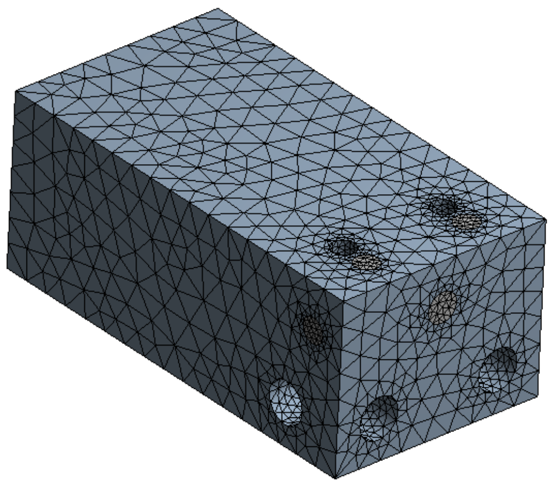


Figure 24 – Medium mesh quality used on the calibration tool

Two different CFD case analyzes where performed on the calibration tool, one with the bolt fully extended and one with the bolt completely inside. This gives a good estimate of the lowest and highest frequency to be achieved with the calibration tool. When the bolt was completely inside, see Figure 25, the frequency response was estimated to 15,500Hz. With the bolt fully extended a frequency response of 5000Hz was estimated, see Figure 26. This provides the ability to vary the frequency response in the calibration tool with 10,000Hz. With use of the calibration tool with correct natural frequency response, it is possible to reach the desired range of frequencies.

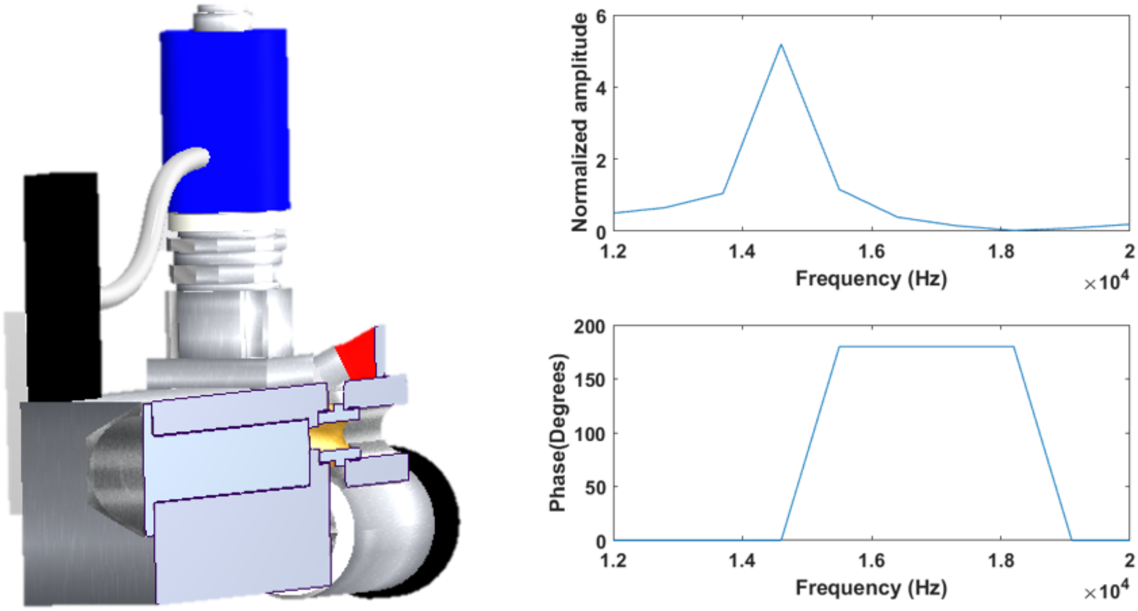


Figure 25 – Bolt completely inside

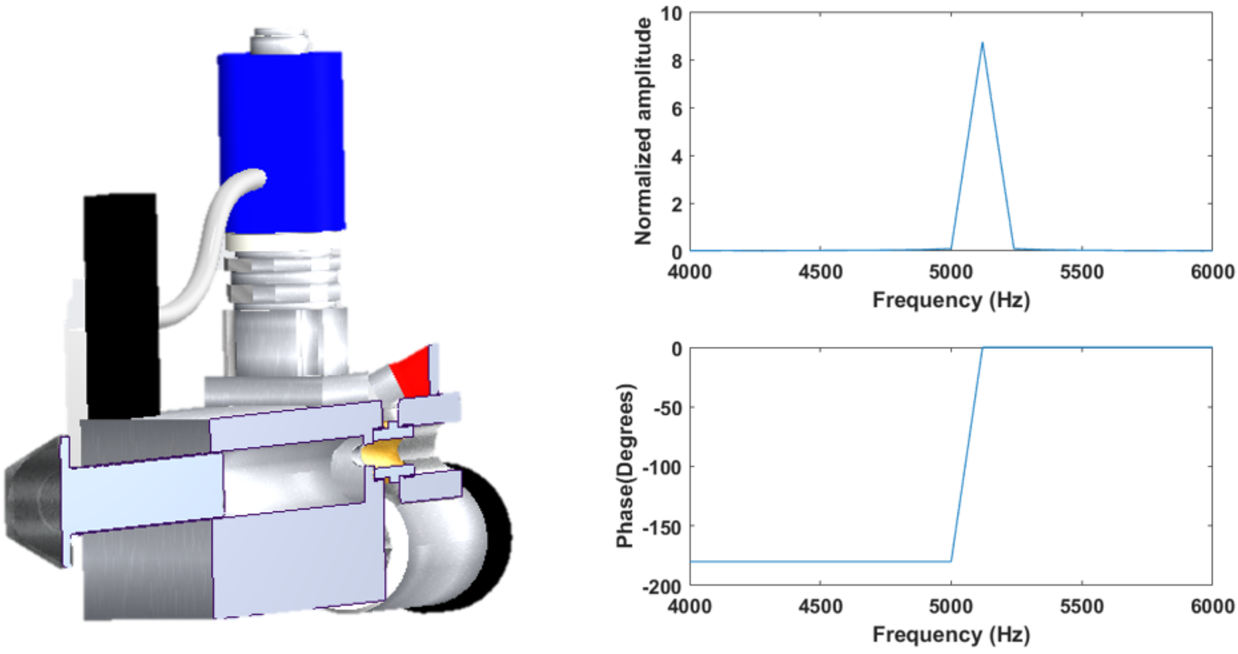


Figure 26 – Bolt fully extended

4.3 Calibration program

A calibration program is developed where MatLab, LabVIEW and an external button is included. The different parts of the calibration program are further discussed in Subsections 4.3.1 - 4.3.3.

4.3.1 External valve control button

To get a more robust calibration system, an external box with a button is made, which is illustrated in Figure 27. This control-box will control the behavior of the ultra-fast diaphragm valves. The benefit of having a physical button that controls the behavior of the valves is that the controlling will be straightforward and visual, versus letting the controller hide inside the logging program. On the box, two outputs and two inputs are mounted, one for each valve. The outputs give signals from the button to the valves if they should be open or closed. The inputs tell the box if the valves are open or closed. The blue cables illustrate the input, and the green cables illustrate the output.

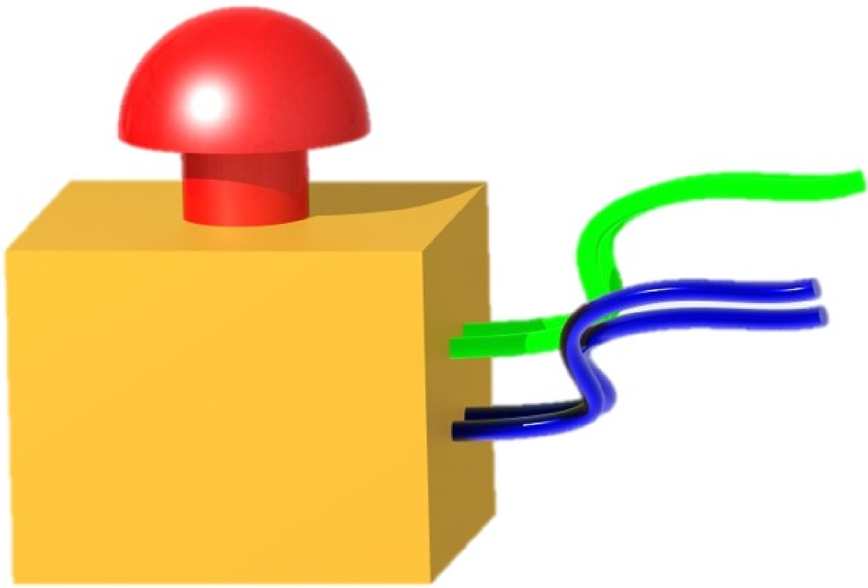


Figure 27 – External button

Only one valve can be open at the time, so the control-box is built with respect to the interlock concept. The vendor or property leaflet that came with the valves could not explain the behavior of the diaphragm valves inside. It is therefore assumed based on the design of the valves, that inside each valve there is a diaphragm piston. The piston can move up and down. Based on the piston position the water can either flow inside the calibration tool or not. Figure 28 illustrates how the piston inside the valves can move up and down, and in this way be able to block the water from passing through. The figure illustrates the situation in the moment the high-pressure valve opens.

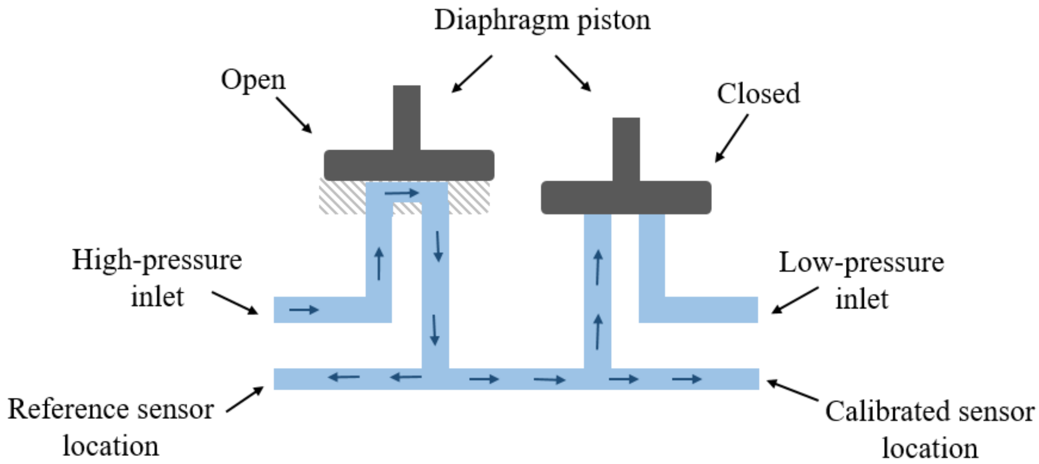


Figure 28 – Mechanism of the diaphragm valves

Since the valves cannot be open at the same time, there is a dependency between the two valves. When the first valve should switch from closed to open, this valve needs to wait until the second valve has been closed. At the same time the second valve has closed the first valve can finally open. The control-box will manage to keep track of this, because each valve always will send its position by help of the blue cable input signals.

Another reason for having a dependency between the two valves, is pressure change caused by the valves due to volume change. When the piston inside a valve opens, water gets pulled with, and the pressure inside the calibration tool drops. Likewise, when the piston closes the pressure inside the calibration tool rises.

For analyzing the results from the calibrated sensor, it is necessary to log the behavior of the valves. This is done by connecting output cables in the two holes, at the back of the control-box, see Figure 29. The LabVIEW logging program discussed in Subsection 4.3.2, will then be able to register the valve behavior.

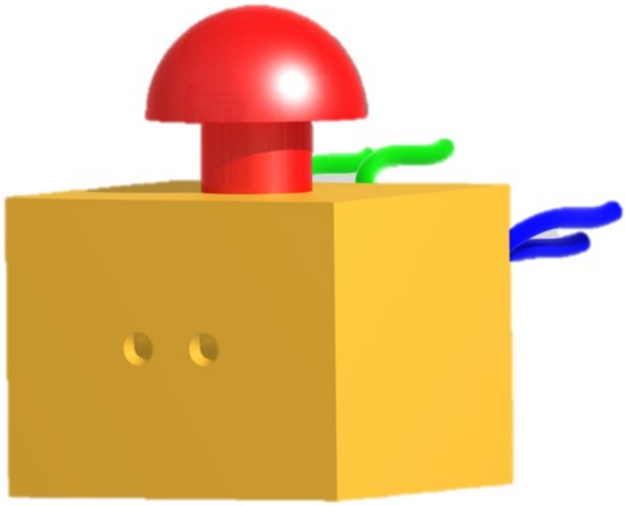


Figure 29 – Outputs of the control-box

4.3.2 LabVIEW

A logging program is further developed based on the logging program used in my project thesis. The logging program is made in LabVIEW, and is used for recording the measurements from the four sensors attached to the calibration tool, which are two steady-state sensors, a reference sensor and a calibrated sensor. The logging program is also able to record the activity of the valves, since the reference sensor and the calibrated sensor will be coordinated with the behavior of the valves. The logging program is made to be capable of handling measurements from both voltage input and bridge inputs.

4.3.2.1 Measurements

By assuming that the highest frequency to be found is 15,500Hz, the logging frequency should at least be 31,000 samples per second to not violate the Nyquist theorem introduced in Section 3.5. It is common to set the logging frequency to ten times the Nyquist frequency, but since the Compact Data Acquisition (CompactDAQ) used has a maximum logging frequency at 50,000 samples per second, the logging frequency is limited to that.

To get sufficient data for the uncertainty analyses of the pressure sensor, 30 runs should be conducted for each pressure sensor. Sufficient runs are also important when using the Student-T distribution and to ensure repeatability of the measurements. Each run should operate under the same conditions, the same pressure inputs, the same occurrence of the pressure step and the same high-pressure source.

4.3.3 Processing data with MatLab

After the measurements are registered in LabVIEW, they are processed with MatLab. From the measured data and theory used in Chapter 3, a Bode-diagram for the calibrated sensor could be made. By use of the Bode-diagram, the natural frequency response could be found. Bode-diagram is discussed in Section 3.2. Furthermore, an uncertainty interval for each frequency can be generated in MatLab by use of the Student-t distribution. This is further discussed in Chapter 6.

For generating the Bode-diagram, *tfestimate,* a build in function in MatLab, is used. This function estimates a transfer function for a single-input/single-output system. The function assumes that the sensor is operating as a discrete-time oscillating system as discussed in Section 3.1.

The sensors used have different voltage output signals, for the same measurement. In order to make a Bode-diagram of the calibrated sensor, it is important that the sensors are analyzed with the same value. To solve this problem, a function which solves the two dimensional system below, Equation (7) and (8), is made.

$$RS_{s1} \cdot C1 + C0 = CS_{s1} \tag{7}$$

$$RS_{s2} \cdot C1 + C0 = CS_{s2} \tag{8}$$

Subscript s1 denotes the value before the step, and subscript s2 denotes the final state after the step. The reference sensor is denoted RS and the calibrated sensor is denoted CS.

Another possibility is to calibrate the reference sensor and the calibrated sensor with steady-state calibration first, and then calibrate the sensors dynamically before the natural frequency is found. But for just looking at the uncertainty due to the natural frequency this is believed to be the easiest way.

5 Experimental setup for the calibration system

Tests of the calibration system were performed in the Waterpower Laboratory at NTNU. This chapter deals with the equipment used during the tests, but not the calibration tool which is carefully explained in Chapter 4.

5.1 Equipment description

In order to get the entire calibration system to work, more equipment is needed than just the calibration tool. Some of the equipment used was already installed in the Waterpower Laboratory, and some parts needed to be constructed. The equipment used is described in Subsections 5.1.1 - 5.1.5.

5.1.1 High-pressure tank

One side of the calibration tool is supplied with high-pressure water, as explained in Subsection 4.2.1. The already existing high-pressure tank in the Waterpower Laboratory is used as a resource for the high-pressure side of the calibration tool. The calibration tool is mounted directly on the high-pressure tank. This is illustrated in Figure 30. The high-pressure tank can supply a 10 bar pressure, which gives the opportunity to achieve all desired calibration pressure levels. The high-pressure tank holds a large volume, and this means that it will not be influenced by the amount of water that is fed to the calibration tool. The large volume gives the ability to keep a constant pressure intensity during the entire calibration process.

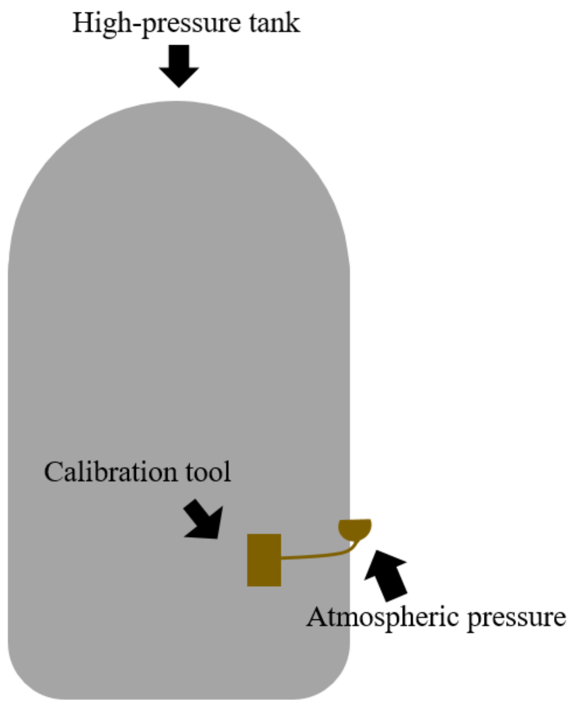


Figure 30 – Calibration tool mounted to the high-pressure tank

The high-pressure tank has already an outlet for water at the bottom which normally is used to measure the water level achieved in the pressure tank. To get the opportunity to measure both the water level in the pressure tank and drain water to the high-pressure side of the calibration tool, a T-pipe is introduced to the system. The water drainage setup can be seen in Figure 31.

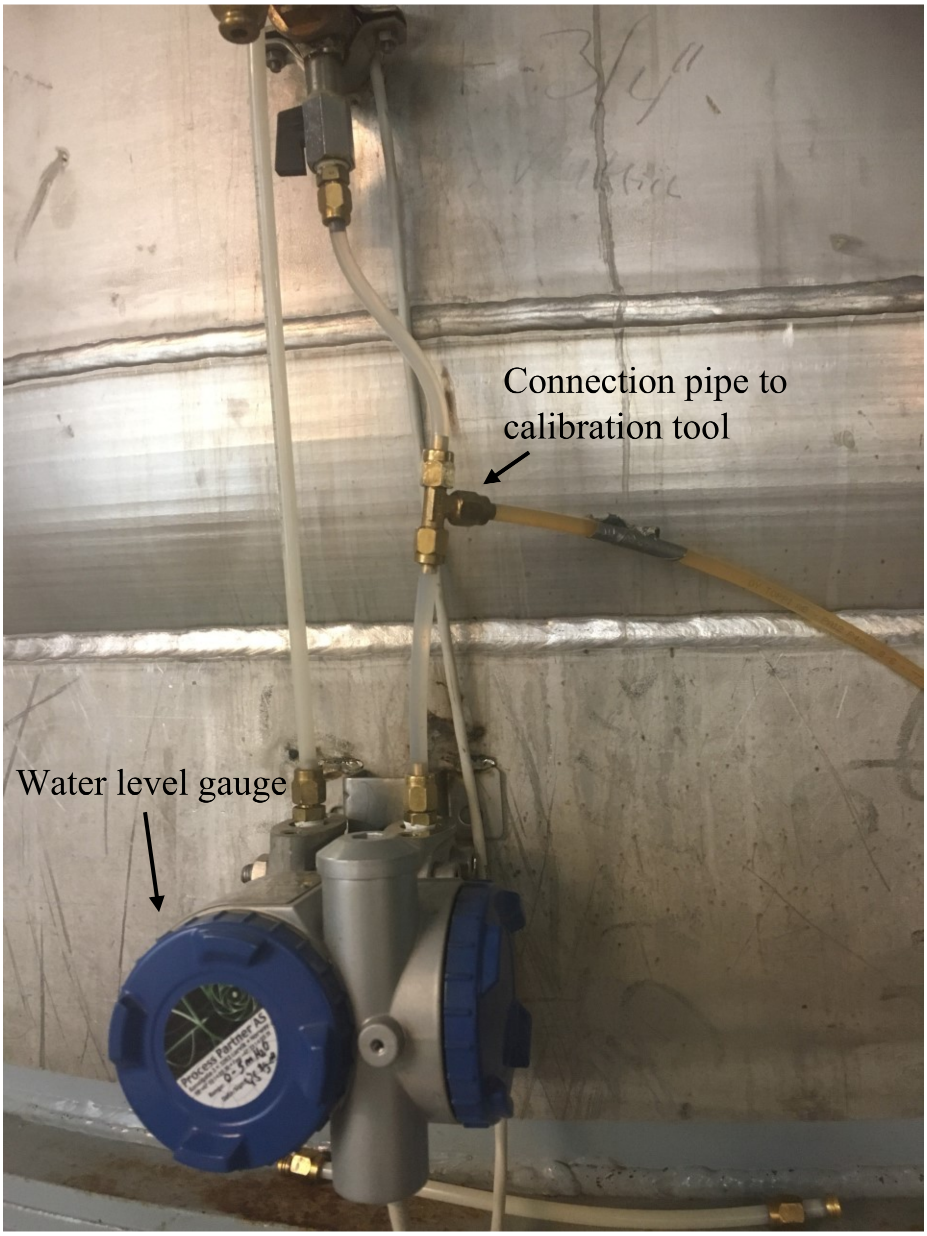


Figure 31 – Water drainage setup

5.1.2 Hydraulic Deadweight Tester

Another possibility to arrange for the high-pressure supply, is to use a Hydraulic Deadweight Tester, see Figure 32.

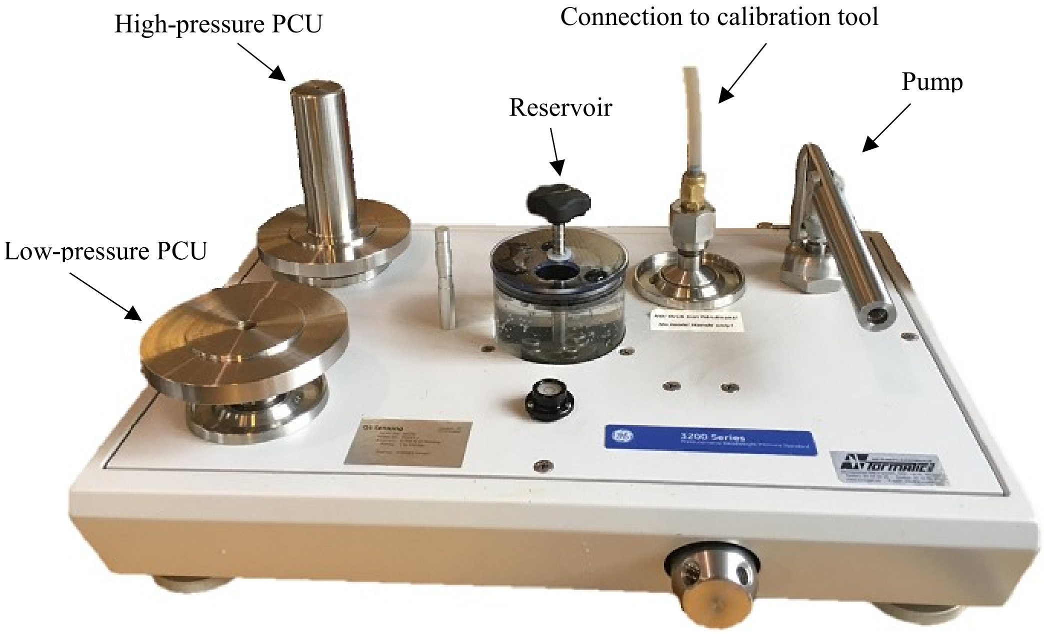


Figure 32 – Hydraulic Deadweight Tester

The Deadweight Tester is the primary standard for pressure measurement. The Deadweight Tester works by loading on accurately calibrated weight masses on the low-pressure piston/Cylinder Unit (PCU). By loading weights, different pressures can be achieved. The total pressure is the weights plus the piston weight carrier assembly.

The system is filled with distilled water in the reservoir, and the pressure inside the Deadweight Tester is increasing by use of the pump. Since liquids are considered incompressible, the piston will rise to balance the downwards force of the piston and weights [23].

The water pressure generated by the system will be input pressure to the high-pressure side of the calibration tool. Since the calibration tool is already filled with atmospheric pressure, the water will be compressed minimally, which results in negligible effect on the pressure drop in the Deadweight Tester.

5.1.3 Bottle with atmospheric pressure

As described in Subsection 4.2.1, the other side of the calibration tool is supplied with water at almost atmospheric pressure. To get the right pressure level and size of the water container supply, a half-liter bottle is used. A narrow tube with an inner diameter of 6mm is connected to the bottle and the calibration tool, as can be seen in Figure 33. There is a hole at the top of the bottle, so that the pressure does not get too low. The standing water column decreases the probability of air coming into the system. With use of a longer tube, it is possible to adjust the low side pressure level slightly.

Figure 33 – Atmospheric pressure container connected to the calibration tool

5.1.4 High-pressure air

As discussed in Subsection 4.2.3, the diaphragm valves are mainly controlled by high-pressure air. The valves are designed for a pressure range from 4bar to 6bar. The instrument air pressure supply is on 10bar and needs therefore to be reduced before the pressure is supplied to the valves. To reduce the pressure, a pressure transformer is fasted between the instrumental air supply and the valve controllers. This can be seen in Figure 34, where the tool is the pressure transformer, the blue pipes go to the valve controllers and the instrument air input supply is on the other side.

Figure 34 – Pressure transformer

5.1.5 Electrical equipment setup

In this subsection, the setup of the electrical equipment will be illustrated and explained. The setup is shown in Figure 35. Description of the components used in the electrical setup corresponding to the numbers in Figure 35 can be seen in Table 2.

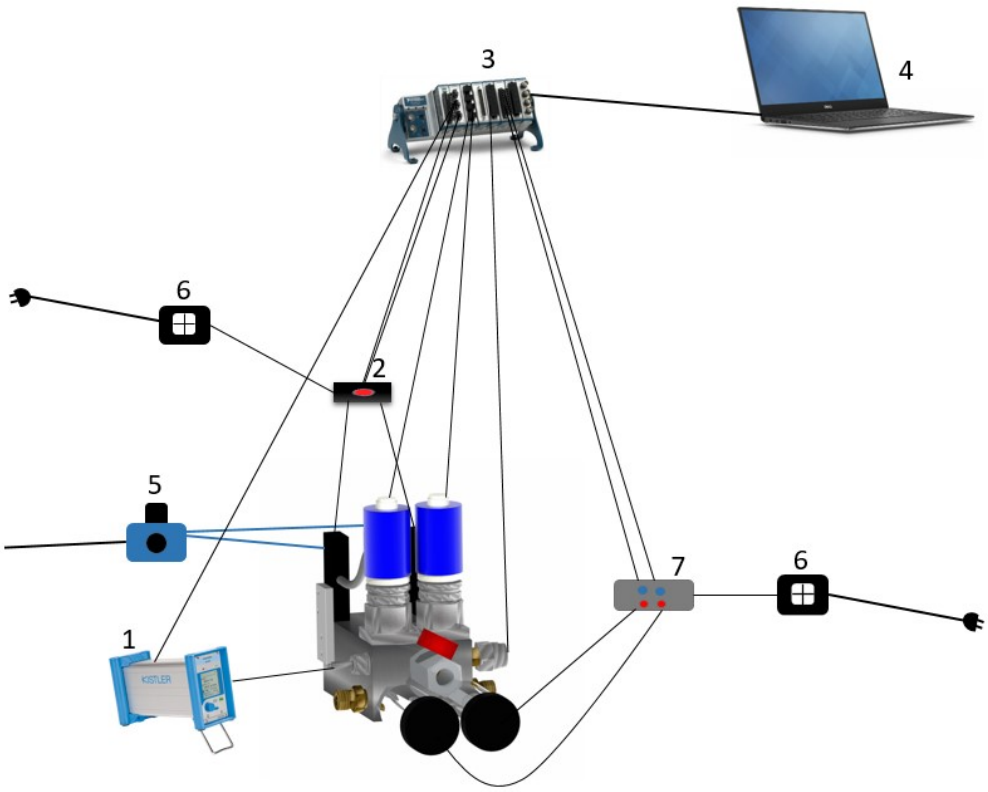


Figure 35 – Electrical equipment setup

Table 2 - Description of components used in the electrical setup

Nr.	Description
1	Amplifier
2	Valve control button
3	Chassi/ CompactDAQ
4	Logging PC
5	Pressure converter
6	Voltage converter
7	Current to voltage transition

As shown in Figure 35, there are several electrical components involved to get the calibration system to work. Component number 3 in the figure represents the CompactDAQ, also called chassis, used. The chassis needs to restrain both voltage inputs and bridge input. For the voltage input the National Instruments (NI) module 9239 is used, and for the bridge input the module NI9237 is used. The reference sensor needs an amplifier, component 1, before it can be connected to the chassis with module NI9237, while the calibrated sensor can be directly mounted to the module NI9239. The steady-state calibrated sensors have current output which is converted to voltage signal in component 7, before they are connected to the chassis module NI9239. The voltage transition needs to have a 24V input, so a voltage converter, component 6, is used. The control-box with the button also needs a 24V input, so a voltage converter is used there as well before it is connected to the chassis module NI9239. Lastly, there is a pressure converter, component 5, used for avoiding too high pressure in the valve controllers, as explained in Subsection 4.2.3.

When the valves open or close, a high voltage peak is given as an output in addition to the step. These peaks may destroy the logging card. To prevent the logging card from being damaged, diodes, transient protections are connected in the conductions for the output of the control-box before the conductions are connected to the chassis module NI9239.

5.2 Steady-state pressure calibration

Steady-state pressure calibration was performed on the two pressure sensors used to gain control of the pressure supply in the calibration system. These sensors were calibrated with Digital pressure indicator DPI 601, illustrated in Figure 36.

Figure 36 – Steady-state calibration system

The calibration was done by introducing different pressures to the pressure sensors, and then the voltage values were recorded. The calibration constants for the two pressure sensors can be seen in Table 3.

Table 3 - Calibration constants

Sensor	C1	C0
PTX 5072, 0 to 10 bar-a	124.98	-248.88
PTX 5072, 0 to 5 bar-a	62.50	-125.32

To get the exact values of the measurements, a 1st degree equation has been used. (See Equation (9))

$$y = C0 + C1 \cdot x \tag{9}$$

where *x* is the voltage value measured in volts. The calibration report for the two pressure steady-state sensors is presented in Appendix E.

6 Uncertainty analyses

This chapter will deal with uncertainty analyses of measurements performed during steady-state and dynamic pressure calibrations. It will also introduce the basic principles of uncertainty analysis. Parts of this chapter are modifications of my project thesis from fall 2016, *Stability of the Francis turbine test rig in the Waterpower laboratory*, Chapter 5 [24].

6.1 Basic principles of uncertainty analysis

Uncertainty analysis strengthens the measurements. In order to say something about the quality of the results, the measurement quality needs to be investigated. The error in a measurement is the difference between what was actually measured and the true value. No measurement of a physical property is free of uncertainty. It is important to identify and measure the different sources of errors. All uncertainty estimates should use the same default for the confidence interval. According to the IEC 60193 standard, the confidence interval should be set to 95% [25].

The IEC 60193 standard addresses three types of errors:

- Spurious errors
- Random errors
- Systematic errors

Spurious errors are usually human errors or instrument errors which make the measurements invalid. These errors should be identified and weeded out as early as possible, so that it does not propagate further in the process as a systematic error.

Random errors are caused by many small, independent influences that prevent a measurement system from getting repeatable measurements by measuring the same size. These errors are affected by the log frequency and operating mode. To reduce random errors, it is important to repeat the measurements.

When the number of measurements is few, the uncertainty related to the random error is estimated by the Student-T distribution, see Equation (10). This equation is used to find the 95% confidence interval around the mean values in the measurements done in the laboratory [26].

$$P\left(\bar{X} - t_{\frac{\alpha}{2}} \cdot \frac{S_x}{\sqrt{N}} \leq \mu \leq \bar{X} + t_{\frac{\alpha}{2}} \cdot \frac{S_x}{\sqrt{N}}\right) = 1 - \alpha \tag{10}$$

where

$$S_x = \sqrt{\frac{1}{1-N}\sum_{i=1}^{N}(x_i - \bar{X})^2}, \qquad og \qquad \bar{X} = \frac{\sum_{i=1}^{N} x_i}{N} \tag{11}$$

Systematic errors are errors which always become the same during similar runs. Therefore, these errors cannot be reduced by increasing the log frequency if the equipment and conditions of the drive remain unchanged. In other words, systematic errors will not affect the repeatability of the measurements. The only way to find if there are systematic errors in one system, is to measure the same in two different systems. If you do not have the necessary equipment to weed out such errors, you must make a subjective decision with the equipment you have. Systematic errors can occur from bad calibration instruments, hysteresis and poor linearity of the measuring instruments. To get a clear picture of the size of the systematic error, it is necessary to analyze the entire measuring process. This includes the calibration of the measuring instruments [25]. A random error during calibration of the measuring instruments, becomes a systematic error during the measurements.

6.2 The total uncertainty in measurements

The total uncertainty in measurements is principally calculated in the same way for the measurements performed with a steady-state calibrated sensor and a dynamically calibrated sensor. The total uncertainty is compiled by the total calibration uncertainty and the uncertainty of each measurement, f_l. Total uncertainty in steady-state calibration is discussed in Section 6.3 and total uncertainty in dynamic calibration is discussed in Section 6.4. The uncertainty in the calibration becomes a systematic uncertainty, f_{sys}, in the total uncertainty. Mathematically, the total uncertainty, f, is calculated with use of Root-Sum-Square (RSS), see Equation (12).

$$f = \pm\sqrt{\left(f_{sys}\right)^2 + (f_l)^2} \tag{12}$$

The uncertainty in each measurement, is estimated using Student-T distribution, see Equation (10).

6.3 Total uncertainty in steady-state calibration

During calibration, steady-state calibration or dynamic calibration, many small independent errors that can be both random and systematic, occur. These errors contribute to the total calibration uncertainty. During steady-state calibration a calibration program in LabVIEW is used. This program already includes the randomness in the calibrated instrument during calibration, systematic uncertainty in the instrument and a regression analysis to fit the calibration points to a linear calibration equation. The uncertainty is calculated with 95% confidence. The total calibration uncertainty is then found by using the RSS on all the uncertainties [26].

With use of steady-state calibration the uncertainty inherent in the natural frequency in the pressure sensor is omitted. With use of steady-state calibration on sensors used for dynamic measurements, the lack of dynamic calibration will become a systematic error in the measurements.

6.4 Total uncertainty in dynamic calibration

Dynamic calibration is not suitable for sensors to be used for steady-state measurements, because dynamic calibration gives unnecessary larger uncertainties than with steady-state calibration. Dynamic calibration is therefore not common to use for acceptance testing on sensors used in steady-state measurements [27].

By use of dynamic calibration, the uncertainty in the measurement will increase, but the quality of the measurements will be improved. When calculating the total uncertainty in dynamic calibration, the same procedure is used as for the steady-state calibration, except that an additional uncertainty term from the dynamic calibration is added. How to find the dynamic calibration uncertainty is descried in Subsection 6.4.1

6.4.1 The procedure for finding the uncertainty in dynamic calibration

This subsection will stepwise explain the procedure for finding the uncertainty in dynamic calibration for the calibration system made in this master's thesis. This procedure for finding the uncertainty in dynamic calibration is not published and therefore needs to be validated by experiments achieved from the calibration system developed.

The goal is to take a certain number of equal measurements as explained in Subsection 4.3.2.1, and by use of theory in Section 3.1, making the transfer function for the calibrated sensor for each run. The transfer functions for all the measurements will then be plotted in one Bode-diagram. Taking the Student-T distribution with a 95% confidence interval, see Equation (10), in every frequency registered and for every measurement. An uncertainty interval will be carried out for each frequency given. For illustration see Figure 37. The red line illustrates the mean value, while the blue dotted lines illustrate the uncertainty interval.

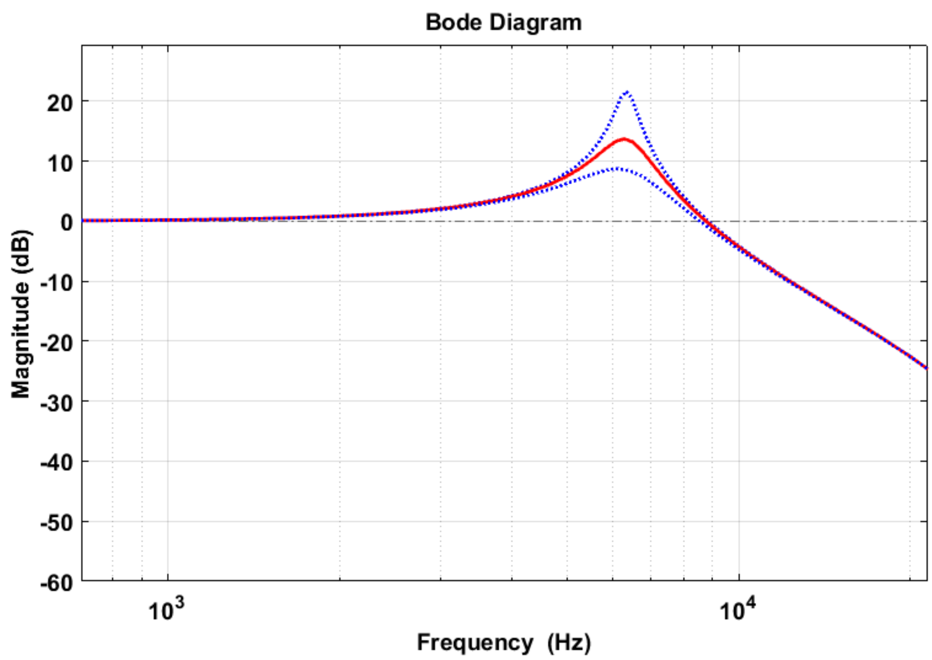


Figure 37 – Illustrating the uncertainty interval

The values are given in decibel, and converted to the output value of a pressure sensor, volt, by use of Equation (4). For finding the uncertainty in a measurement, the output volt value needs first to be corrected for. The correction for a given frequency is done by decreasing the output volt value with the distance from the 0dB line to the mean value at that given frequency. The uncertainty for the frequency is therefore the uncertainty interval marked in blue. If all the runs give exactly the same transfer function, the uncertainty interval will be zero. The increased volt value could directly be corrected for, and there is no need for adding the dynamic calibration uncertainty term into the total uncertainty in the measurement.

Since each measurement that is included in making the uncertainty interval for the calibrated sensor should have the same conditions for each run, the steady-state input pressure and the valves are logged. With use of the steady-state calibrated pressure sensors, it is possible to quality measure that the input pressure will be the same for each run. With logging the behavior of the valves, it is possible to adjust the measurements taken so each run will achieve the pressure step at the same time. The valve will send out a signal at 0V when it is closed, and approximately 9.4V when it is open, an example is seen in Figure 38.

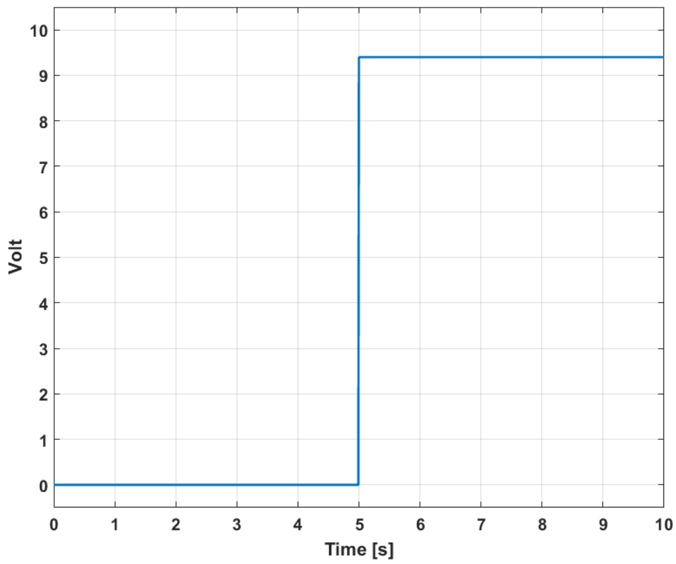


Figure 38 – Valve state

It is also important that the logging points are the same for each measurement run before and after the pressure step occurs. If the number of logging points differs for each run, the shortest measurement series is used and the other runs are adapted to this run.

As explained in Subsection 4.3.2, the logging rate is set to 50 000 samples per second. This logging rate is high enough to measure all the frequencies to be achieved, and for that reason, a regression line between the frequencies will probably not be necessary. This needs to be investigated.

7 Construction of the calibration tool

The calibration tool was constructed included steel machining at the Waterpower laboratory workshop, from the descriptions and drawings presented in Sections 4.1, 4.2 and Appendix D.1. The component dimensions connected to the calibration tool, as valves and sensors, were basis for the detailed specifications of the calibration tool.

Mounting of the calibration tool system was performed according to the drawings, and everything was successfully mounted except from the cavern space which should fit the adjustable bolt. The details of the machined bolt and the cavern space which seem to create the problems are described below.

When going into the details, it should be mentioned that the calibration tool was not exactly machined as described in Section 4.2. The part that was not constructed as expected was the adjustable bolt. Instead of producing a bolt with threads from top to bottom, as a completely threaded screw, it became a bolt with threads at the top and a distance down the shaft, and then an almost smooth surface down towards the bottom.

At the bottom it was also mounted an O-ring gasket for completely sealing the system. If the O-ring gasket at the bottom did not seal satisfactory, the O-ring gasket at the top could also be used to secure sealing. With this new type of bolt, it was not possible to adjust the cavity space inside the calibration tool. The solution could have been to create multiple bolts of this

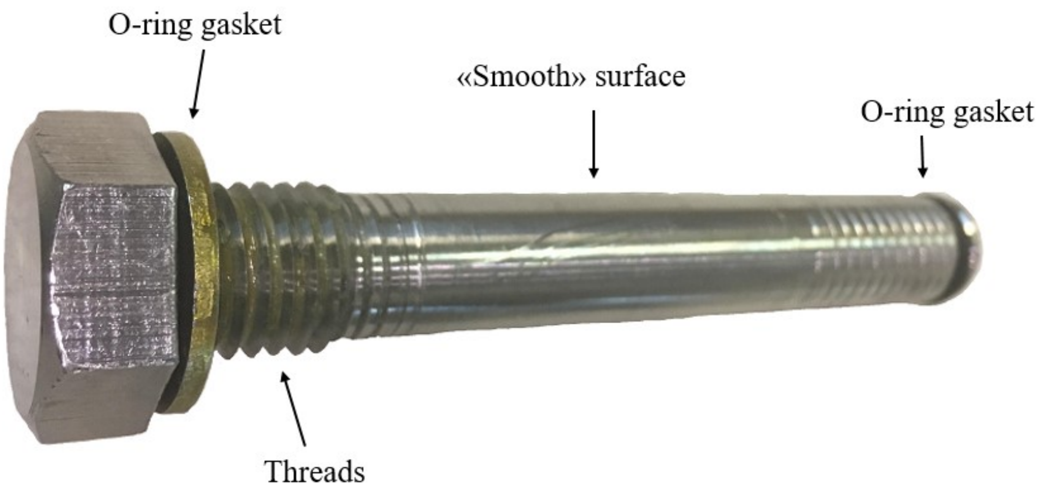


Figure 39 – The new bolt

type with different shank lengths, and exchange the bolts for adjusting the cavity space. The new bolt is illustrated in Figure 39.

The reason why the adjustable bolt did not become as expected, was due to lack of appropriate milling instruments and problems with the threads that should be conducted inside the calibration tool cavity. Figure 40 shows how the new calibration tool looked inside where the adjustable cavity volume should have been.

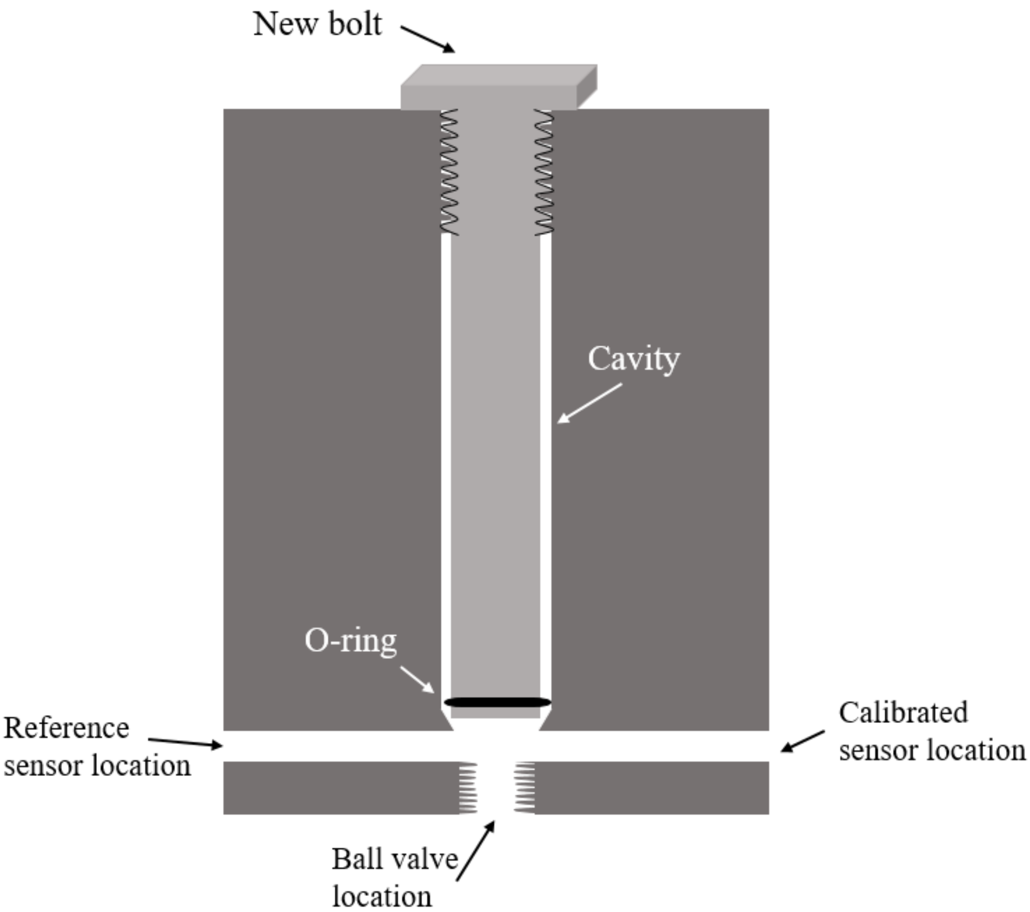


Figure 40 – Inside the calibration tool, after machining

The tests which were possible to accomplish with this equipment, are presented in Chapter 8.

8 Results and discussion

The desired test target for the calibration was to achieve a pure pressure step as presented in Figure 4. During the first test of the calibration system, it was quickly observed that the calibration system did not work as expected. In this chapter, the methods that were undertaken to determine what was wrong with the system, will be described and the findings will be discussed for each section. Finally, the applications of this calibration system will be presented.

8.1 Noisy step

The first tests of the calibration system that were conducted showed a lot of noise in the pressure step. With only use of the O-ring gasket at the bottom of the bolt, as described in Chapter 7, the water started leaking out. It was therefore not produced results with just one O-ring gasket at the bottom. With use of the O-ring gasket at the top as well, the calibration tool became completely sealed and some results were achieved. The results are presented in Figure 41.

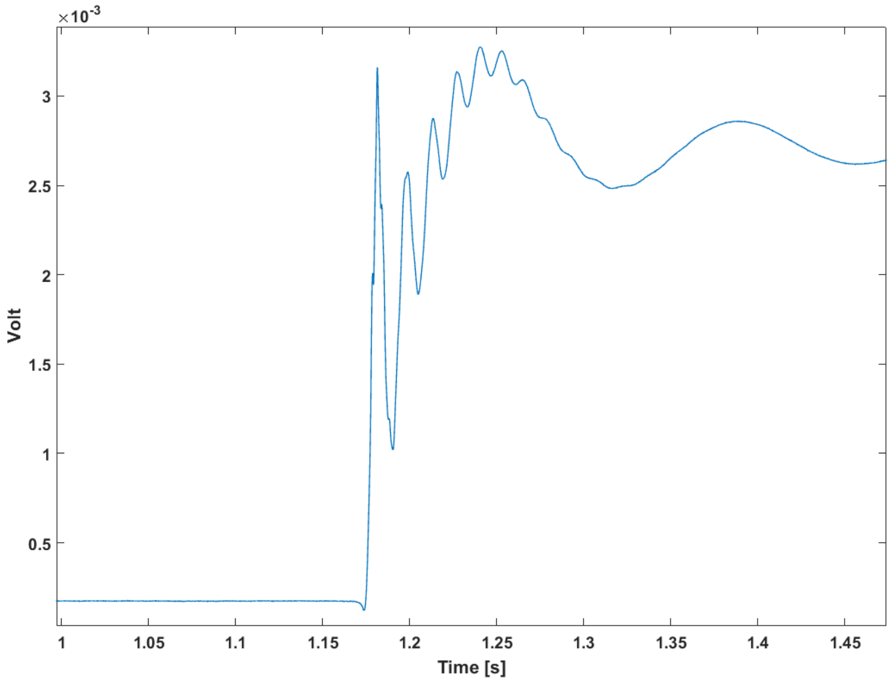


Figure 41 – Bolt with two O-ring gaskets

As the figure shows, this is far from a perfect step. The reason for this weird behavior is believed to be due to the structure of the bolt and the corresponding cavity inside. When the high-pressure water enters the calibration tool, the pressure is too high for the O-ring gasket, and the O-ring gasket is not capable of avoiding leakage of water into the cavity between the bolt and the tool walls. It can be seen in Figure 41 that the system is on its way to make a suitable step, but since the O-ring gasket is not sealing the system sufficiently, the pressure signal starts oscillating. The first down peak is believed to be the first time the water enters the cavity and the pressure drops. With this construction it is impossible to release all the air pockets inside this cavity, and the water pressure will oscillate.

Multiple adjustments were conducted to the bolt to make sure where the fault was located. The second test was to test the calibration system with the O-ring gasket just at the top of the bolt. With this method it should be possible to release all the air inside and in theory the step should be improved. The results could be seen in Figure 42.

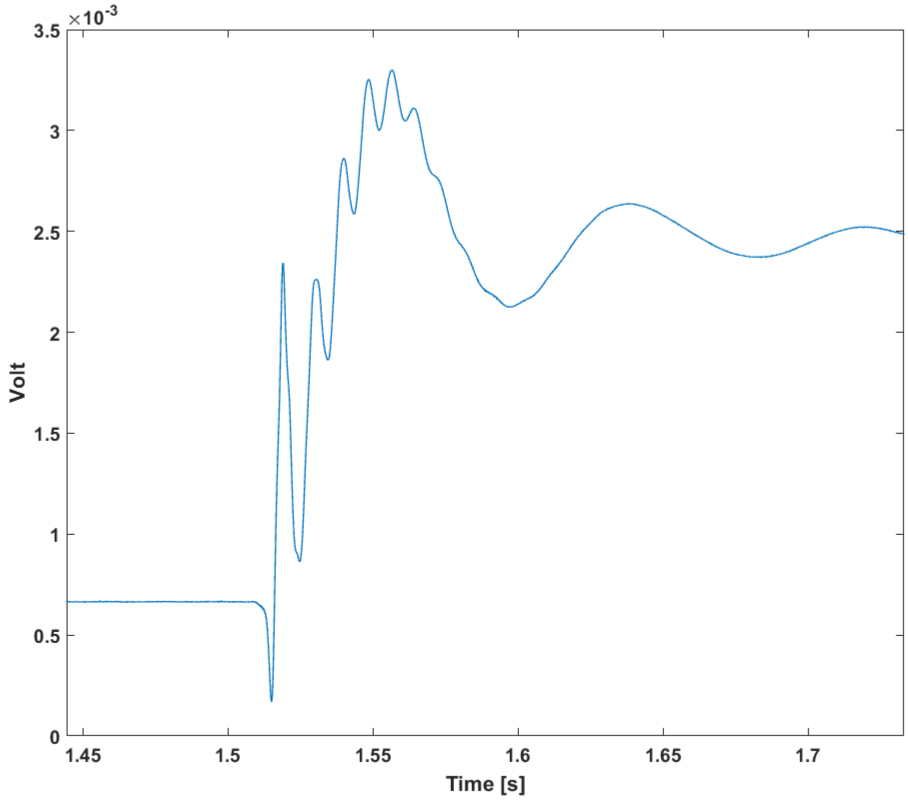


Figure 42 – Without O-ring gasket at the bottom at the bolt

The results show that this is not an accurate step either. The reason for this behavior is probably the difficulty of releasing air inside the cavity where the bolt is placed. It will then be created a standing wave in the cavity which destroys the results with noise. Multiple tests were performed for removing all air in the system. The calibration system got multiple blowouts with water to push air pockets out. It was also tilted in all possible directions, for releasing air. Figure 43 shows one of the tilting setups adapted to the calibration tool. An attempt was also made where the bolt was used to deflate before measurements were taken, instead of using the ball valve. Despite all attempts, the results remain similar to those shown in Figure 42.

Figure 43 – Tilting setup for the calibration tool

The next opportunity became therefore to try to seal the entire cavity where the bolt was located. For sealing the entire cavity several experiments were conducted. First, thread sealing tape was used with a bigger O-ring gasket at the bottom of the bolt. The system became almost sealed in the first run, but after several runs the thread tape was worn out.

The next attempt was to glue the cavity with a two-component metal glue, but this did not work perfectly either. Further, thread sealant solution was used without luck. The last attempt became to use Quick Steel Epoxy solution. Finally, the cavity next to the bolt became completely sealed and a step without noise was achieved. Figure 44 illustrates the step achieved when the steel solution was used.

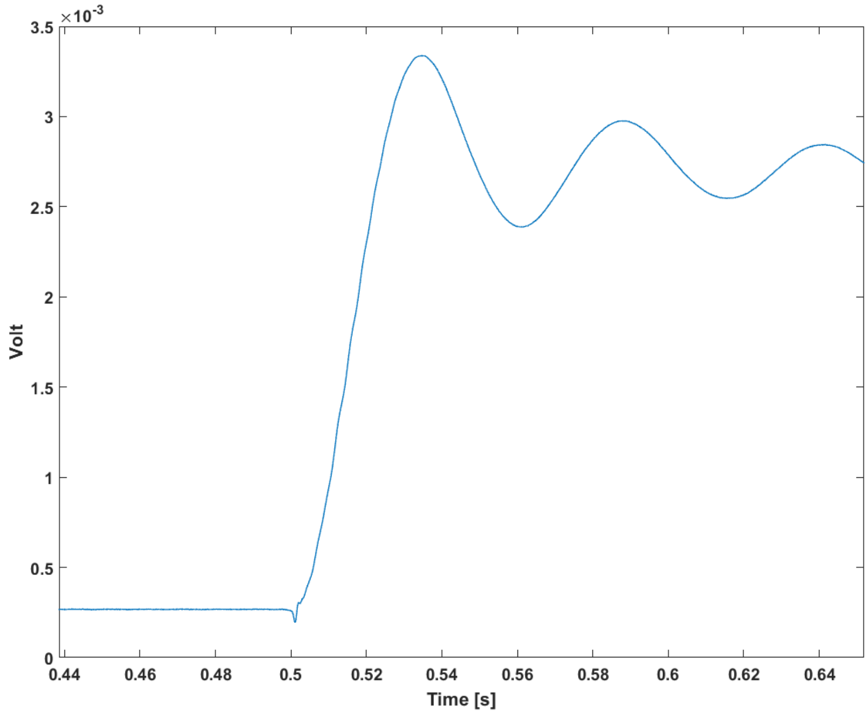


Figure 44 – Use of Quick Steel Epoxy

After the bolt was completely sealed with Quick Steel Epoxy solution, a test with air in the calibration tool was conducted. The result can be seen in Figure 45. The results show similar behavior as in Figure 42, even though the peaks are not as distinctive. The results confirmed the theory that the noise behavior achieved earlier was caused by air in the system. This result also emphasizes the importance of having a system completely free from air before the calibration starts.

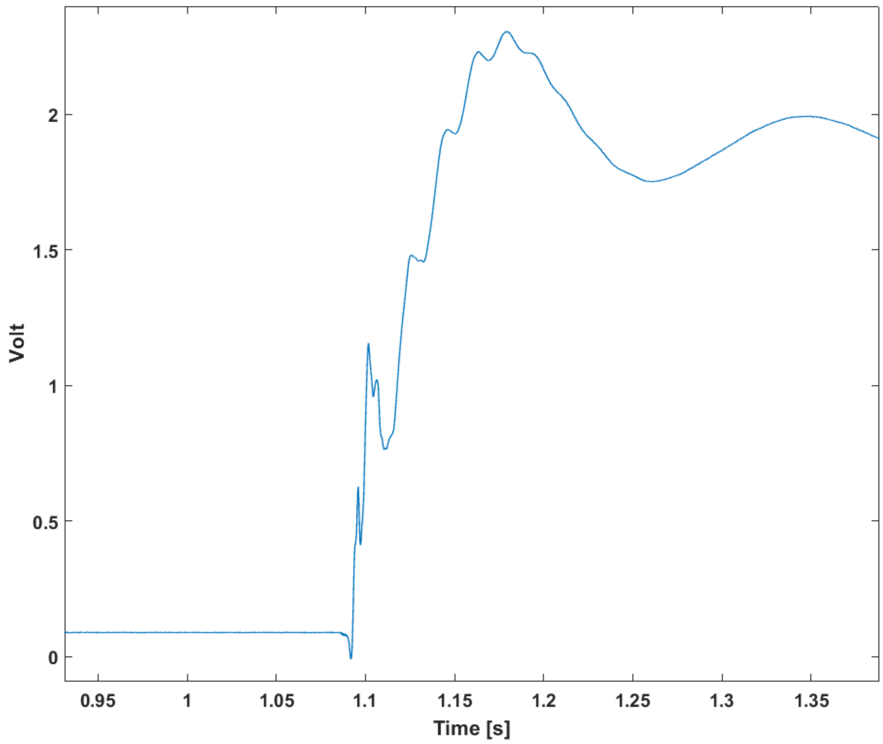


Figure 45 – Air in the calibration tool

8.2 Slow fluctuations and rise time

In addition to the noise in the measurements, it was observed slow fluctuations prior to the final state. It was also observed a slow rise time for the step, 29ms. In this section, methods used to understand why the slow fluctuations and slow rise time occurred will be illustrated and discussed.

8.2.1 Elastic pipe from the high-pressure supply

The first hypothesis was that the pipe that was sending water into the calibration tool from the high-pressure side was the reason for the slow fluctuations. When the valve opens, the water column pressures all the way from the high-pressure supply and to the sensor to be calibrated, see Figure 28 for illustration.

The pipe connected to the high-pressure supply is made of plastic, and due to that the pipe is elastic. Since the pipe is elastic, the extension of the pipe could result in the slow fluctuations which occurred. As there was no access to other pipes with different elasticity in the laboratory, the length of the pipe was made shorter. Since the pipe had the same elasticity, this test could indicate the effect of the pipe length. The new setup can be seen in Figure 46.

Figure 46 – Shorter pipe setup

Unfortunately, the results remained the same, as in Figure 44, and this theory was rejected.

8.2.2 Too low pressure level in the high-pressure tank

Another possibility was that the applied pressure was too low. This could result in water, which was entering the calibration tool, being pulled back into the pipe connected to the high-pressure tank, and causing oscillations. Tests were therefore conducted with higher pressure in the tank. The slow fluctuations did still occur.

8.2.3 The behavior of the valves

As discussed in Subsection 4.3.1, it was believed that the optimal use of the valves was to open and close the valves at the same time to not let the step get affected by the valves behavior. When a valve opens, the water gets pulled with, and the pressure drops in the cavity. When a valve closes the pressure rises inside the cavity. This behavior is due to the diaphragm piston inside the valve.

By testing the valves behavior in real life, it could be concluded that switching of the valves at the same time, was not optimal. Switching the valves at the same time made also unnecessary noise and discontinuities in the step.

To obtain optimal use of the valves, different tests were conducted. By generating a negative pressure step, the rise time of the step increased. Increasing the rise time of the step by generating a negative step has also been mentioned by Choi et. al [28]. Even though the rise time increased, the step did not become good enough to be used. Because of the valves behavior, there was seen a new discontinuity in the step and the slow fluctuations did still occur. This discontinuity could be seen in Figure 47, marked with a red circle.

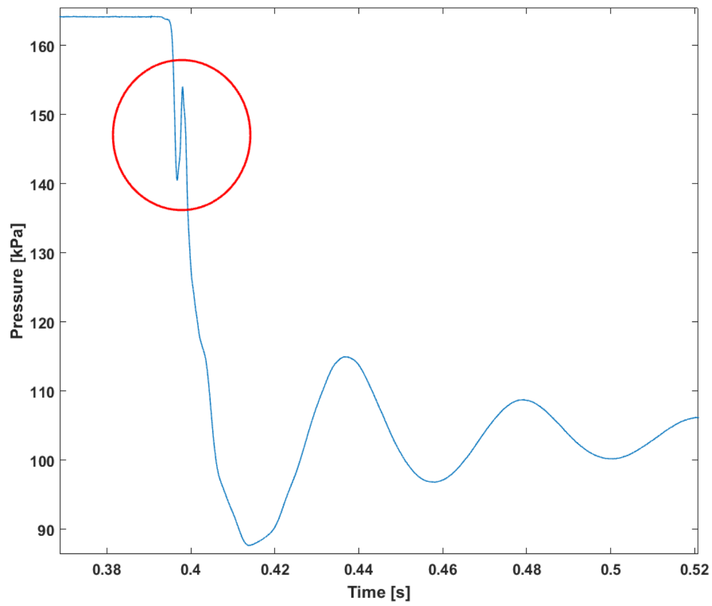


Figure 47 – Negative pressure step

Two methods caused least disturbances in the step. The first method is based on closing both the low-pressure valve and high-pressure valve before the measuring starts. During the measurements, the high-pressure valve opens. This use of valves was early found out to be one of the best and has therefore been applied during the previous tests.

The second alternative method is to have the low-pressure valve closed and the high-pressure side open before the measuring starts. During the measurements, the high-pressure valve closes. Further in this chapter, these two valve operating methods are used on the calibration system with the Quick Steel Epoxy solution to find out why the calibration system still does not behave as desired.

Because of the slow rise time the step achieved, every sensor used was fast enough to measure the step. Since all sensors gave similar results it means that the reason for the weird step behavior was not due to the sensors, but was made by the calibration system. Because every applied sensor measured the same behavior, it was impossible to use these results to analyze the behavior of the calibration system in the manner described in Section 3.1. The solution became to use the measurements registered by the reference sensors, and compare the measured behavior with a generated perfect step. In this way, it is possible to analyze the calibration system behavior. The analysis will include the behavior of every component in the system.

Transfer function theory, described in Section 3.1, was conducted in the same way as explained, but instead of using the transfer function to the calibrated sensor, the transfer function of a perfect step was used. The first analyses are performed on the results from the method where the high-pressure valve opens during the measurements. The reference sensor behavior compared to a perfect step can be seen in Figure 48.

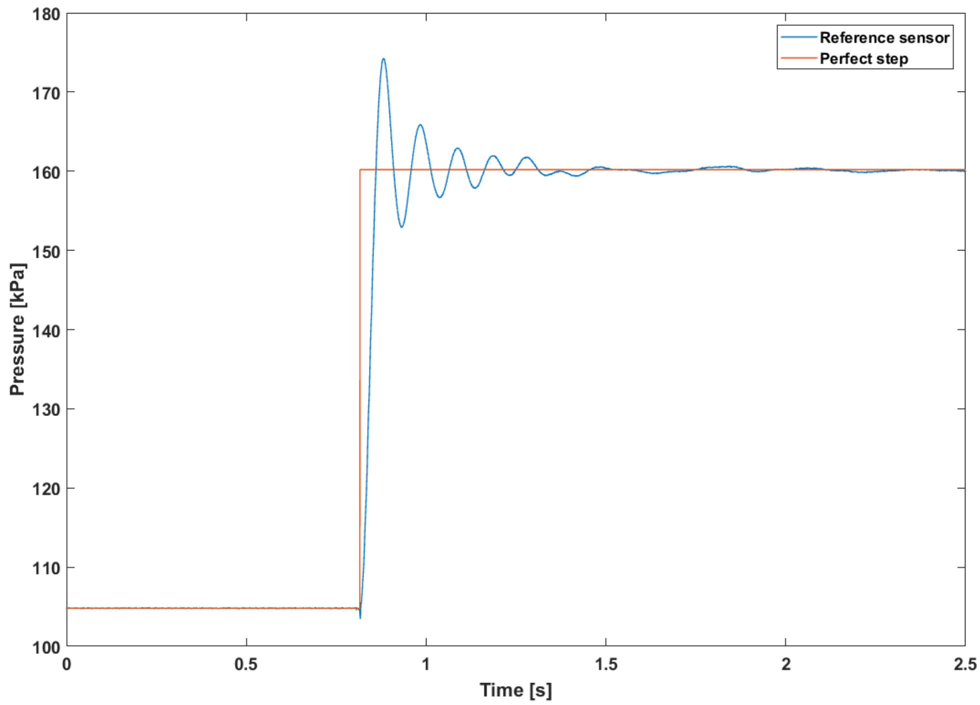


Figure 48 – Reference sensor and a perfect step, opening high-pressure valve

From the figure it can be observed that the step generated by the calibration system has a rise time of 64.5ms. The slow fluctuations prior to the final state can also easily be observed.

By using the built in function in MatLab, *tfestimate,* described in Subsection 4.3.3 the magnitude versus frequency Bode plot for the calibration system is achieved. Figure 49 shows the Bode plot conducted.

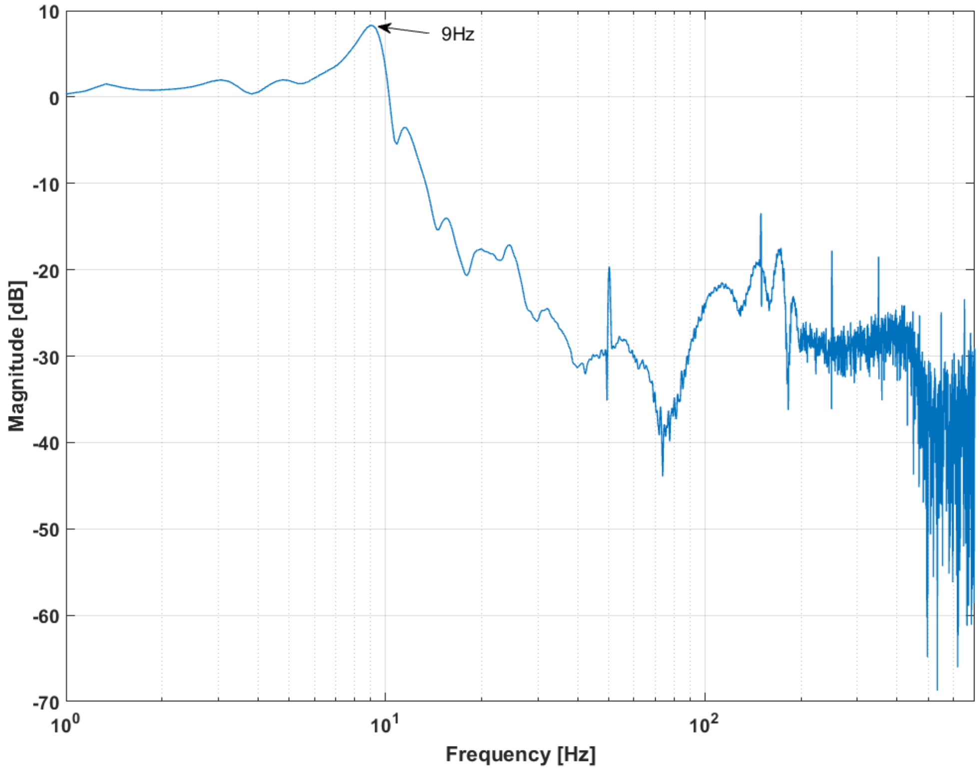


Figure 49 – Bode plot, opening high-pressure valve

By analyzing the Bode plot, a peak at 9Hz could be seen. This peak is caused by the slow fluctuations prior to the final state. This frequency is the only frequency discovered above the 0dB line.

The second analysis is performed on the results from the method where the high-pressure valve closes during the measurement. The same procedure is used for analyzing the frequencies generated by the calibration system. The reference sensor behavior compared to a perfect step can be seen in Figure 50.

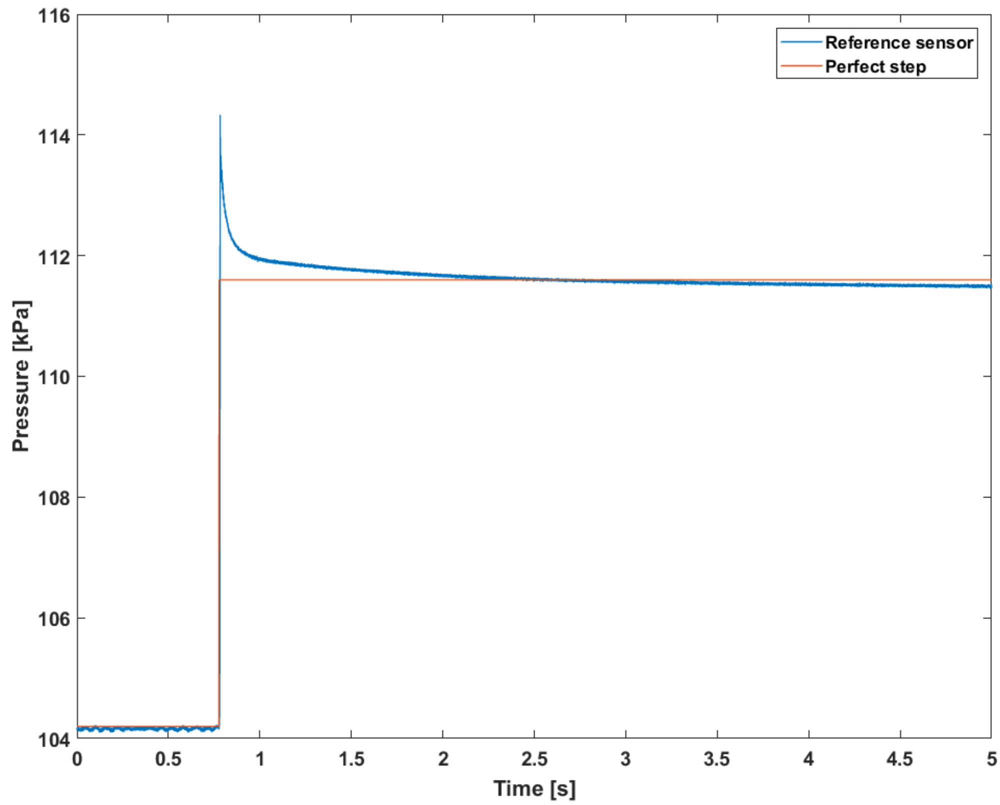


Figure 50 – Reference sensor and perfect step, closing high-pressure valve

It can be seen from Figure 50 that the slow fluctuations have disappeared, and the rise time to the step generated by the calibrated system has decreased to 8ms. The high peak is the pressure surge reinforced when the valve is closing. It can also be observed that even though the system should have reached its final state after approximately 1 second, the pressure is still decreasing. This behavior could be due to the valve not being completely sealed, and some water leaks out back into the pipe connected to the high-pressure tank. It is a higher pressure in the calibration tool cavity, caused by the pressure surge.

By using the built in function, *tfestimate,* described in Subsection 4.3.3, the magnitude versus frequency Bode plot for the calibration system is achieved. Figure 51 shows the Bode plot conducted.

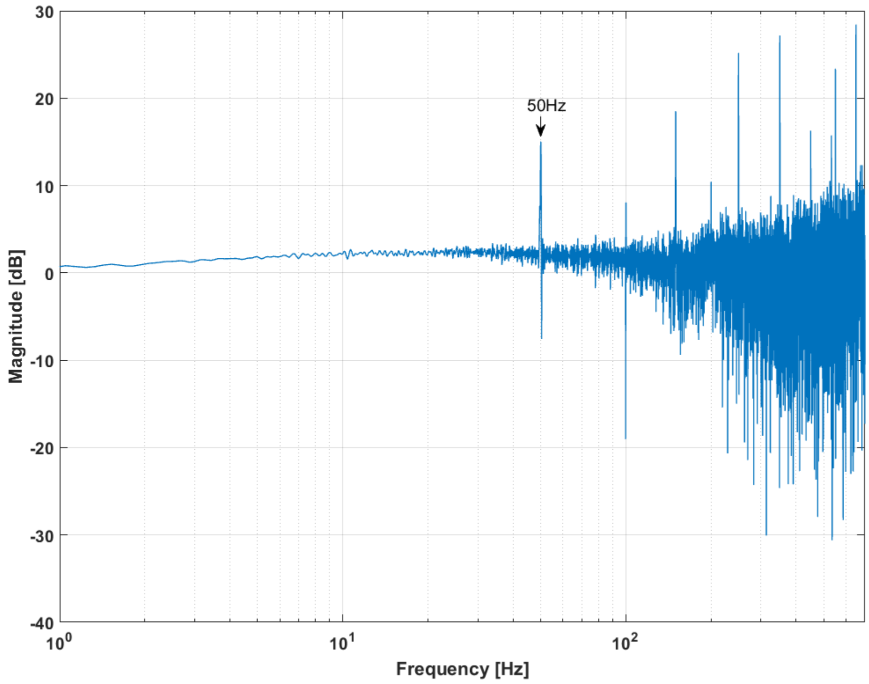


Figure 51 – Bode plot, closing high-pressure valve

By analyzing the results achieved, in Figure 51, no peak at 9Hz can be observed. The first peak is at 50Hz, and most likely represents the grid current frequency. Comparing Figure 51 and Figure 49, it can be seen that the frequencies in Figure 49 after 9Hz is damped with almost 30dB, hence the calibration system is working as a low pass filter with passband from 0Hz to 9Hz. Because of this, it can be determined that the slow fluctuations prior to the final state is working as a low pass filter in the calibration system, and is therefore caused by physical impacts from the valves. Since the slow fluctuations are operating as a low pass filter, delay in the system occurs. This delay can also be seen by comparing Figure 48 and Figure 50. The delay is therefore assumed to be the reason for the slow rise time achieved in Figure 48.

Unfortunately, it was impossible to know that the valve properties would be so important for the results before they were tested in reality. This is due to missing information from the vendor and property leaflet that followed the valves, which could not explain the behavior of the valve internals.

By analyzing the results, it can be concluded that the valve pistons are operating as a mass spring damping system. When the valve is open, the piston is not in a fixed position, and starts to oscillate due to the applied force of high-pressure water. When the valve is closed, on the other hand, the piston is in a fixed position. Figure 52 illustrates the assumed new piston behavior, in the moment the high-pressure valve opens.

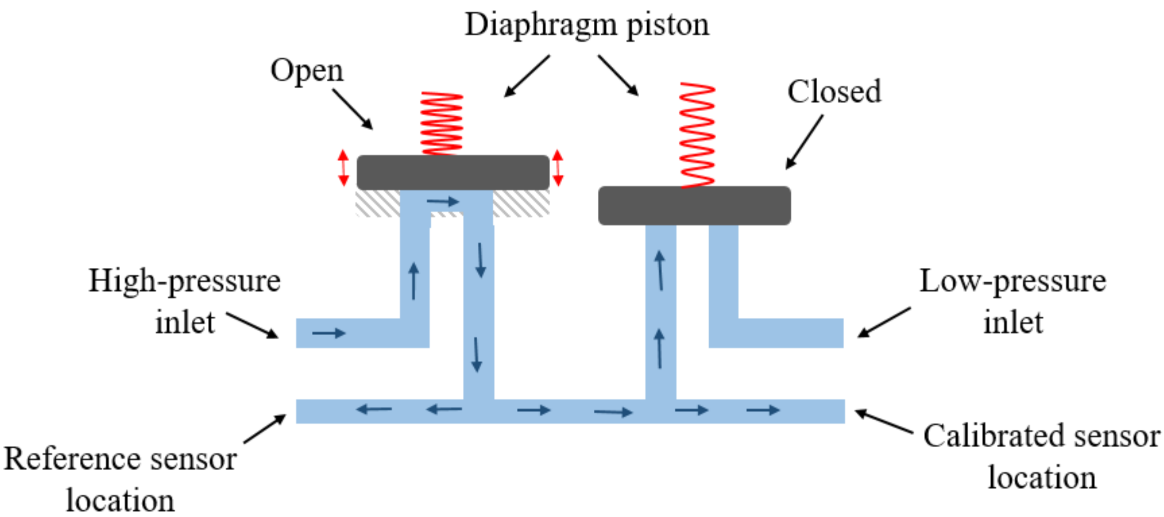


Figure 52 – The real diaphragm valve mechanism

8.3 Frequency analysis of the calibration system

By the use of the case described in the previous subsection, where the high-pressure valve closes during the measurements, it is possible to generate some informative results about the calibration system. The step generated is analyzed with Fast Fourier Transform (FFT), in this section.

The analysis is performed on the reference sensor. The analysis is conducted on the behavior of the step prior to the final state. Figure 53 visualizes the part which is analyzed, between the two dashed lines marked in red.

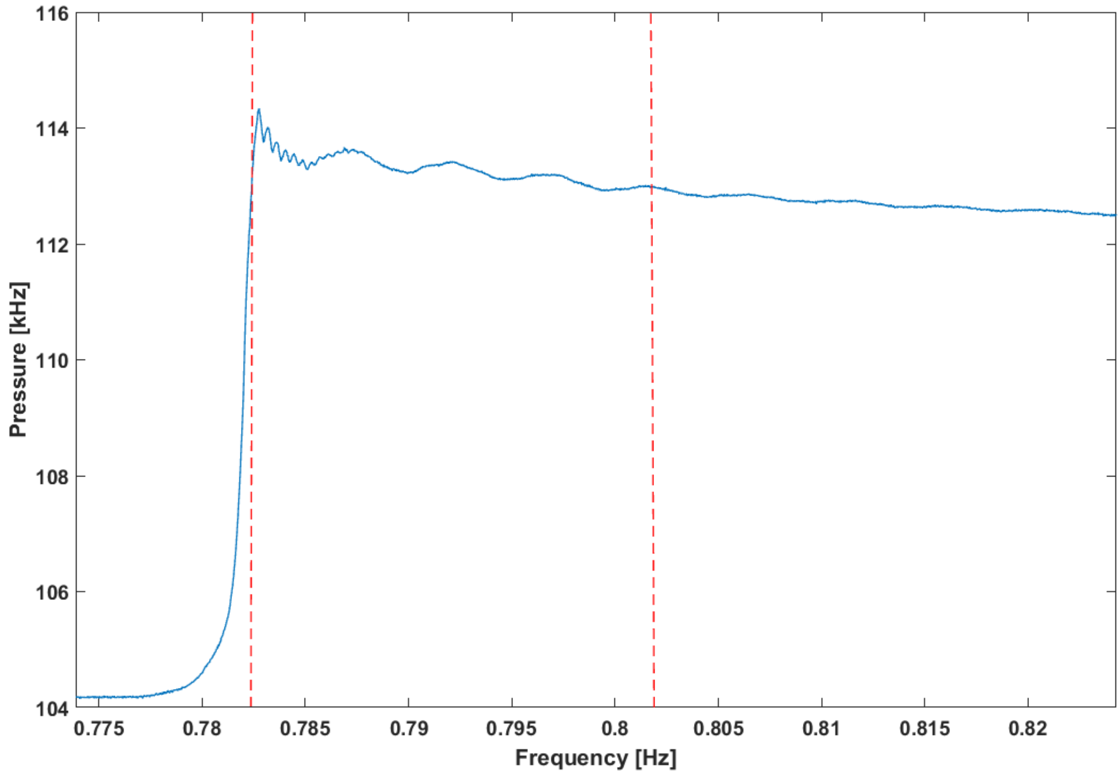


Figure 53 – Part to be analyzed

The reason for analyzing the results in this way, is because the behavior prior to the final state represents the natural frequencies which occur in the system [29]. The FFT is used with multiple Hamming windows and an overlap of 50% for canceling out random noise in the measurement. The FFT analysis performed on the behavior prior to the final state can be seen in Figure 54.

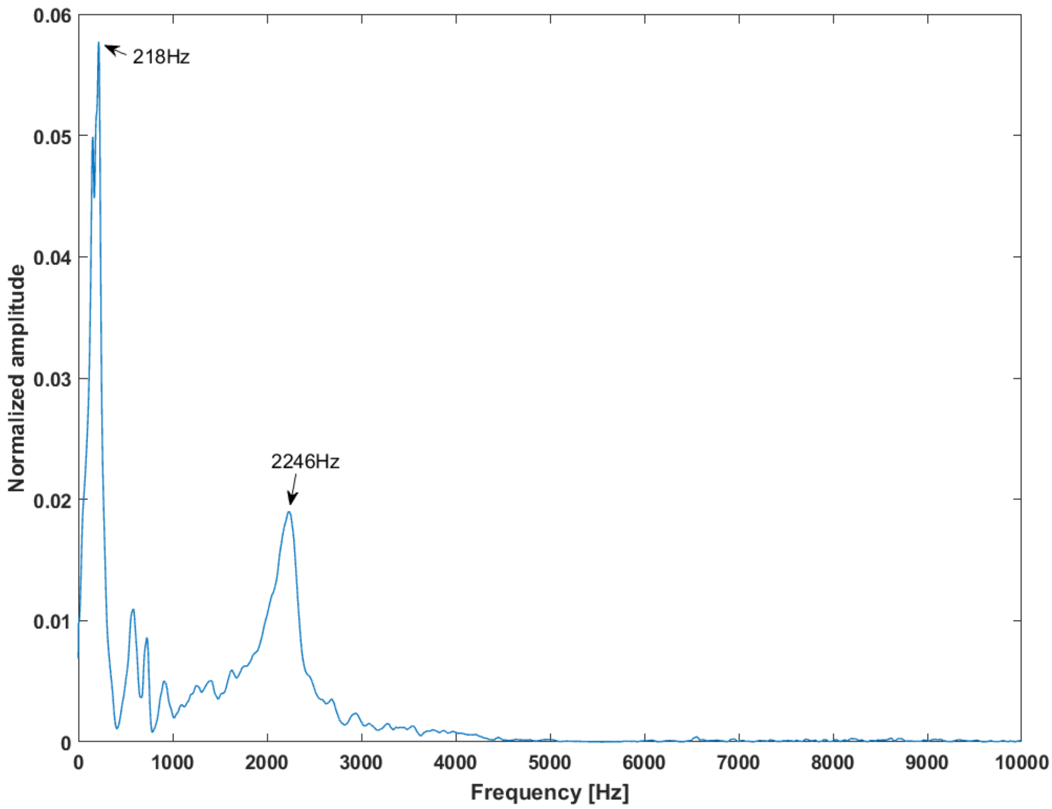


Figure 54 – FFT of the reference sensor

It can be observed a frequency peak at 218Hz in the figure, and this frequency is believed to be the slower fluctuations which occur right before the measurement stabilizes completely after the step. The next frequency peak is located at 2246Hz. This peak is assumed to be due to the frequencies of the fast fluctuations which occur right after the step. This frequency is the highest natural frequency achieved with this calibration system. The fluctuations which cause the frequencies can also be seen in Figure 53. The pyramid-resembling behavior of the peaks is due to the way the FFT analysis is performed where the step is generated multiple times after each other, so the periods are overlapping.

By knowing that the calibration system is generating a frequency of 2246Hz, it is possible to analyze some of the dynamic behavior of a sensor to be calibrated. The analysis of a calibrated sensor could be performed by comparing the frequencies measured by the calibrated sensor with the frequencies measured by the reference sensor. If the calibrated sensor is showing the same frequency peak at 2246Hz with same normalized amplitude, it can be concluded that the calibrated sensor is capable of measuring frequencies at 2246Hz or lower without an extra uncertainty term. If the calibrated sensor and the reference sensor have similar behavior, the uncertainty in the measurements can then be determined as completed by steady-state calibration.

There is a limitation of this method. If the calibrated sensor is intended to measure lower frequencies then 2246Hz, and does not achieve the same frequency peak at 2246Hz, it cannot be concluded if the sensor needs an extra dynamic calibration uncertainty term related to the measurements or not.

Due to lack of time, experimental investigation of this method was not performed. Some possible aspects to investigate are suggested in further work.

8.4 Calibration system used to verify dynamic pressure sensors

The calibration system developed in this master's thesis can also be used to verify the behavior of a dynamic pressure sensor. A dynamic pressure sensor is only measuring the change in pressure during measurements. The output of the dynamic pressure sensor is therefore the derivative of the pressure value. For converting to an absolute pressure value, an amplifier is used to integrate the derived pressures.

By generating multiple pressure steps with the developed calibration system, it is possible to verify if the dynamic sensor and the amplifier are responding as they should. It is done by using a reference sensor and observing that the dynamic sensor and amplifier are reproducing the same behavior.

For locating the error if the dynamic sensor does not follow the behavior of the reference sensor, either replacing the amplifier and see if the behavior changes, or replacing the dynamic sensor could be done. In this master's thesis, this method for verifying the behavior of a dynamic sensor has not been done, due to lack of time. This could be done in a later project thesis or master's thesis.

8.5 High-pressure supply

Both the high-pressure tank and the Deadweight tester were tested for creating an optimal calibration system. In principle both could be used. The difference between those two methods is that the high-pressure tank makes it easier to achieve the same high-pressure supply for each run.

Large amounts of water are also needed to remove all air inside the calibration tool. With use of the Deadweight tester, distilled water needs to be filled at least twice during one calibration. With use of the high-pressure tank, it is also more effective to make blowouts with water, so all air in the system is released. The high-pressure tank holds a large volume of water, and a water blowout of approximately one liter results in negligible difference in pressure level.

9 Conclusion

A dynamic calibration system was designed, developed and tested in this master's thesis. The calibration system did not work as desired, but it has a range of applications. There were several reasons for the unexpected calibration system behavior.

The machining of the calibration tool was not performed in accordance with the drawings. This lead to air pockets in the system which again made a lot of noise in the measurement signals. The solution was to block the entire adjustable cavity with a Quick Steel Epoxy steel solution. A system free from air is extremely important before calibration starts.

The valves had a narrow operating range. Most of the attempts performed on the valves for getting the optimal valve use, ruined the step because of the diaphragm pistons behavior. The valve did operate as a mass spring damping system. The unfixed behavior caused slow fluctuations prior to the final state after the step, resulting in a delay in the rise time of the step. The optimal valve use was to have the low-pressure valve closed before the measurements started, and to close the high-pressure valve during the measurement.

When the high-pressure valve closes during the measurement, the system is capable of generating an almost suitable step. It was indicated with the use of FFT that the highest natural frequency achieved in the system was 2246Hz. By knowing this frequency, it could be determined if a sensor to be calibrated does not need an extra uncertainty term. The calibration system developed could also be used to verify if a dynamic pressure sensor and amplifier behave in a correct manner. These methods need although to be verified with additional experiments.

It could also be concluded that the high-pressure tank is the most suitable way for applying high pressure water to the calibration tool.

As stated in this master's thesis, and earlier research articles, it is proved to be difficult to generate a perfectly working dynamic calibration system. Having that said, it is an important topic when dynamic pressure measurements are needed because of the uncertainty caused for instance by the natural frequency of the sensors.

10 Recommendation for Further Work

In this chapter, recommendations for further work are presented. This chapter is divided into four sections. The first section proposes use of the same calibration tool as adapted in this master's thesis. The second section is a proposal for a new design of the calibration tool. The third section will discuss general improvements for the entire calibration system. The last section contains proposed analyses that can be performed on the sensor after calibration.

10.1 The calibration tool constructed in this master's thesis

Before too many modifications are made on the system, it may be worth looking into individual factors. What could be done is listed below:

- Use a sensor with natural frequency of 500Hz or less, as the calibrated sensor, for investigating if the procedure for finding the uncertainty caused by the natural frequency of the sensor is feasible to apply. The procedure is explained in Subsection 6.4.1. The tests could be used on the already existing calibration system, with the method where the high-pressure valve closes during measurements.

- Investigate if the method described in Section 8.3, about comparing frequencies, is durable. The method should be explored with a sensor containing a natural frequency lower than 2246Hz and a sensor containing higher natural frequency than 2246Hz.

- Conduct tests on a dynamic sensor and corresponding amplifier, and verify the method explained in Section 8.4.

- Use ball valves for switching from low to high pressure, instead of the diaphragm valves already used. The ball valves should be connected to the high-pressure and low-pressure inputs. By use of ball valves, it can be proved or disproved that the diaphragm valves are one of the main reasons for the calibration system not working as expected. This could be proved because the ball valves are opened and closed with another mechanism than diaphragm valves.

10.2 Suggestion of a new calibration tool design

After the tests are conducted with the already developed calibration tool, and hopefully the results show that this is something to develop further, a new and improved calibration tool could be made. The new and improved calibration tool should contain a smaller cavity and fewer internal pipelines than the previous one. The system should also be constructed so the air is released from the highest level. The main concepts of a new calibration tool are listed below.

- Remove the steady-state calibrated sensors, used to control measure the pressure supply. Instead, perform a static calibration of the reference sensor and the calibrated sensor before dynamic calibration starts. These sensors are used to gain control of the pressure supply.

- The ball valve is unnecessary and can be removed. The low-pressure side is used to deflate.

- Change the position for the reference sensor and the calibrated sensor with the high-pressure inlet and the low-pressure inlets. Changing the positions of these components makes it easier to deflate from the highest level. The new positions could be seen in Figure 55.

- The diaphragm valves need to be replaced by some valves which behave like ball valves, and are just as fast as the diaphragm valves used in this master's thesis. They should also have the mechanism to be controlled from an external source. The valves should be directly mounted on the pressure water supply inlets.

- There are different ways to improve the calibration tool including the adjustable bolt. It is important that the calibration tool is completely sealed, and the cavity space should be adjustable.

    - Suggestion to a new bolt and calibration tool design can be seen in Figure 55. It is important that the entire system is completely sealed, so the machining must be done extremely carefully. For varying the natural frequency of the tool, the bolt could be milled from the bottom. A number of bolts with different milled lengths can be made. Hence, this gives stepwise cavity space and is not freely adjustable. Thread sealants solution could be applied to the bolt before use.

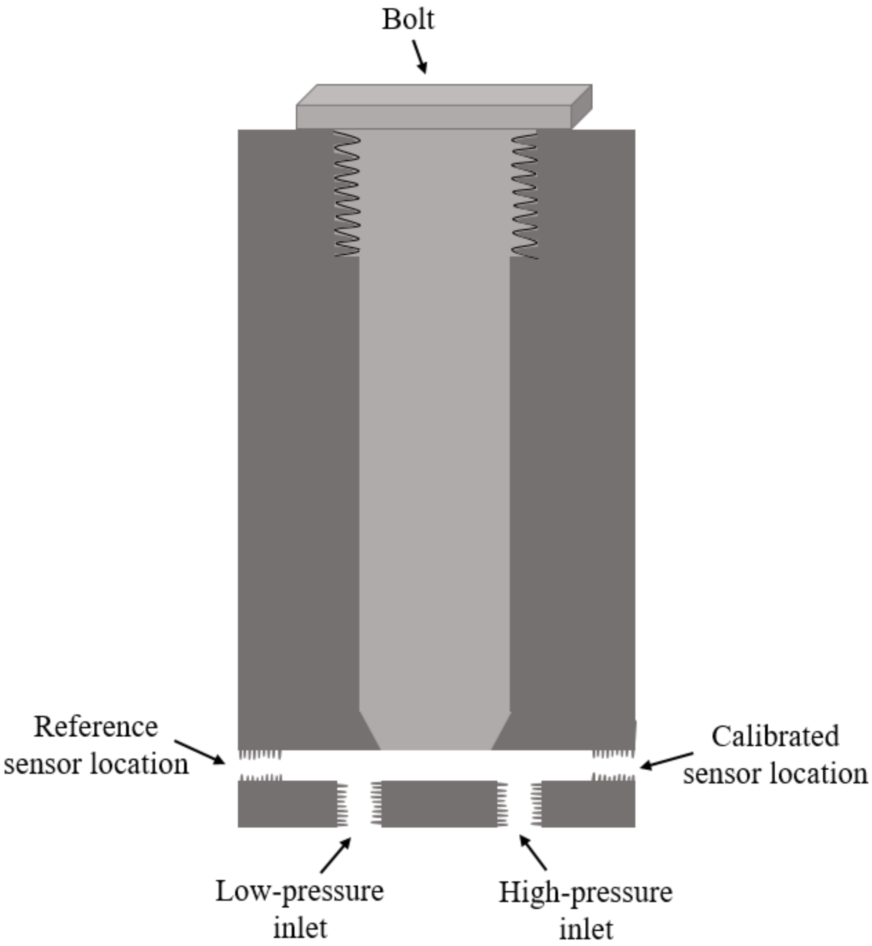


Figure 55 – Calibration tool with improved bolt system

- Another possibility is to have a bolt without threads all the way inside the calibration tool and threads above. See Figure 56. A very careful machining with high accuracy is needed as the first design improvement, to avoid distance between bolt and calibration tool. In the region where the bolt is going into the calibration tool, a stuffing box should be installed to tighten the bolt. A mechanical system like a fixed nut above the stuffing box is needed for screwing and it will be possible to adjust the bolt to generate different cavities. Thread sealants solution could be applied to the bolt before use.

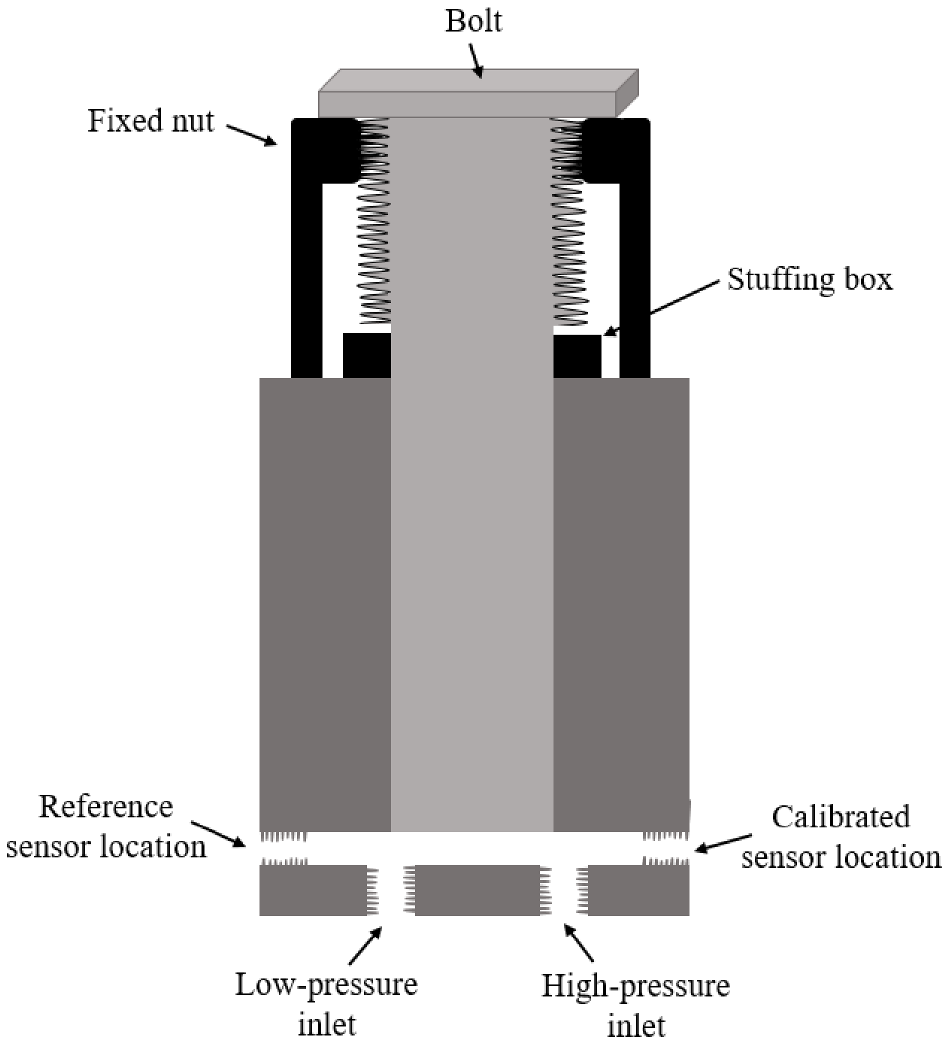


Figure 56 – Calibration tool with stuffing box

10.3 Suggestions to general improvements of the calibration system

Several parts of the calibration system can be improved for getting a more user friendly and effective system. The following points are improvements of a calibration system, which is already capable of finding the natural frequency of a sensor.

- An improved edition of the calibration program made in LabVIEW is needed. The program should be made in a way where the only function is to start the program, and the program itself is generating 30 equal steps. This means that the program needs to have a direct contact with the valves.

- The program should also be able to generate a calibration report. If the frequency measured by the calibrated sensor is above the 0dB line, the constants for getting the mean value should be easy to collect from the calibration report. The uncertainty interval in each frequency measured, should also be easy to collect.

- Since the calibration system did not work as expected in this master's thesis, the theory of not needing a regression line between the frequencies was not investigated properly. If the theory of not needing a regression line is disproved, a function for generating a regression line between the frequencies should be made in the program as well.

- If the new improved calibration system will generate frequencies higher than 25,000Hz, a CompactDAQ which allowed higher logging frequency than 50,000Hz is needed.

- The water reservoir for the low-pressure side could be improved by making a more professional setup.

- A procedure for finding the uncertainty achieved with dynamic calibration should be made.

10.4 Analyses performed with a dynamic calibration system

As stated in Section 1.1, there are no international agreements on how the calibration analysis of the pressure sensor should be performed. According to ISA-37.16.01 standard [8] and Hjelmgren [3] several aspects can be investigated as

- Sensitivity
- Amplitude response
- Phase response
- Natural frequency
- Ringing frequency
- Damping ratio
- Rise time
- Overshoot

In this master's thesis, natural frequency is the only aspect investigated. By using the developed calibration system or an improved calibration system, it would be interesting to test the different aspects listed above, and figure out which methods are best suitable for the dynamic measurements performed at the Waterpower Laboratory at NTNU.

With a functional dynamic calibration system, some analyses could be performed in the Laboratory. Dynamic and steady-state pressure calibration could be conducted on the pressure sensors used at the Pelton test rig in the Waterpower laboratory. The uncertainty could be determined by use of the dynamical calibration procedure and the steady-state calibration procedure, and then the uncertainties should be compared. Dynamic calibration of the pressure sensors installed in the runner of the Francis rig could also be performed.

References

[1] M. Nilsson, "Dynamic Calibration of Pressure Sensors," 2016.

[2] Ham-Let, "Surface Mount Ultra Fast Valve," ed. http://www.ham-let.com/catalogue/group/6921/nameblock/Surface-Mount.

[3] J. Hjelmgren, "Dynamic Measurement of Pressure - A Literature Survey," 2002.

[4] A. M. Hurst, S. Carter, D. Firth, A. Szary, and J. V. Weert, "Real - Time, Advanced Electrical Filtering for Pressure Transducer Frequency Response Correction," 2015.

[5] Omega, "DPX101 High-Frequency Pressure Sensor," 1993.

[6] A. C. G. C. Diniz, A. B. S. Oliveira, J. N. S. Vianna, and F. J. R. Neves, "Dynamic calibration methods for pressure sensors and developmet of standard devices for dynamic pressure," 2006.

[7] J. P. Damion, "Means of Dynamic Calibration for Pressure Transducers."

[8] ISA-37.16.01, "A Guide for the Dynamic Calibration of Pressure Transducers," 2002.

[9] A. M. Hurst, T. R. Olsen, S. Goodman, J. V. Weert, and T. Shang, "An Experimental Frequency Response Characterization of MEMS Piezoresistive Pressure Transducers," 2014.

[10] J. Lally and D. Cummiskey, "Dynamic Pressure Calibration," 2005.

[11] N. d. M. Nascimento, A. B. d. S. Oliveira, and F. J. R. Neves, "Construction of a new fast - opening device for dynamic calibration of pressure transducers," 2007.

[12] Z. Wang, Q. Li, Z. Wang, and H. Yan, "Novel Method for Processing the Dynamic Calibration Signal of Pressure Sensor," 2015.

[13] LNE, "Dynamic Calibration of Pressure Sensors."

[14] H.-P. Halvorsen, "Reguleringsteknikk vha. MathScript," 2016.

[15] J. G. Balchen, T. Andresen, and B. A. Foss, "Reguleringsteknikk," 2004.

[16] Klister, "Piezoelectric Pressure Sensor," ed. www.kistler.com/by/en/products/components/pressure-sensors/#piezoelectric__pressure__sensor__p_e_250_bar_3625_psi_601_c_a_a.

[17] C. Sullivan, "Engineering Sciences 22 - Systems, Bode Plots," ed. www.dartmouth.edu/~sullivan/22files/Bode_plots.pdf, 2004.

[18] Y. Wang, "A Practical Data Processing Analysis for Water Impact Problem " 2015.

[19] L.-K. Xuan, Y. Liu, J.-F. Gong, P.-J. Ming, and Z.-Q. Ruan, "A time-domain finite volume method for the prediction of water muffer transmission loss considering elastic walls," 2017.

[20] A. Nishikawa and D. W. Slaton, "The Effect of A Helmholtz Resonator's Neck Geometry On The Aero-Acoustic Excitation of Resonance," 2009.

[21] C. Bergan, "Trykkpulsasjoner i Francisturbiner," Project thesis, NTNU 2013.

[22] B. A. Olshausen, "Aliasing," 2000.

[23] G. Semsing, "Hydraulic Deadweight Tester User's Manual," 2006.

[24] A. S. Melaaen, "Stability of the Francis turbine test rig in the Waterpower laboratory," Project thesis, NTNU 2016.

[25] IEC60193, "International standard, Hydraulic turbines, storage pumps and pumpturbines - Model acceptance testes, Chapter 3.9," 1999.

[26] B. W. Solemslie, "Compendium in Instrumentation, Calibration and Uncertainty Analysis, NTNU," 2013.

[27] Kulite, "Transducer handbook ", ed. www.kulite.com/assets/media/2017/05/section8.pdf.

[28] I.-M. Choi, T.-H. Yang, H.-W. Song, S.-S. Hong, and S.-Y. Woo, "High Dynamic Pressure Standard Using a Step Pressure Generator " 2012.

[29] P. F. Dunn, "Measurement and Data Analysis for Engineering and Science - Third Edition," 2014.

Appendix

- Appendix A – Published article
- Appendix B – Sensors properties
    - B.1 – Steady-state sensors
    - B.2 – Calibrated sensor
    - B.3 – Reference sensor
- Appendix C – Valve characteristics
- Appendix D – Construction work drawings
    - D.1 – Calibration tool
    - D.2 – Control-box
- Appendix F – Calibration report, steady-state calibration
    - UNIK 5000 PTX5072, 0bar to 10bar absolute
    - UNIK 5000 PTX5072, 0bar to 5bar absolute
- Appendix F – Calibration report, reference sensor Kistler 601C
- Appendix G – Risk assessment

Appendix A – Published article

Proceedings of the International Symposium on Current Research in Hydraulic Turbines

CRHT – VII

April 04, 2016, Turbine Testing Lab, Kathmandu University, Dhulikhel, Nepal

Paper no. _ _ _

Calibration and Uncertainty Analysis of Pressure Sensors used for Dynamic Measurements

Aase Sørum Melaaen[1*], Einar Agnalt[1] and Ole Gunnar Dahlhaug[1]

[1]*Department of Energy and Process Engineering, Norwegian University of Science and Technology, Alfred Getz veg 4, 7491 Trondheim, Norway*

** Corresponding author (aasesm@stud.ntnu.no)*

Abstract

The calibration of dynamic pressure sensors is challenging. Often, steady-state pressure is used to calibrate the dynamic pressure sensors. Steady-state calibration adds uncertainty in dynamic measurements, because it do not represent the dynamic behavior of a sensor. This is the motivation for the master thesis presented in this paper, written at the Waterpower Laboratory at NTNU in spring 2017. This master thesis investigates methods for performing dynamic calibration. The best method is believed to be the use of an aperiodic pressure generator, because of its large range of frequencies and pressures, and the low cost and simple construction. The dynamic calibration method developed in this master thesis is based on a step-response method with use of ultra-fast valves with response time less than 5 ms.

Keywords: Dynamic calibration, pressure sensors, step-response, ultra-fast valve, transfer function, uncertainty

1. Introduction

The Waterpower Laboratory at the Norwegian University of Science and Technology calibrates pressure sensors with steady-state pressure, even though the sensors are used for dynamic measurements, i.e., measurements of pressure changing with time. The purpose of this master thesis is to establish a method for dynamic calibration of pressure sensors.

Calibrating a pressure sensor dynamically is essential to determine its dynamic behavior. Determining and locating the frequency response of the pressure sensors will automatically give measurements that are more reliable and accurate.

There is no standard for dynamic pressure calibration, but various methods have been explored. This article will highlight these methods, and discuss advantages and disadvantages for each method. Finally, a method for dynamic calibration established in this master thesis will be carefully explained, and expected results for this method will be discussed.

2. Previous work

Many research projects about dynamic pressure measurements have included dynamic calibration of pressure sensors. Determination of the dynamic features of a sensor in a reliable and accurate way is critical to achieve reliable research results. It is insufficient to measure the exact value of the measured quantity in an accurate manner, the output should also reproduce the time and frequency behavior of the quantity [1].

There is no standard method for dynamic calibration. Several scientific articles describe the two methods to experimentally characterize the dynamic behavior of a pressure sensor [1-4]. The two main ways are to generate either a periodic or an aperiodic pressure pulsation. These methods are discussed more thoroughly in subsection 2.1 and 2.2.

2.1. Periodic pressure generator

Dynamic calibration preformed by using a periodic pressure generator is also denoted as harmonic tests. This calibration is done by generating a sinusoidal pressure input of a given amplitude and frequency to the sensor that is being calibrated. Since the exact amplitude and frequency cannot be determined at input, another pressure sensor with high dynamic sensitivity is needed as a reference sensor [3]. Varying the input frequency point-by-point gives the opportunity to determine the transfer function.

There are different ways to make a periodic pressure generator, but there are three main concepts [2]. The first is based on pressure in a cavity that changes sinusoidally. The second concept is based on variation in volume or mass inside a cavity. The last concept is based on direct control of the input frequency with use of a modulation motor. The periodic pressure generator can in practice be difficult to control and build [1]. To avoid a high distortion rate, the input frequency and amplitude must be low. This causes periodic pressure generators to be of limited use since the available range is way below the user's requirements. Thus, aperiodic pressure generators are needed [2, 3].

2.2. Aperiodic pressure generator

Dynamic calibration done by an aperiodic pressure generator, also denoted as transient tests, is preformed by generating a pressure step to the sensor that is being calibrated. The sensor being calibrated should then reproduce the step. Usually a reference pressure sensor is also included in the aperiodic pressure generator test. By use of these two sensors, a transfer function can be determined [5].

There are two main ways to make an aperiodic pressure generator [3, 5-7]. The first concept is based on generating the pressure step with use of a shock tube. A shock tube is basically made up by two tubes, separated by a thin diaphragm [3, 6, 8]. In the two different sections different pressure levels are developed. When the thin diaphragm between the two tubes ruptures, the high level pressure flows towards the low level pressure and compresses it. This will form a step, which is registered by both the sensor being calibrated and the reference sensor.

The other concept of an aperiodic pressure generator is based on using a fast-opening device. This method is easy to implement and can reach a wide area of frequencies and pressures [1, 5]. The fast-opening device system is made up by two cavities with different

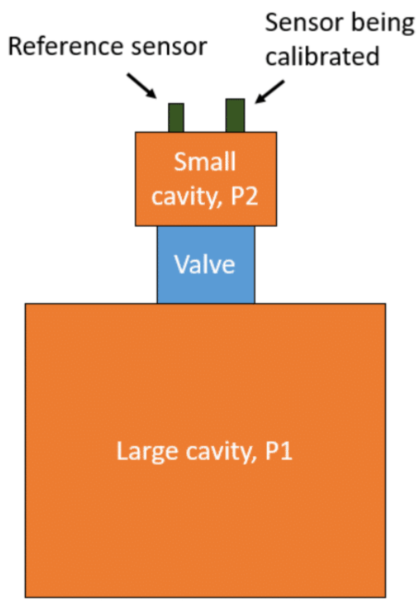


Figure 1 - Principle behind fast-opening device step generator.

pressure levels and sizes. An ultra-fast valve separates the two areas, and when the valve opens, the high level pressure area moves to the low level pressure area, where the sensor being calibrated and the reference sensor is placed. By using the two sensors, a transfer function for the sensor being calibrated can be developed. Figure 1 shows the principle behind a fast-opening device step generator.

3. Experimental setup

The dynamical calibration method for pressure sensors developed in current master thesis is based on the concept of an aperiodic pressure generator with use of a fast-opening device, which was explained in Subsection 2.2. The reason way this method is used, is for its good range of frequencies and pressures, and also the low cost and work for building the calibration tool. The frequency range wanted to calibrate for is from 0Hz to 5000Hz. Including developing a calibration tool, a logging program used for calibration is developed.

3.1. Calibration tool

The calibration tool developed is a box with a small cavity. The pressure inside this cavity changes rapidly. Both high-pressure and low-pressure are supplied to the box by small pipes connected through the sides of the box. Figure 2 illustrates the box with the high-pressure and low-pressure inlet.

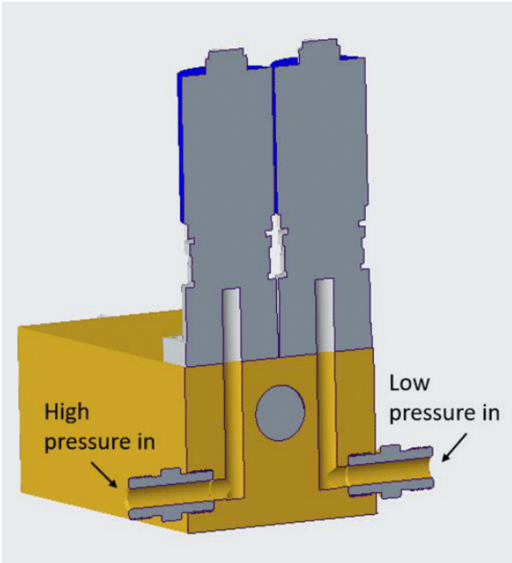


Figure 2 – High-pressure and low-pressure input

Furthermore, two valves, which control the supply of the different pressure levels inside the cavity, are attached on top of the calibration box. These valves have a response time less than 5ms, and in theory they will ensure that the alternation between high and low pressure is so fast that it generates a perfect pressure step. Figure 3 illustrates the valves on the top of the calibration box.

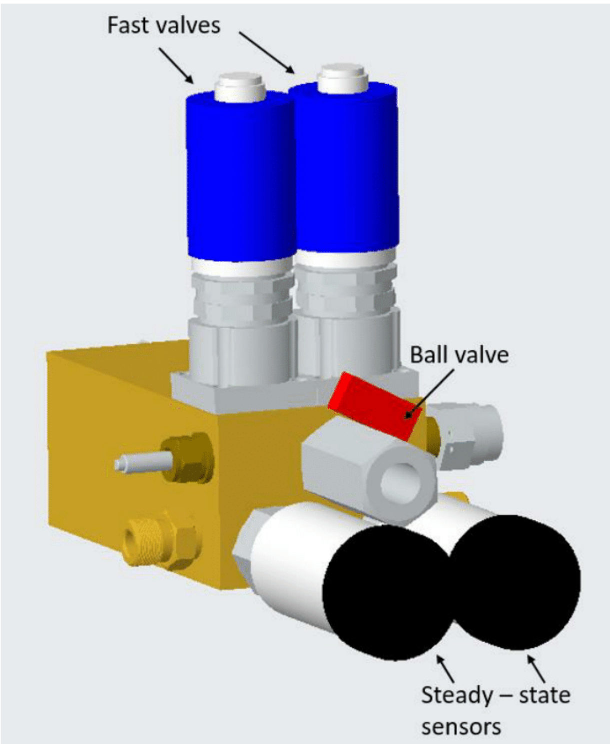


Figure 3 - Calibration toolbox

In Figure 3, two steady-state pressure sensors can also be observed. These are used for quality measuring the input high-pressure and low-pressure. A ball valve is also mounted on the calibration box, as can be seen in Figure 3. This ball valve is applied to deflate before calibration begins. Air in the cavity will cause the frequency to be lower than desired.

In theory, the input to the calibrated sensor should be a perfect pressure step. A perfect pressure step contains all frequencies. Such a step is impossible to make. A reference sensor is therefore used for measuring the input. Figure 4 shows a perfect step in blue compared with a realistic step in red. In Figure 5, the location of the reference sensor and the sensor being calibrated are shown. Figure 5 also illustrates the cavity inside the box. It is important to have a conscious awareness of the frequency response this cavity will create. The frequency response will behave as a low pass filter, which removes frequencies higher than its own. To improve frequency response control, water is used as medium during calibration. The calibration box is also equipped with an adjustable bolt which can be seen in Figure 6. This bolt makes it possible to adjust the cavity volume, so different frequency responses can be achieved. Frequency response will be further discussed in Subsection 4.3 and in Section 5.

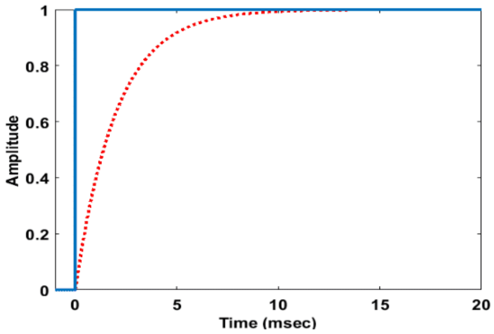


Figure 4 - Perfect and realistic step

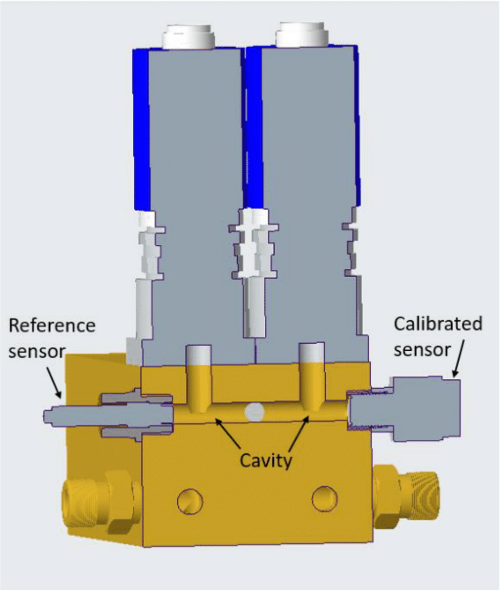


Figure 5 - Cavity and sensors

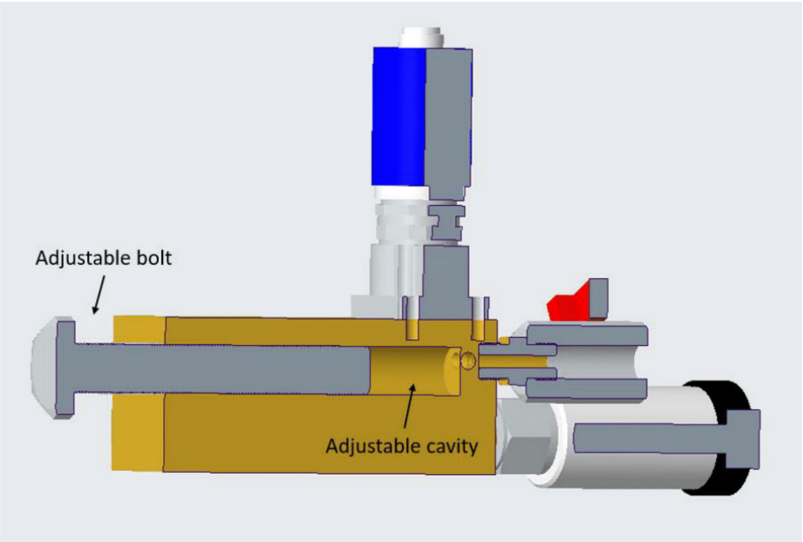


Figure 6 - Adjustable bolt and cavity

3.2. Setup in the Waterpower Laboratory

The plan is to use the existing high-pressure tank standing in the Waterpower Laboratory as a resource for the high-pressure side of the calibration box. The calibration box will then be mounted directly on the high-pressure tank. This is illustrated in Figure 7. The high-pressure tank can reach a pressure at 10 bar, which gives the opportunity to achieve all desired calibration pressure levels. The high-pressure tank holds a large volume, this means that it will not be influenced of water that is fed to the calibration box. This gives the ability to keep a constant intensity during the entire calibration process.

The low-pressure side will be connected to atmospheric pressure. The idea is to connect the box by a small pipe to a bucket containing water at atmospheric pressure. This is also illustrated in Figure 7.

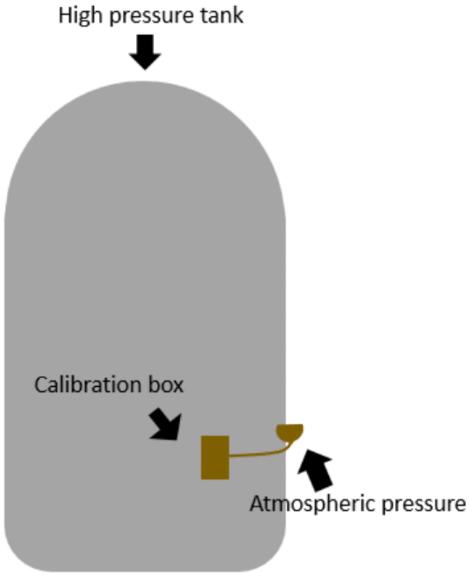


Figure 7 - Calibration box mounted to the high-pressure tank

3.3. Calibration program

A calibration program is going to be developed where both MatLab and LabVIEW will be adopted. LabVIEW will record the measurements from the four sensors in the calibration box. LabVIEW will also make sure that the valves open and close at the right time. When one valve is going from open to closed, the other valve need immediately to switch from close to open. The measurements are further processed in MatLab. The MatLab program will consist of build-in functions that will plot the Bode-diagram for the calibrated sensor. Bode-diagram is discussed in Subsection 4.2.

4. Theoretical background

In order to be able to create the calibration tool, theory regarding transfer function, bode diagram and Helmholtz response were used.

4.1. Transfer-function

Steady-state calibration characterize pressure sensors by its sensitivity. Characterizing a pressure sensor by its sensitivity is insufficient for dynamic calibration since the input varies with time [2]. Describing a pressure sensor using a differential equation gives a trivial solution. A better way to describe the calibrated sensor is with its transfer function. Transfer function completely quantifies and qualifies its dynamical behavior, considering gain and phase as functions of frequency [3].

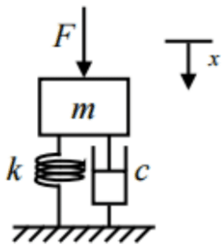


Figure 8 - Mass-damping system

The properties of a pressure sensor is assumed to be represented by a linear second order differential equation, with mass *m*, stiffness *k* and viscous damping factor *c* [3, 6], illustrated in Figure 8. Equation (1) describes the system

$$\frac{d^2x}{dt^2} + \frac{c}{m}\frac{dx}{dt} + \frac{kx}{m} = \frac{f(t)}{m} \tag{1}$$

With use of the Laplace Transform, the transfer function which describes the characteristic of a pressure sensor is given by Equation (2)

$$G(s) = \frac{OUT(s)}{IN(s)} = \frac{K\omega_o^2}{s^2 + 2\,\zeta\omega_o s + \omega_o^2} \tag{2}$$

where abbreviations, constants and variables are shown in the Table 1.

Table 1 - Abbreviations, constants and variables used in Equation (2)

Component	Description	Unit
OUT(s)	Laplace Transform of the output	-
IN(s)	Laplace Transform of the input	-
K	Gain	-
ω_o	Natural frequency of the system	*[rad/sec]*
s	Complex variable	-
ζ	Damping ratio	-

With use of the calibration box developed, an almost perfect pressure step can be created. The transfer function to the step is given in Equation (3), a first order transfer function with no time – delay [9]. When the calibration box is in operation, there is no need for implementing this function in the possessing data. This equation is just used for estimating the expected results from the pressure sensor calibration.

$$H(s) = \frac{K}{Ts + 1} \tag{3}$$

K is the gain and T is the time constant.

The calibrated sensor is recording its own characteristics, the frequency response to the calibration box and the pressure step generated. Likewise, the reference sensor is recording its own characteristics, the frequency response to the calibration box and the pressure step generated. By assuming the reference sensor used have high dynamic sensitivity, the characteristics of the calibrated sensor can be investigated by dividing the recorded transfer function of the calibrated sensor recorded on the transfer function of the recorded reference sensor. The process is illustrated in Figure 9.

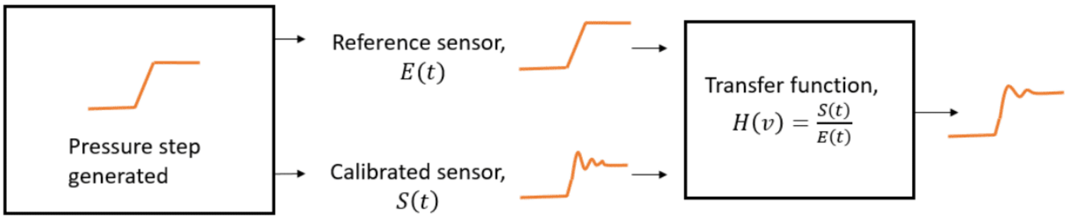


Figure 9 - Generate the transfer function

4.2. Bode diagram

The characteristics will be analyzed with use of a bode diagram. A bode diagram illustrates graphically the frequency response of a system. Bode diagrams normally illustrate the magnitude in decibels or the phase shift against the logarithm of frequency response [10].

4.3. Cavities and passage resonance

When building the calibration box, connecting lines and cavities cannot be avoided. These elements make frequencies in the calibration box, which sensors will detect. These frequencies need to be examined, so that the calibrated sensor do not end up getting responses in the same frequency range.

Theoretically, these frequencies can be determined using Helmholtz Resonance theory [11]. This theory defines the resonance frequency developed when a cavity is connected to a passage. The frequency can be expressed with Equation (4) [12]

$$f = \frac{c}{2\,\pi} \sqrt{\frac{S_{neck}}{V_0\, L'}} \tag{4}$$

where V_0 is the volume of the cavity, c is the speed of sound, S_{neck} is the cross section area of the passage and L' is the passage length.

4.4. Uncertainty analysis

Dynamic calibration gives lager uncertainties than with static calibration. Dynamic calibration is therefore not common to use for acceptance testing on static sensors [13]. Dynamic calibration makes it although possible to prove the natural frequency, f_n, of the calibrated sensor. The useful frequency range of the sensor can be found by knowing its natural frequency. As a guideline, frequencies measured should be less than $0.1 \cdot f_n$, if not correction for the natural frequency is done [14]. The uncertainty will decrease in the measurement by knowing the frequency response of the sensor.

5. Simulated results

Since the calibration box is not completely finished yet, tests have not been completed. In this chapter simulated results will be present.

5.1. Frequency response in the calibration box

Simulation in Ansys have been done for estimating the generated frequency response from the calibration box. Simulations with the bolt fully extended and completely inside have been done. This gives a good estimate of the lowest frequencies to be achieved with the calibration box. With the bolt fully extended a frequency response of 5000Hz was estimated, this is illustrated in Figure 10. Figure 11 shows the calibration box when the bolt is fully extended. When the bolt was completely inside, see Figure 13, the frequency response was measured to 15,500, as shown in Figure 12. This provides the ability to varying the frequency in the box with 10,000Hz.

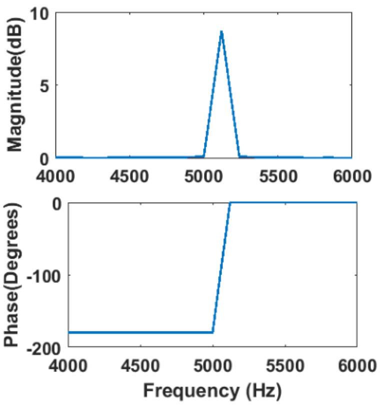


Figure 10 - Bolt fully extended

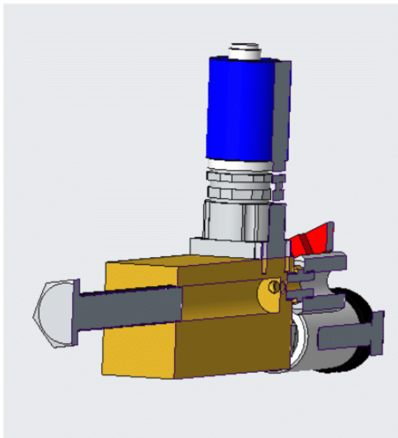


Figure 11 - Bolt fully extended

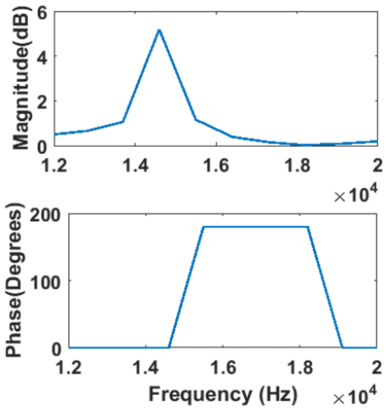


Figure 12 - Bolt completely inside

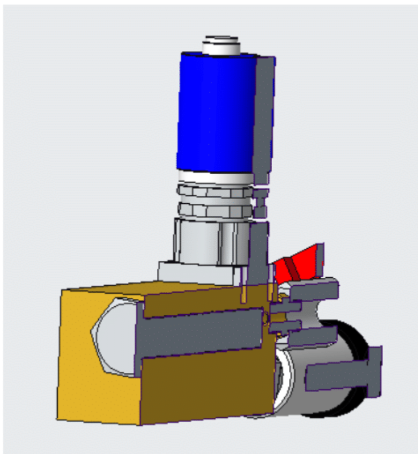


Figure 13 - Bolt completely inside

5.2. Theoretical analysis of calibration data

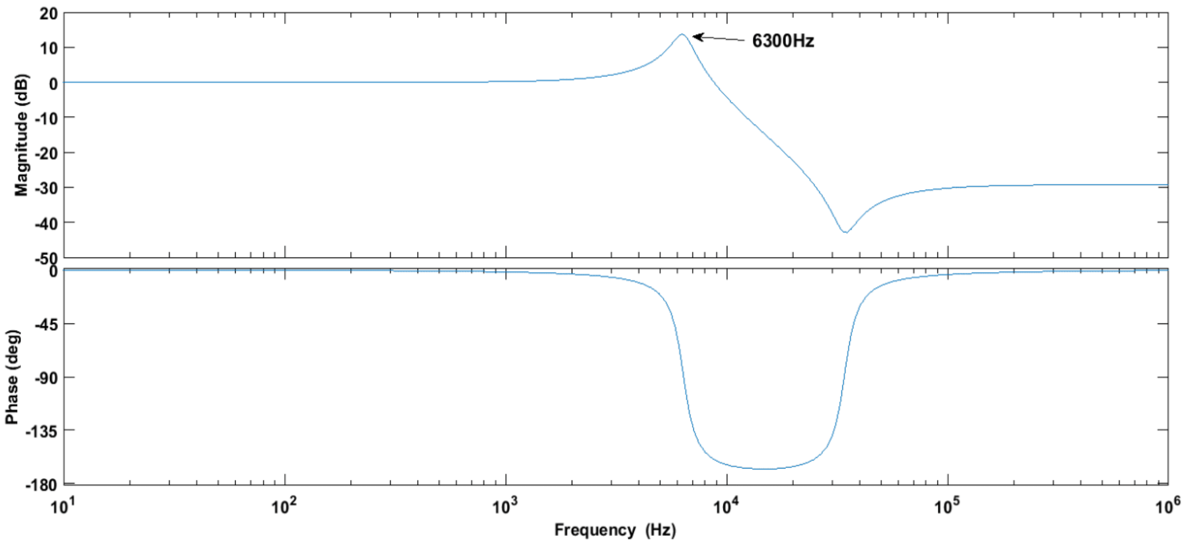


Figure 14 - Bode diagram

By assuming the calibration tool can develop a perfect pressure step, expected results of the calibrated sensor can be estimated. The reference sensor have high dynamic sensitivity with a natural frequency lager than 215kHz [15]. The calibrated sensor with a damping factor of 0.1 gives the bode diagram of the calibrated sensor, illustrated in Figure 14. It can be observed that the calibrated sensor will have a natural frequency of 6300Hz.

6. Conclusion

At this point, it is difficult to conclude how well the calibration system is going to work. Based on calculations and design of the calibration box, there are major reasons to be positive to the finished model.

7. References

[1] A. C. G. C. Diniz, A. B. S. Oliveira, J. N. S. Vianna, and F. J. R. Neves, "Dynamic calibration methods for pressure sensors and developmet of standard devices for dynamic pressure," 2006.

[2] J. P. Damion, "Means of Dynamic Calibration for Pressure Transducers."

[3] ISA-37.16.01, "A Guide for the Dynamic Calibration of Pressure Transducers," 2002.

[4] A. M. Hurst, T. R. Olsen, S. Goodman, J. V. Weert, and T. Shang, "An Experimental Frequency Response Characterization of MEMS Piezoresistive Pressure Transducers," 2014.

[5] N. d. M. Nascimento, A. B. d. S. Oliveira, and F. J. R. Neves, "Construction of a new fast - opening device for dynamic calibration of pressure transducers," 2007.

[6] M. Nilsson, "Dynamic Calibration of Pressure Sensors," 2016.

[7] A. M. Hurst, S. Carter, D. Firth, A. Szary, and J. V. Weert, "Real - Time, Advanced Electrical Filtering for Pressure Transducer Frequency Response Correction," 2015.

[8] Z. Wang, Q. Li, Z. Wang, and H. Yan, "Novel Method for Processing the Dynamic Calibration Signal of Pressure Sensor," 2015.

[9] H.-P. Halvorsen, "Reguleringsteknikk vha. MathScript," 2016.

[10] J. G. Balchen, T. Andresen, and B. A. Foss, "Reguleringsteknikk," 2004.

[11] L.-K. Xuan, Y. Liu, J.-F. Gong, P.-J. Ming, and Z.-Q. Ruan, "A time-domain finite volume method for the prediction of water muffer transmission loss considering elastic walls," 2017.

[12] A. Nishikawa and D. W. Slaton, "The Effect of A Helmholtz Resonator's Neck Geometry On The Aero-Acoustic Excitation of Resonance," 2009.

[13] Kulite, "Transducer handbook ".

[14] Omega, "DPX101 High-Frequency Pressure Sensor," 1993.

[15] Klister, pp. https://www.kistler.com/by/en/products/components/pressure-sensors/#piezoelectric__pressure__sensor__p_e_250_bar_3625_psi_601_c_a_a.

Appendix B – Sensors properties

B.1 – Steady-state calibrated sensors

GE
Measurement & Control

UNIK 5000

Pressure Sensing Platform

The new UNIK 5000 is a high performance configurable solution to pressure measurement. The use of micromachined silicon technology and analogue circuitry enables best in class performance for stability, low power and frequency response. The new platform enables you to easily build up your own sensor to match your own precise needs. This high performance, configurable solution to pressure measurement employs modular design and lean manufacturing techniques to offer:

High Quality

The combination of a high technology sensor, together with advanced signal conditioning and packaging techniques, provides an ideal long term solution for reliable, accurate and economical measurements

Bespoke as Standard

Custom-built from standard components, manufacturing sensors to your requirement is fast and simple; each UNIK 5000 is a "bespoke" pressure sensing solution, but with the short lead times and competitive pricing you would expect from standard products.

Expertise

We have the people and the knowledge to support your needs for accurate and reliable product performance; our team of experts can help you make the right sensor selection, guiding you and providing the help and tools you need. It is important to ensure that the sensor material and performance selected are suitable for your application.

GE imagination at work

Features

- Ranges from 70 mbar (1 psi) to 700 bar (10000 psi)
- Accuracy to ±0.04% Full Scale (FS) Best Straight Line (BSL)
- Stainless Steel construction
- Frequency response to 3.5 kHz
- High over pressure capability
- Hazardous Area certifications
- mV, mA, voltage and configurable voltage outputs
- Multiple electrical & pressure connector options
- Operating temperature ranges from –55 to 125°C (-67 to 257°F)

5000 Specifications

Measurement

Operating Pressure Ranges

Gauge ranges

Any zero based range 70 mbar to 70 bar
(1 to 1000 psi) (values in psi are approximate)

Sealed Gauge Ranges

Any zero based range 10 to 700 bar
(145 to 10000 psi)

Absolute Ranges

Any zero based range 100 mbar to 700 bar
(1.5 to 10000 psi)

Differential Ranges

Wet/Dry

Uni-directional or bi-directional 70 mbar to 35 bar
(1 to 500 psi)

Wet/Wet

Uni-directional or bi-directional 350 mbar to 35 bar
(5 to 500 psi)

Line pressure: 70 bar max (1000 psi)

Barometric Ranges

Barometric ranges are available with a minimum span of 350 mbar (5.1 psi)

Non Zero Based Ranges

Non zero based ranges are available. For non zero based gauge ranges, please contact GE Measurement & Control to discuss your requirements.

Over Pressure

- 10 × FS for ranges up to 150 mbar (2 psi)
- 6 × FS for ranges up to 700 mbar (10 psi)
- 2 × FS for barometric ranges
- 4 × FS for all other ranges (up to 200 bar for ranges ≤70 bar and up to 1200 bar for ranges >70 bar)

For differential versions the negative side must not exceed the positive side by more than:

- 6 × FS for ranges up to 150 mbar (2 psi)
- 4 × FS for ranges up to 700 mbar (10 psi)
- 2 × FS for all other ranges up to a maximum of 15 bar (200 psi)

Containment Pressure

Ranges up to 150 mbar (2 psi) gauge 10 × FS
Ranges up to 70 bar (1000 psi) gauge 6 × FS
(200 bar (2900 psi) max)
Ranges up to 70 bar (1000 psi) absolute
200 bar (2900 psi)
Ranges above 70 bar (1000 psi)
1200 bar (17400 psi)

Differential (-ve port) must not exceed positive port by more than 6 × FS (15 bar (200 psi) maximum)

Supply and Outputs

Electronics Option	Description	Supply voltage (V)	Output	Current Consumption (mA)
0	mV Passive	2.5 to 12	10 mV/V^	<2 at 10 V
1	mV Linearised	7 to 12	10 mV/V^	<3
2	mA	7 to 28**	4-20 mA	<30
3	0 to 5 V 4-wire	7 to 16**	0 to 5 V	<3
4	0 to 5 V 3-wire	7 to 16**	0 to 5 V*	<3
5	Basic Configurable (3-wire)	See below~	See below	<3
6	0 to 10 V 4-wire	12 to 16**	0 to 10 V	<3
7	0.5 V to 4.5 V Ratiometric	5.0 ± 0.5	0.5 to 4.5 V	<3
8	Configurable (4-wire)	7 to 36	See below	See below
9	Configurable (3-wire)	7 to 36	See below	See below

^ with a 10 V supply mV output sensors give 100 mV over the full scale pressure.
- *Output is ratiometric to the supply voltage*
- *Output reduces pro-rata for pressure ranges below 350 mbar (5 psi)*

**0 to 5 V 3-wire output is non true zero. At pressures below 1% of span the output will be fixed at approximately 50 mV*
***32 V in non-hazardous area operation*
~ Supply voltage is between [Maximum Output + 1 V] (7 V minimum) to 16 V (32 V in non-hazardous area operation)

Basic Configurable (Option 5), Configurable 4-Wire (Option 8), Configurable 3-Wire (Option 9)

Any pressure signal output configurations will be available, subject to the following limitations:

Output specification	Basic Configurable (Option 5)	Configurable (Options 8, 9)
Minimum span:	4 V	2 V
Maximum span:	10 V	20 V
Maximum output limit:	11 V	±10 V
Maximum zero offset:	Span / 2	±Span
Current consumption:	< 3 mA	< 20 mA @ 7 Vdc decreasing to < 5 mA @ 32 Vdc
Reverse output response:	No	Yes
Maximum operating temperature:	+125˚C	+80˚C

Output voltage range can be specified to a resolution of 0.1 V.
The output will continue to respond to 110% FS. i.e. if a 0 to 10 V output is specified, the output will continue to increase proportionally to applied pressure until at least 11 V.
Option 5: Not true zero, the output will saturate at < 50 mV.
Options 8, 9: On startup <100 mA drawn for 10 ms typically.
Options 8, 9: Shunt calibration: not available with reverse output.

Examples

Configuration	Allowed	Not Allowed
Basic Configurable (Option 5)	0 to 5 V	1 to 4 V (span too small)
	0.5 to 4.5 V	4 to 11 V (offset too big)
	1 to 6 V	
	1 to 11 V	
Configurable (Options 8, 9)	-10 to 0 V	0 to 12 V (outside ±10 V limits)
	0 to 5 V	6 to 10 V (offset too big)
	-5 to 5 V	0 to 0.5 V (span too small)
	-2 to 10 V	
	1 to 6 V	
	10 to 0 V	

Power-Up Time

- mV, Voltage and current versions: 10 ms
- Configurable 3-wire and 4-wire versions: 500 ms

Insulation

- 500 Vdc: 100 MΩ
- 500 Vac: ≤ 5 mA leakage current (mV and mA versions only).

Shunt Calibration

Shunt Calibration provides a customer accessible connection which, when applied, causes a shift in output of 80% FS in order to simulate applied pressure.
It is fitted to the mV, Configurable 4-wire and Configurable 3-wire versions as standard. It is not available with DIN, M12 x 1 or M20 x 1.5 electrical connectors (options 7, D, G and R)

Shunt calibration is activated in different ways depending on the electrical connector and version:

- mV versions: connect Shunt Cal to -ve Supply or, where available, connect both Shunt Cal connections together.
- Configurable 4-wire and Configurable 3-wire versions: connect Shunt Cal to -ve Output or, where available, connect both Shunt Cal connections together.

Note: Not available with reverse output.

Performance Specifications

There are three grades of performance specification: Industrial, Improved and Premium.

Accuracy

Voltage, Current and mV Linearised

Combined effects of non-linearity, hysteresis and repeatability:

Industrial: ±0.2% FS BSL
Improved: ±0.1% FS BSL
Premium: ±0.04% FS BSL

mV Passive

≤ 70 bar
Industrial/Improved: ±0.25% FS BSL
Premium not available
> 70 bar
Industrial/Improved: ±0.5% FS BSL
Premium not available

Note: For the barometric pressure range, accuracy is of span, not full scale.

Zero Offset and Span Setting

Demountable electrical connector options allow access to potentiometers that give at least ±5% FS adjustment (see Electrical Connector section)

Factory set to:

Product Description	Industrial	Improved and Premium
Current and Voltage Versions (Demountable Electrical Connections and Cable Gland)	±0.5% FS	±0.2% FS
Current and Voltage Versions (All Other Electrical Connections)	±1.0% FS	±1.0% FS
mV Versions	±3.0 mV	±3.0 mV

Long Term Stability

±0.05% FS typical (±0.1% FS maximum) per year increasing pro-rata for pressure ranges below 350 mbar

Temperature Effects

Four compensated temperature ranges can be chosen.
Industrial Accuracy performance:
-10 to +50°C (14 to +122°F): ±0.75% FS Temperature error band (TEB)
-20 to +80°C (-4 to +176°F): ±1.5% FS TEB
-40 to +80 °C (-40 to +176°F): ±2.25% FS TEB
-40 to +125°C (-40 to +257°F): ±2.25% FS TEB
Improved and Premium Accuracy performance:
-10 to +50°C (14 to +122°F): ±0.5% FS TEB
-20 to +80°C (-4 to +176°F): ±1.0% FS TEB
-40 to +80°C (-40 to +176°F): ±1.5% FS TEB
-40 to +125°C (-40 to +257°F): ±1.5% FS TEB

Temperature effects increase pro-rata for pressure ranges below 350 mbar (5 psi) and are doubled for barometric ranges.

Line Pressure Effects (Differential Version Only)

Zero shift: <±0.03% span/bar of line pressure
Span shift: <±0.03% span/bar of line pressure
Effects increase pro-rata for differential pressure ranges below 700 mbar (10 psi).

Physical Specifications

Environmental Protection

- See Electrical Connector section
- Hyperbaric Pressure: 20 bar (300 psi) maximum

Operating Temperature Range

See Electrical Connector section

Pressure Media

Fluids compatible with stainless steel 316L and Hastelloy C276.
For the wet/dry differential version, negative pressure port: fluids compatible with stainless steel 316L, stainless steel 304, Pyrex, silicon and structural adhesive.

Enclosure Materials

Stainless steel (body), nitrile- or silicone-rubber (o-rings, gaskets), EPDM (gaskets), PVDF (depth cone), PTFE (vent filter), Nickel plated brass (lock rings), glass filled nylon (electrical connector assemblies), delrin (depth cone). Cable sheaths as specified (see Electrical Connector).

Pressure Connector

Available options are

- G1/4 Female*
- G1/4 Male Flat
- G1/4 Male 60° Internal Cone
- G1/4 Male Flat Long
- G1/4 Male Flat with Snubber
- G1/4 Male Flat with Cross Bore Protection
- G1/4 Male with Nipple
- G1/4 Quick Connect
- G1/8 Male 60° Internal Cone
- G1/2 Male via Adaptor*
- 1/4 NPT Female*
- 1/4 NPT Male
- 1/8 NPT Male
- 1/2 NPT Male via Adaptor
- 7/16-20 UNF Female
- 7/16-20 UNF Male Short Flat
- 7/16 UNF Long 37° Flare Tip
- 7/16-20 UNJF Male 74° External Cone
- 3/8-24 UNJF
- 1/4 Swagelok Bulkhead
- M10 X 1 80° Internal Cone
- M12 X 1 60° Internal Cone
- M14 X 1.5 60° Internal Cone
- M20 X 1.5 Male
- Depth Cone (G1/4 Female Open Face)
- M12 x 1.0 74° External Cone
- Quick Release Male
- VCR Female*
- VCR Male*
- NW16 Flange
- R3/8 Male
- R1/4 Male

Choose connectors marked * for pressure ranges over 70 bar. Other pressure connectors may be available, contact GE to discuss your requirement.

General Certifications

RoHS 2002/95/EC
CRN Certified 0F13650.517890YTN ADD1/REV1, 0F13828.2 (sensor types K and O) and CSA 0F13650.56 ADD1 for pressure ranges up to and including 350 bar (5000 psi)

Electrical Connector

Various electrical connector options are available offering different features:

Code Number	Description	Max Operating temp range °C	°F	IP rating	Zero span Adjust
0	No Connector	-55 to +125	-67 to +257	-	Y
1	Cable Gland	-40 to +80	-40 to +176	65	N
2	Raychem Cable	-55 to +125	-67 to +257	65	N
3	Polyurethane Depth	-40 to +80	-40 to +176	68	N
4	Hytrel Depth	-40 to +80	-40 to +176	68	N
6/E	Bayonet MIL-C-26482	-55 to +125	-67 to +257	67	N
7	DIN 43650 Form A Demountable	-40 to +80	-40 to +176	65	Y
A/F	Bayonet MIL-C-26482 Demountable	-55 to +125	-67 to +257	65	Y
C	1/2 NPT Conduit	-40 to +80	-40 to +176	65	N
D	Micro DIN (9.4 mm pitch)	-40 to +80	-40 to +176	65	N
G	M12x1 4pin	-55 to +125	-67 to +257	67	N
K	Zero Halogen Cable Demountable	-40 to +80	-40 to +176	65	Y
M	Tajimi R03-R6F	-25 to +85	-13 to +185	65	N
R	M20 x 1.5 Inline	-40 to +80	-40 to +176	65	Y

Note: Electronics output options 8 and 9 are restricted to a maximum operating temperature of 80°C (176°F).
Note: Hazardous area approved versions are restricted to a maximum operating temperature range of -40°C to 80°C (-40°F to 176°F).
Note: Electrical connector option R IP65 rating only with suitable conduit/cable fitting.

CE Conformity

Pressure Equipment Directive 97/23/EC: Sound Engineering Practice
ATEX 94/9/EC (Optional)
EMC Directive 2004/108/EC

BS EN 61000-6-1: 2007	Susceptibility - Light Industrial
BS EN 61000-6-2: 2005	Susceptibility - Heavy Industrial (except mV versions)
BS EN 61000-6-3: 2007	Emissions - Light Industrial
BS EN 61000-6-4: 2007	Emissions - Heavy Industrial
BS EN 61326-1: 2006	Electrical Equipment for Measurement, Control and Laboratory Use
BS EN 61326-2-3: 2006	Particular Requirements for Pressure Transducers

Hazardous Area Approvals (optional)

General applications
- IECEx/ATEX Intrinsically Safe 'ia' Group IIC
- INMETRO Intrinsically Safe 'ia' Group IIC
- NEPSI Intrinsically Safe 'ia' Group IIC
- FM Approved (Canada & US) Intrinsically Safe Exia Class I, Division 1, Groups A, B, C & D and Class I, Zone 0 AEx/Ex ia Group IIC; Single Seal

Mining applications
- IECEx/ATEX Intrinsically Safe 'ia' Group I
- INMETRO Intrinsically Safe 'ia' Group I

For full certification details, refer to the type-examination certificates (or approval listings) and supplied hazardous area installation instructions.

Electrical Connector

Connector Type	Option code		Electronics Option					
			4 to 20 mA	Voltage (3-wire) and Basic Configurable	Voltage (4-wire)	Configurable Voltage (4-Wire)	Configurable Voltage (3-Wire)	mV
Molex	0	1 Red	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply
		2 Yellow	-	+ve Output	+ve Output	+ve Output	+ve Output	+ve Output
		3 Green	-	-	-ve Output	-ve Output	0V Common	-ve Output
		4 Blue	-ve Supply	0V Common	-ve Supply	-ve Supply	0V Common	-ve Supply
		5 Orange	-	-	-	Shunt Cal	Shunt Cal	Shunt Cal
		6 Black	Case	Case	Case	Case	Case	-
Cable (Not Raychem)	1, 3, 4, C	Red	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply
		Yellow	-	+ve Output	+ve Output	+ve Output	+ve Output	+ve Output
		Blue	-	-	-ve Output	-ve Output	0V Common	-ve Output
		White	-ve Supply	0V Common	-ve Supply	-ve Supply	0V Common	-ve Supply
		Orange	-	-	-	Shunt Cal	Shunt Cal	Shunt Cal
		Black	-	-	-	-	-	-
		Screen	-	-	-	-	-	-
Raychem Cable	2	Red	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply
		White	-	+ve Output	+ve Output	+ve Output	+ve Output	+ve Output
		Green	-	-	-ve Output	-ve Output	0V Common	-ve Output
		Blue	-ve Supply	0V Common	-ve Supply	-ve Supply	0V Common	-ve Supply
		Black	-	-	-	Shunt Cal	Shunt Cal	Shunt Cal
		Screen	-	-	-	-	-	-
Bayonet	6, A	A	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply
		B	-ve Supply	+ve Output	+ve Output	+ve Output	+ve Output	+ve Output
		C	-	-	-ve Output	-ve Output	0V Common	-ve Output
		D	-	0V Common	-ve Supply	-ve Supply	0V Common	-ve Supply
		E	-	-	-	Shunt Cal	Shunt Cal	Shunt Cal
		F	-	-	-	-	-	Shunt Cal
DIN A Micro DIN	7 D	1	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply
		2	-ve Supply	0V Common	-ve Supply	-ve Supply	0V Common	-ve Supply
		3	-	+ve Output	+ve Output	+ve Output	+ve Output	+ve Output
		E	Case	Case	-ve Output	-ve Output	0V Common	-ve Output
Bayonet Alternative Wiring Options	E, F	A	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply
		B	-	0V Common	-ve Supply	-ve Supply	0V Common	-ve Supply
		C	-	+ve Output	+ve Output	+ve Output	+ve Output	+ve Output
		D	-ve Supply	-	-ve Output	-ve Output	0V Common	-ve Output
		E	-	-	-	Shunt Cal	Shunt Cal	Shunt Cal
		F	-	-	-	Shunt Cal	Shunt Cal	-
M12 X 1 4-Pin	G	1	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply
		2		+ve Output	+ve Output	+ve Output	+ve Output	+ve Output
		3	-ve Supply	0V Common	-ve Supply	-ve Supply	0V Common	-ve Supply
		4	Case	Case	-ve Output	-ve Output	0V Common	-ve Output
Zero Halogen Cable (Demountable)	K	Pink	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply
		White	-	+ve Output	+ve Output	+ve Output	+ve Output	+ve Output
		Green	-	-	-ve Output	-ve Output	0V Common	-ve Output
		Blue	-ve Supply	0V Common	-ve Supply	-ve Supply	0V Common	-ve Supply
		Grey	-	-	-	Shunt Cal	Shunt Cal	Shunt Cal
		Brown	-	-	-	-	-	-
		Yellow	-	-	-	-	-	-
		Screen	-	-	-	-	-	-
Tajimi R03-R6F	M	A	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply	+ve Supply
		B	-	0V Common	-ve Supply	-ve Supply	0V Common	-ve Supply
		C	-ve Supply	Case	Case	Case	Case	-
		D	-	-	-ve Output	-ve Output	0V Common	-ve Output
		E	Case	+ve Output	+ve Output	+ve Output	+ve Output	+ve Output
		F	-	-	Shunt cal	Shunt cal	Shunt Cal	Shunt cal
M20 x 1.5 Female Demountable	R	+ve	+ve Supply	-	-	-	-	-
		-ve	-ve Supply	-	-	-	-	-

Ordering Information

See the online configuration tool at www.unik5000.com

(1) Select model number

Main Product Variant
PMP Amplified Pressure Transducer
PDCR mV Pressure Transducer
PTX 4-20 mA Pressure Transmitter

Product Series
5 UNIK 5000

Diameter and Material
0 25mm Stainless Steel

Electrical Connector Note 6
0 No Electrical Connector **Note 7**
1 Cable Gland (Polyurethane Cable)
2 Raychem Cable
3 Polyurethane Cable (Depth)
4 Hytrel Cable (Depth)
6 MIL-C-26482 (6-pin Shell Size 10) (Mating connector not supplied)
7 DIN 43650 Form A Demountable (Mating connector supplied)
A Demountable MIL-C-26482 (6-pin Shell Size 10) (Mating connector not supplied)
C 1/2" NPT Conduit (Polyurethane cable)
D Micro DIN (9.4 mm Pitch) (Mating connector supplied)
E MIL-C-26482 (6 pin Shell Size 10) Alternative Wiring (Mating connector not supplied)
F Demountable MIL-C-26482 (6 pin Shell Size 10) Alternative Wiring (Mating connector not supplied)
G M12 x 1 4-pin male (Mating connector not supplied)
K Zero Halogen Cable Demountable
M Tajimi R03-R6F
R M20 x 1.5 Inline Female Conduit Demountable **Note 8**

Electronics Option
0 mV Passive 4-wire (PDCR) **Note 1**
1 mV Linearised 4-wire (PDCR)
2 4 to 20 mA 2-wire (PTX)
3 0 to 5 V 4-wire (PMP)
4 0 to 5 V 3-wire (PMP)
5 Basic Configurable 3-wire (PMP)
6 0 to 10 V 4-wire (PMP)
7 0.5 to 4.5 V Ratiometric 3-wire (PMP) **Note 5**
8 Configurable 4-wire (PMP) **Note 4, 5**
9 Configurable 3-wire (PMP) **Note 4, 5**

Compensated Temperature Range
TA -10 to +50 °C (14 to +122 °F)
TB -20 to +80 °C (-4 to +176 °F)
TC -40 to +80 °C (-40 to +176 °F)
TD -40 to +125 °C (-40 to +257 °F) **Note 2, 5**

Accuracy
A1 Industrial
A2 Improved
A3 Premium

Calibration
CA Zero/Span Data
CB Room Temperature
CC Full Thermal

Hazardous Area Approval Note 6
H0 None
H1 IECEx/ATEX Intrinsically Safe 'ia' Group IIC
H2 IECEx/ATEX Intrinsically Safe 'ia' Group I
H6 FM (C & US) Intrinsically Safe 'ia' Group IIC/ABCD
HA IECEx/ATEX Intrinsically Safe 'ia' Groups I/IIC [H1 + H2]
HS IECEx/ATEX/FM (C & US) Intrinsically Safe 'ia' Groups IIC/ABCD [H1 + H6]
J1 IECEx/ATEX/NEPSI Intrinsically Safe 'ia' Group IIC
JA INMETRO Intrinsically Safe 'ia' Group IIC
JB INMETRO Intrinsically Safe 'ia' Group I
JF INMETRO Intrinsically Safe 'ia' Group I/IIC [JA + JB]

Pressure Connector

PA	G1/4 Female **Note 3**	**PV**	7/16-20 UNF Female
PB	G1/4 Male Flat	**PW**	Depth Cone (G1/4 Female Open Face)
PC	G1/4 Male 60° Internal Cone	**PX**	7/16-20 UNF Male Short Flat
PD	G1/8 Male 60° Internal Cone	**PY**	3/8-24 UNJF
PE	1/4 NPT Female **Note 3**	**PZ**	M10 x 1 80° Internal Cone
PF	1/4 NPT Male	**RA**	VCR Female **Note 3, 9**
PG	1/8 NPT Male	**RB**	G1/4 Male Flat with Snubber
PH	M20x1.5	**RC**	G1/4 Male Flat with Cross Bore Protection
PJ	M14x1.5 60° Internal Cone	**RD**	M12 x 1.0 74° External Cone
PK	M12x1 Internal Cone	**RE**	Quick Release Mount
PL	7/16-20 UNJF Male 74° External Cone	**RF**	VCR Male **Note 3, 9**
PN	G1/2 Male via Adaptor **Note 3**	**RQ**	NW16 Flange
PQ	G1/4 Quick Connect	**RU**	R3/8 Male
PR	1/2 NPT Male via Adaptor **Note 3**	**RV**	R1/4 Male
PS	1/4 Swagelok Bulkhead	**RW**	G1/4 Male with Nipple
PT	G1/4 Male Flat Long		
PU	7/16-20 UNF Long 37° Flare Tip		

PTX 5 0 7 2 - TA - A2 - CB - H0 - PA **Typical Model Number**

Ordering Notes

Note 1 Premium Accuracy is not available on this version
Note 2 Please ensure that the electrical connector selected is option 0, 2, 6, A, E, F or G.
Note 3 Select one of these pressure connectors for pressure ranges over 70 bar
Note 4 Max operating temperature is 80°C (176°F)
Note 5 Hazardous area certifications not available
Note 6 Hazardous area certifications are restricted by electrical connector options in line with the following table:

	Connector													
Approval	0	1	2	3	4	6/E	7	A/F	C	D	G	K	M	R
H0	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
H1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	-	-	Y
H2	Y	-	Y	Y	Y	Y	-	-	Y	-	Y	-	-	-
H6	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	-	-	-
HA	Y	-	Y	Y	Y	Y	-	-	Y	-	Y	-	-	-
HS	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	-	-	-
J1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	-	-	Y
JA	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	-	-	Y
JB	Y	-	Y	Y	Y	Y	-	-	Y	-	Y	-	-	-
JF	Y	-	Y	Y	Y	Y	-	-	Y	-	Y	-	-	-

Note 7 Available with component certification, use of which requires incorporation into certified apparatus with an IP rated enclosure appropriate to the certification type supplied.
Note 8 Electronics option 2 only.
Note 9 Pressure ranges less than 500 bar.

2) State pressure range and units: e.g. 0 to 10 bar, -5 to + 5 psi

Unit options are:

Symbol	Description
bar	bar
mbar	millibar
psi	pounds/sq. inch
Pa	Pascal
hPa	hectoPascal
kPa	kiloPascal
MPa	MegaPascal
mmH_2O	mm water
cmH_2O	cm water
mH_2O	metres water
inH_2O	inches water
ftH_2O	feet water
mmHg	mm mercury
inHg	inches mercury
kgf/cm^2	kg force/sq. cm
atm	atmosphere
Torr	torr

3) State Pressure reference: e.g. gauge

Reference options are:

gauge
absolute
barometric
sealed gauge
wet/dry differential
wet/wet differential

4) State cable lengths and units: Integer values only, e.g. 1m cable, 8 ft. Minimum length 1 m (3 ft) cable (only required on certain electrical connectors). Maximum cable length 100 m (300 ft) for approval options not H0; 200 m (600 ft) for approval option H0.

5) Output options 5, 8 and 9: State voltage output at minimum and maximum pressure: e.g. output –1 to 9 V

Typical order examples:

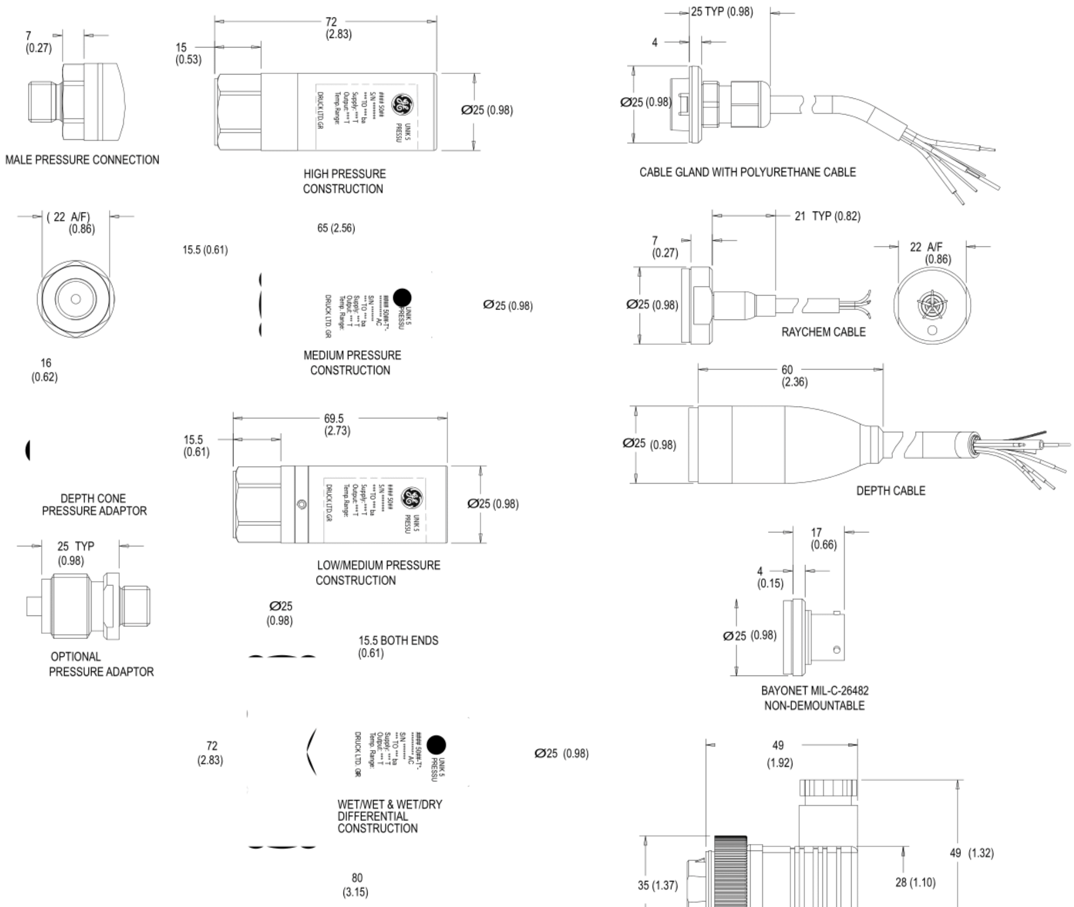
PTX5012-TB-A2-CA-H0-PA, 0 to 10 bar, gauge, 3 m cable
PMP5028-TD-A3-CC-H0-PE, -15 to 75 psi, gauge, 15ft cable, output voltage -1 to 5 volts
PDCR5071-TB-A1-CB-H0-PB, 0 to 100 bar, sealed gauge

Accessories

Mating connector for MIL-C-26482 (Electrical connector options 6, A, E and F) under part number S_163-009,

Note: Not considered suitable for use in hazardous areas due to light metals content and low ingress protection (IP) rating.

Mechanical Drawings



NOTES:

[1] DIMENSIONS SHOWN ARE FOR STANDARD LENGTH PRODUCTS WITH THE FOLLOWING ELECTRICAL OUTPUT OPTIONS:

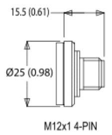
mV LINEARISED (PDCR)
4 TO 20 mA (PTX)
STANDARD VOLTAGE OPTIONS (PMP)
BASIC CONFIGURABLE (PMP)

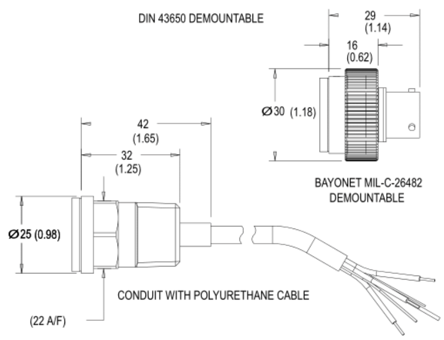
FOR mV PASSIVE (PDCR) - SUBTRACT 10 mm (0.39 in)
FOR CONFIGURABLE 4-WIRE AND CONFIGURABLE 3-WIRE (PMP) - ADD 15 mm (0.59 in)

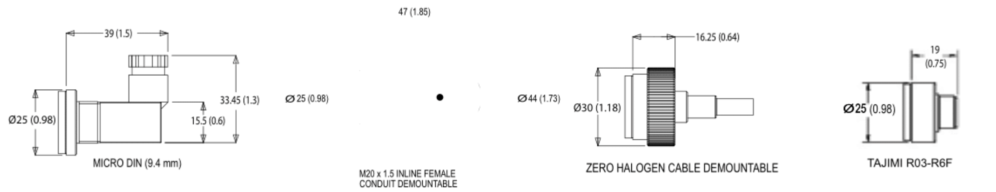
[2] REFER TO PAGE 4 FOR LIST OF PRESSURE CONNECTION OPTIONS (ORIENTATION NOT CRITICAL)

[3] ALL DIMENSIONS ARE IN MILLIMETRES (INCHES IN PARENTHESES)

[4] **HIGH PRESSURE IS >70 BAR**
MEDIUM PRESSURE
INDUSTRIAL ACCURACY >1 BAR TO ≤ 50 BAR
LOW/MEDIUM PRESSURE
INDUSTRIAL ACCURACY ≤ 1 BAR, ≥ 50 BAR TO ≤ 70 BAR
IMPROVED/PREMIUM ACCURACY ≤ 70 BAR







www.ge-mcs.com

920-483J

B.2 – Calibrated sensor

kulite®

MINIATURE HIGH PRESSURE PRESSURE TRANSDUCER

HKM-375 (M) CO SERIES

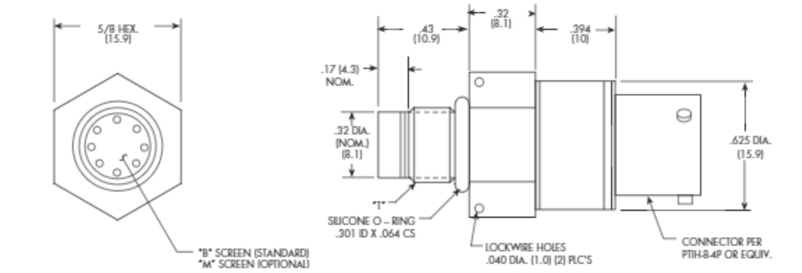
- Excellent Stability
- All Welded Construction
- Silicon on Silicon Integrated Sensor **VIS**®
- Robust Construction
- High Natural Frequencies
- 3/8-24 UNJF or M10 X 1 Thread
- Intrinsically Safe Applications Available (i.e. IS-HKM-375)

The HKM-375 is a miniature threaded pressure transducer. The hexagonal head and o-ring seal make it easy to mount and simple to apply.

The HKM-375 utilizes a flush metal diaphragm as a force collector. A solid state piezoresistive sensing element is located immediately behind this metal diaphragm which is protected by a metal screen. Force transfer is accomplished via non-compressible silicone oil. This sensing sub assembly is welded to a stainless steel body.

This advanced construction results in a highly stable, reliable and rugged instrument with all the advantages of significant miniaturization, excellent repeatability, low power consumption, etc. The miniaturization process also yields a marked increase in the natural frequencies of the transducers, making them suitable for use even in shock pressure measurements.

Kulite recommends the KSC-2 signal conditioner to maximize the measurement capability of the HKM-375 transducer.



PIN	DESIGNATION
A	+ INPUT
B	- INPUT
C	+ OUTPUT
D	- OUTPUT

P/N	"T"
375	3/8-24 UNJF-3A
375M	M 10 x 1

INPUT	Pressure Range	17 250	35 500	70 1000	170 2500	350 5000	700 10000	1400 BAR 20000 PSI
	Operational Mode	Absolute, Sealed Gage						
	Over Pressure	2 Times Rated Pressure to 1000 PSI (70 BAR) 1.5 Times Rated Pressure Above 1000 PSI to a Max. of 30000 PSI (2100 BAR)						
	Burst Pressure	3 Times Rated Pressure to a Max. of 35000 PSI (2400 BAR)						
	Pressure Media	Any Liquid or Gas Compatible With 15-5 PH or 316 Stainlesss Steel (All Media May Not Be Suitable With O-Ring Supplied)						
	Rated Electrical Excitation	10 VDC/AC						
	Maximum Electrical Excitation	12 VDC/AC						
	Input Impedance	1000 Ohms (Min.)						
OUTPUT	Output Impedance	1000 Ohms (Nom.)						
	Full Scale Output (FSO)	100mV (Nom.)						
	Residual Unbalance	± 5 mV (Typ.)						
	Combined Non-Linearity, Hysteresis and Repeatability	± 0.1% FSO BFSL (Typ.), ± 0.5% FSO (Max.)						
	Resolution	Infinitesimal						
	Natural Frequency of Sensor Without Screen (KHz) (Typ.)	Greater Than 400 KHz						
	Acceleration Sensitivity % FS/g Perpendicular	2.2×10^{-4}	1.1×10^{-4}	6.2×10^{-5}	2.6×10^{-5}	1.5×10^{-5}	1.3×10^{-5}	8.0×10^{-6}
	Insulation Resistance	100 Megohm Min. @ 50 VDC						
ENVIRONMENTAL	Operating Temperature Range	-65°F to +250°F (-55°C to +120°C)						
	Compensated Temperature Range	+80°F to +180°F (+25°C to +80°C) Any 100°F Range Within The Operating Range on Request						
	Thermal Zero Shift	± 1% FS/100° F (Typ.)						
	Thermal Sensitivity Shift	± 1% /100° F (Typ.)						
	Linear Vibration	10-2,000 Hz Sine, 100g. (Max.)						
	Humidity	100% Relative Humidity						
	Mechanical Shock	20g half Sine Wave 11 msec. Duration						
PHYSICAL	Electrical Connection	PTIH-8-4P Connector or Equivalent						
	Weight	17 Grams (Max.)						
	Pressure Sensing Principle	Fully Active Four Arm Wheatstone Bridge Dielectrically Isolated Silicon on Silicon						
	Mounting Torque	80 Inch-Pounds (Max.) 9 Nm						

Note: Custom pressure ranges, accuracies and mechanical configurations available. Dimensions are in inches. Dimensions in parenthesis are in millimeters. All dimensions nominal. (C) Continuous development and refinement of our products may result in specification changes without notice. *Kulite miniature pressure transducers are intended for use in test and research and development programs and are not necessarily designed to be used in production applications. For products designed to be used in production programs, please consult the factory.*

KULITE SEMICONDUCTOR PRODUCTS, INC. • One Willow Tree Road • Leonia, New Jersey 07605 • Tel: 201 461-0900 • Fax: 201 461-0990 • http://www.kulite.com

B.3 – Reference sensor

Pressure

KISTLER
measure. analyze. innovate.

Piezoelectric Pressure Sensor

Type 601C...

For Test & Measurement Applications

The miniature pressure sensors of the 601C series are, due to their high sensitivity, suited for a variety of applications where very small pressure pulsations need to be measured. In addition, the optimized diaphragm ensures accurate dynamic pressure measurements, even when the diaphragm is simultaneously exposed to a high temperature transient.

- Pressure range up to 250 bar (3626 psi)
- High sensitivity
- Membrane optimized for thermal transients
- Small sensor size
- Short rise time & high natural frequency
- Extremely wide operating temperature range
- Charge (PE) or Voltage (IEPE) output

Description

Due to their high natural frequencies, piezoelectric pressure sensors can be used for a variety of applications where dynamic pressures need to be measured. Another unique characteristic of piezoelectric pressure sensors is their ability to measure small pressure fluctuations that are superimposed on top of high static pressures with exceptional resolution. By contrast, piezoresistive pressure sensors are the right choice when measuring static pressure curves.

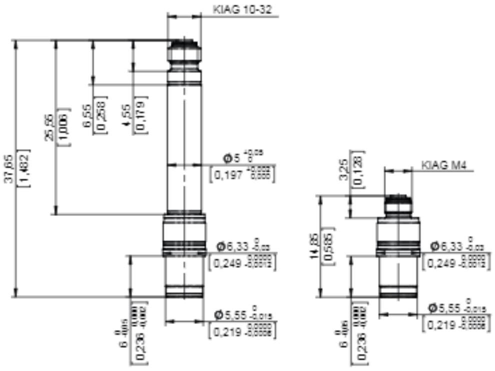
At the core of the all-welded, hermetically sealed 601C series there is a high performance PiezoStar® crystal grown by Kistler. This PiezoStar crystal gives the sensor a far higher sensitivity than an equivalently sized pressure sensor based on synthetic Quartz, which results in a lower noise level and so enables lower pressure to be measured more accurately.

The pressure to be measured acts on the sensor's diaphragm and compresses the PiezoStar crystal. The compressed crystal produces a charge which is proportional to the pressure. Finally the charge signal needs to be converted, by a charge amplifier, into a voltage which can then be read.

Two variants of the sensor are available, charge output (PE) and voltage output (IEPE resp. Piezotron®). The instruction manual gives an overview on the characteristics of both variants, an indication of which type of application they are best suited to and the full measuring chain.

Typical Applications

- Pressure pulsations on pumps, compressors, etc.
- Dynamic measurements with high transient temperatures as Ex-Proof, pyrotechnical devices, closed vessel testing, energetic material testing, etc.



Technical Data – PE Sensors [1]

Type 601CA...

Output signal		pC	Charge (PE)
Pressure range		bar	0 ... 250
		psi	0 ... 3626
Calibrated partial range		%	2, 20, 100
Overload		bar	300
		psi	4350
Sensitivity (typ.)		pC/bar	–37.0
		pC/psi	–2.5
Linearity	typ.	%FSO	≤0.1
	max.	%FSO	≤0.5
Operating temperature range		°C	–196 ... 350
		°F	–321 ... 662
Rise time (10 ... 90 %)		µs	<1.4
Natural frequency [2]		kHz	>215
Temp. coefficient of sensitivity			
25 ... 100 °C / 77 ... 212 °F		%	≈+0.7
25 ... 350 °C / 77 ... 662 °F		%	≈+4.4
25 ... –196 °C / 77 ... –321 °F		%	≈–7.7
Acceleration sensitivity (axial)		bar/g	≤0.0020
		psi/g	≤0.0290
Acceleration sensitivity (radial)		bar/g	≤0.0001
		psi/g	≤0.0015
Insulation resistance		Ω	$\geq 10^{13}$
Weight	Type 601CAA / 601CAB	grams	4.5 / 1.9
Sensor material housing & diaphragm			17-4 S.S.

[1] Indications are valid for 23 °C / 73 °F (if not specified otherwise)
[2] Calculated from rise time

601C_003-199e-10.15

KISTLER
measure. analyze. innovate.

Technical Data – IEPE Sensors [1]

Type 601CBA...		00250.0	00070.0	00035.0	00014.0	00007.0	00003.5	00001.5
Output signal	V	Voltage (IEPE)						
Pressure range	bar	0 ... 250	0 ... 70	0 ... 35	0 ... 14	0 ... 7	0 ... 3.5	0 ... 1.5
	psi	0 ... 3626	0 ... 1000	0 ... 500	0 ... 200	0 ... 100	0 ... 50	0 ... 22
Maximum dymamic pressure step	bar	±250	±243	±117	±47.6	±24.1	±12.4	±5.2
(without damage)	psi	±3626	±3524	±1697	±690	±350	±180	±75
Maximum pressure	bar	250						
(static + dynamic)	psi	3626						
Sensitivity (typ.)	mV/bar	20	71	143	357	714	1429	3333
	mV/psi	1.4	4.9	9.9	25	49	99	230
Linearity typ.	%FSO	≤0.2						
max.	%FSO	≤1.0						
Operating temperature range	°C	–55 ... 120						
	°F	–67 ... 248						
Rise time (10 ... 90 %)	µs	<1.4						
Natural frequency [2]	kHz	>215						
Time constant	s	3						2
Low frequency response –3dB	Hz	0.050						
–5 %	Hz	0.152						
Temp. coefficient of sensitivity 25 ... 120 °C / 77 ... 212 °F	%	≈+0.8						
Acceleration sensitivity (axial)	bar/g	≤0.0020						
	psi/g	≤0.0290						
Acceleration sensitivity (radial)	bar/g	≤0.0001						
	psi/g	≤0.0015						
Weight (typ.)	grams	3.6						
Sensor material housing & diaphragm		17-4 S.S.						

[1] Indications are valid for 23 °C / 73 °F (if not specified otherwise)
[2] Calculated from rise time

Mounting

Please check the manual for an overview on the different mounting options.

Included Accessories

	Type/Art.-No.
• Sensor seal copper (5 pcs)	1131

Optional Accessories

	Type/Art.-No.
• Floating clamp nut (metric hex)	6423B00
• Floating clamp nut (imperial hex)	6423B10
• Adapter M10	6503B0A
• Adapter 3/8-24-UNF	6503B1A

Please check the manual for details and further accessories.

Ordering Example

PE sensor with standard housing 601CAA
PE sensor with short housing 601CAB
IEPE sensor (250 bar/3625 PSI) 601CBA00250.0

PiezoStar® and Piezotron® are registered trademarks of Kistler Holding AG.

Ordering Key

Type 601C ☐ ☐ ☐

Output Signal

with charge output (PE)	A
with voltage output (IEPE)	B

Housing

Standard housing (PE and IEPE)	A
Short housing (only PE)	B

Pressure Range (only IEPE)

250 bar / 3625 psi	00250.0
70 bar / 1000 psi	00070.0
35 bar / 500 psi	00035.0
14 bar / 200 psi	00014.0
7 bar / 100 psi	00007.0
3.5 bar / 50 psi	00003.5
1.5 bar / 22 psi	00001.5

Appendix C – Valve characteristics

IN-LINE METAL DIAPHRAGM PNEUMATICALLY-OPERATED ULTRA FAST VALVES

The Ultra-Fast series is designed for atomic layer deposition applications, high cycling, high temperature and ultra-high purity processes, under severe repeatability demands. With its unique (patent pending No. US61/910,079) flow adjustment mechanism, this series allows flow fine-tuning during operation. Optional extended bonnet and cooling fin provide superb solution for high temperature applications.

IN-LINE VALVE SPECIFICATIONS

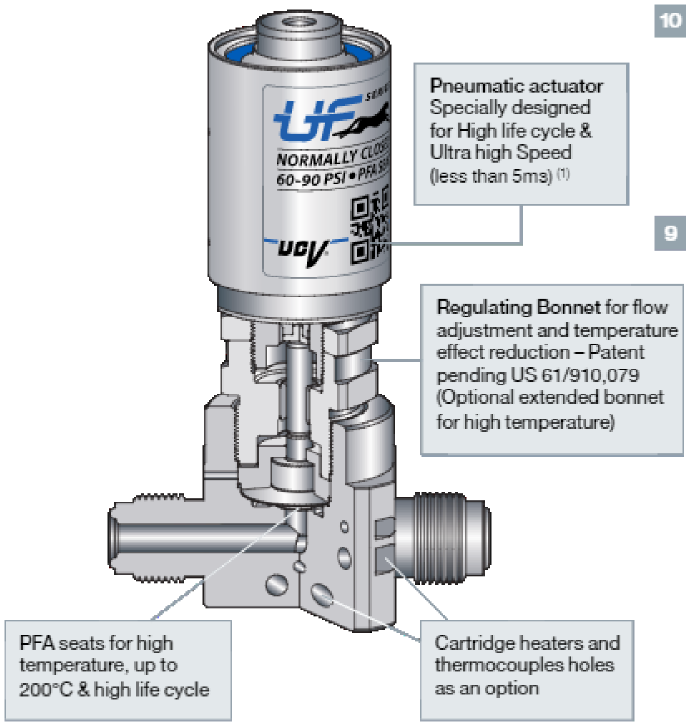
Structure	Direct-seal metal-diaphragm valve without seal packing Pneumatically operated
Pressure	**Vacuum to 150 psi (10 bar)**
Temperature: Standard bonnet	14 to 248°F (-10 to 120°C)
Extended bonnet	**14 to 392°F (-10 to 200°C)**
Leakage: Inboard Leakage	$\le 3x10^{-11}$ atm cc He/sec
Across the seat	**$\le 1x10^{-9}$ atm cc He/sec (1)**
Particle	No particle detected above 0.1µm.
Operated	**High speed Pneumatic, NC***
CV value	0.25 / 0.6, Adjustable
Port configurations	**2-port straight, 2-port L, 3-port, 4-port**
Surface Finish Ra (Ave)-Standard	5µin, Electropolished surface
Air Supply	60-90 psig (4 - 6 bar)
Valve Response Time	Less than 5ms (1)
Air Connection	**M5**

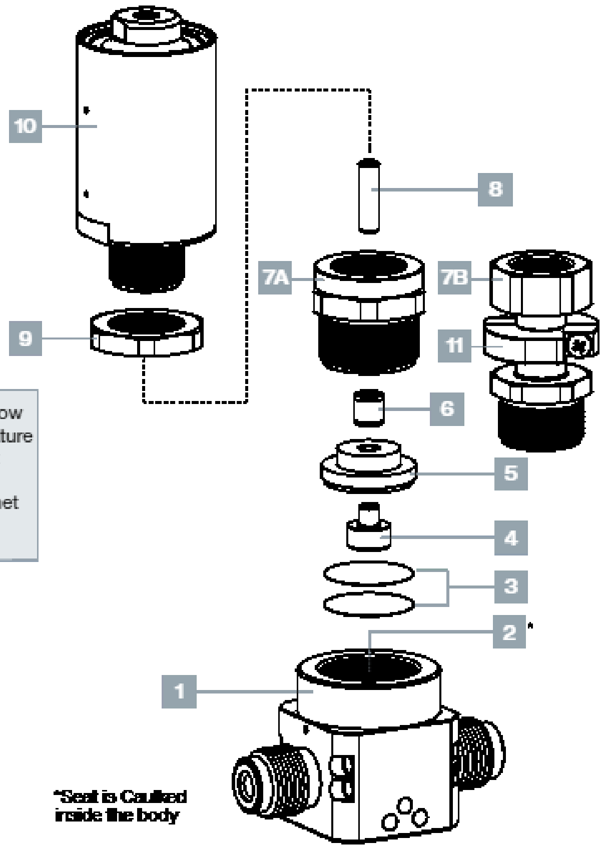
(1) For 1/4" body size, for valve only
***NC-Normally Closed**

MATERIALS

Item No.	Part No.	Material
1*	Body	Stainless steel, 316L VAR or VIM/VAR**
2*	Seat (Caulked)	PFA
3*	Diaphragm	Co-Cr-Ni Alloy
4	Act. Button	Stainless steel, 316L
5	Act. Button Holder	Stainless steel, ASTM 630 H900
6	Bushing	Carbon steel + PTFE
7A	Regulating Bonnet	Stainless steel, 316L
7B	Extended Regulating Bonnet	Stainless steel, 316L
8	Connection Rod	Stainless steel, 304
9	Locking Nut	Stainless steel, 304
10	Actuator Assembly	Stainless steel, 316L
11	Cooling Fin	Aluminium 6061

***Wetted parts ** Per SEMI F20**





UF SERIES

SURFACE-MOUNT, METAL DIAPHRAGM PNEUMATICALLY-OPERATED ULTRA FAST VALVES

The surface mount design complies with SEMI PR 3.1 for 1.112'' C-seal. This series is manufactured according to UHP specifications of SEMI F-20 with pneumatic operating mechanisms.

SURFACE-MOUNT VALVE SPECIFICATIONS

Structure	Direct-seal metal-diaphragm valve without seal packing Pneumatically operated
Pressure	Vacuum to 150 psi (10 bar)
Temperature: Standard bonnet	14 to 248°F (-10 to 120°C)
Extended bonnet	14 to 392°F (-10 to 200°C)
Leakage: Inboard Leakage	≤ 3x10⁻¹¹ atm cc He/sec
Across the seat	≤ 1x10⁻⁹ atm cc He/sec (1)
Particle	No particle detected above 0.1µm.
Operated	High speed Pneumatic, NC*
CV value	0.25 / 0.6, Adjustable
Port configurations	2-port, 3-port
Surface Finish Ra (Ave)-Standard	5µin, Electropolished surface
Air Supply	60-90 psig (4 - 6 bar)
Valve Response Time	Less than 5ms (1)
Air Connection	M5

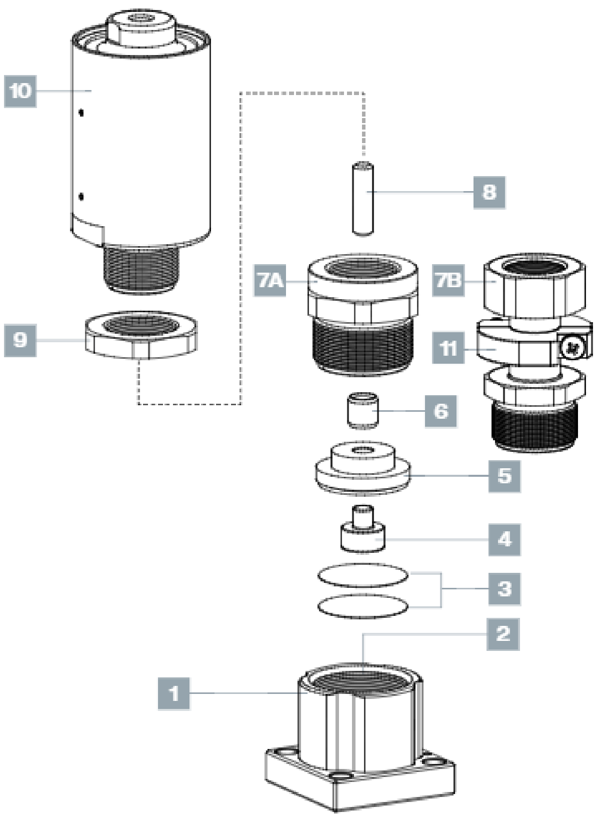
(1) For 1/4" body size, for valve only

*NC-Normally Closed

MATERIALS

Item No.	Part No.	Material
1*	Body	Stainless steel, 316L VAR or VIM/VAR**
2*	Seat (Caulked)	PFA
3*	Diaphragm	Co-Cr-Ni Alloy
4	Act. Button	Stainless steel, 316L
5	Act. Button Holder	Stainless steel, ASTM 630 H900
6	Bushing	Carbon steel + PTFE
7A	Regulating Bonnet	Stainless steel, 316L
7B	Extended Regulating Bonnet	Stainless steel, 316L
8	Connection Rod	Stainless steel, 304
9	Locking Nut	Stainless steel, 304
10	Actuator Assembly	Stainless steel, 316L
11	Cooling Fin	Aluminium 6061

*Wetted parts ** Per SEMI F20



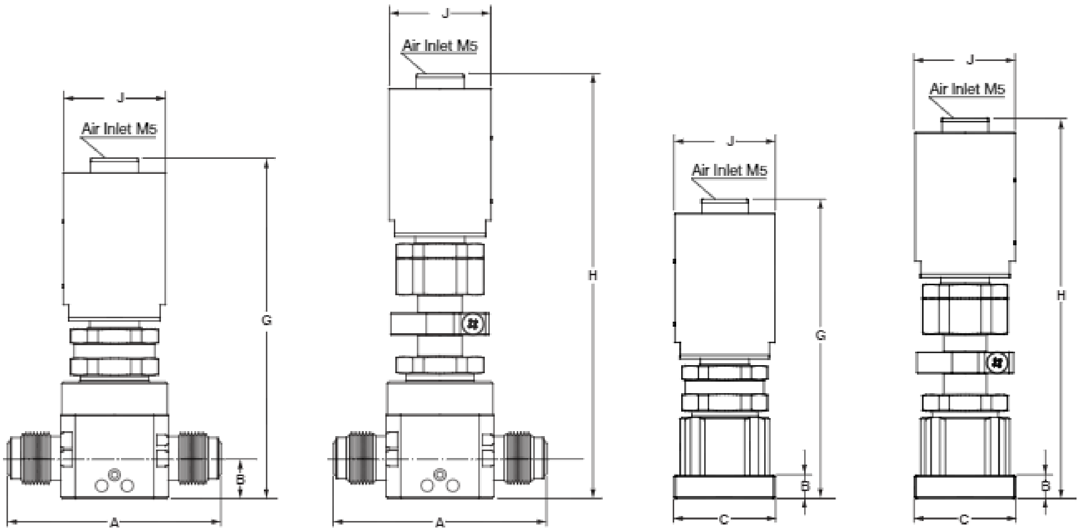
UF SERIES

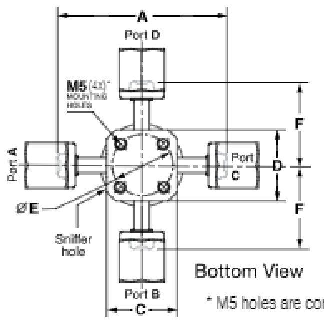
STANDARD CONFIGURATION DIMENSIONS

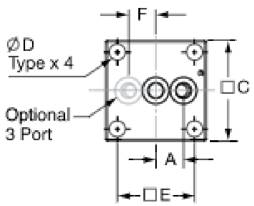
VALVE DIMENSIONS - INCH (MM)

Body Size	SERIES	End Connection	A in	A mm	B in	B mm	C in	C mm	D in	D mm	E in	E mm	F in	F mm	G in	G mm	H in	H mm	J in	J mm
1/4"	UF	Male face seal	2.30	58.4	0.43	11.0	1.16	29.4	1.16	29.4	1.00	25.4	1.15	29.2	3.69	93.8	4.62	117.3	1.10	28.0
		Swivel male face seal	2.78	70.6									1.39	35.3						
		Swivel female face seal	2.78	70.6									1.39	35.3						
		Butt weld	1.75	44.4									0.88	22.2						
	UFS	Surface mount	0.30	7.7	0.26	6.6	1.12	28.4	0.17	4.4	0.85	21.7	0.30	7.7	3.33	84.6	4.26	108.1	1.10	28.0
1/2"	UF	Male face seal	2.99	76.0	0.69	17.5	1.46	37.0	1.46	37.0	1.10	28.0	1.50	38.0	4.93	125.3	5.86	148.8	1.34	34.0
		Swivel male face seal	3.93	100.0									1.97	50.0						
		Swivel female face seal	3.93	100.0									1.97	50.0						
		Butt weld	2.16	55.0									1.08	27.5						
	UFS	Surface mount	0.46	11.6	0.31	8.0	1.50	38.1	0.20	5.2	1.19	30.2	0.46	11.6	4.45	113.2	5.38	136.8	1.34	34.0

Dimensions are for reference only, and are subject to change.







* M5 holes are compatible with 10-32 mounting screws

ORDERING INFORMATION

Valve Description Example:

UF 2 0 - 4 V F LC - BW 4 GF 4 - [ ] - [ ] - [ ] (OPTIONAL)

Port (A) – BW; Port (B) – GF

Valve Series	
UF	Inline
UFS	Surface mount

Valve Type	
2	2-Port Valve
3	3-Port Valve
4	4-Port Valve[2]

Port Designator
0,1,2,3,4,5

Body Designator	
4	1/4" Body
8	1/2" Body

Body Material	
V	SS316L VAR or VIM/VAR(1)

Seat Material	
F	PFA

Actuation Device	
LC	Air Operated N.C.

End Connection[2]	
BW	Butt Weld
GF	Swivel female Face-seal
GM	Swivel male Face-seal
M	Male Face-seal

End Size	
4	1/4"
6*	3/8"
8	1/2"

* For BW Only

High temp. Options	
X	Extender
F	Extender with fin

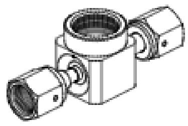
Control options	
D	Solenoid valve, DC
LS	Limit switch

Heating Option[3]	
H	Cartrige Holes for Thermocouple and Heater
H1	Cartrige Holes with Thermocouple
H2	Cartrige Holes with Heater
H3	Cartrige Holes with Thermocouple and Heater

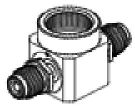
(1) Per SEMI F20-0305 | (2) For inline valves only | (3) 1/8 in. through holes For UF20 valves only

PORT DESIGNATOR - (TOP VIEW)

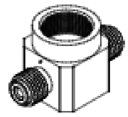
Valve Configuration	Port Designator	Schematic Flow Chart	Valve Configuration	Port Designator	Schematic Flow Chart	Valve Configuration	Port Designator	Schematic Flow Chart
2 Port Valve **UF2_** (A, C, Sniffer Hole)	0		3 Port Valve **UF3_** (A, C, D, Sniffer Hole)	0		4 Port Valve **UF4_** (A, B, C, D, Sniffer Hole)	0	
	1 L-Port			1			1	
	2 L-Port			2			2	
				3			3	
				4				
				5				



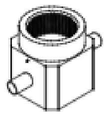
Swivel Female Face-Seal Ends



Swivel Male Face-Seal Ends



Male Face-Seal Ends



Butt Weld Ends

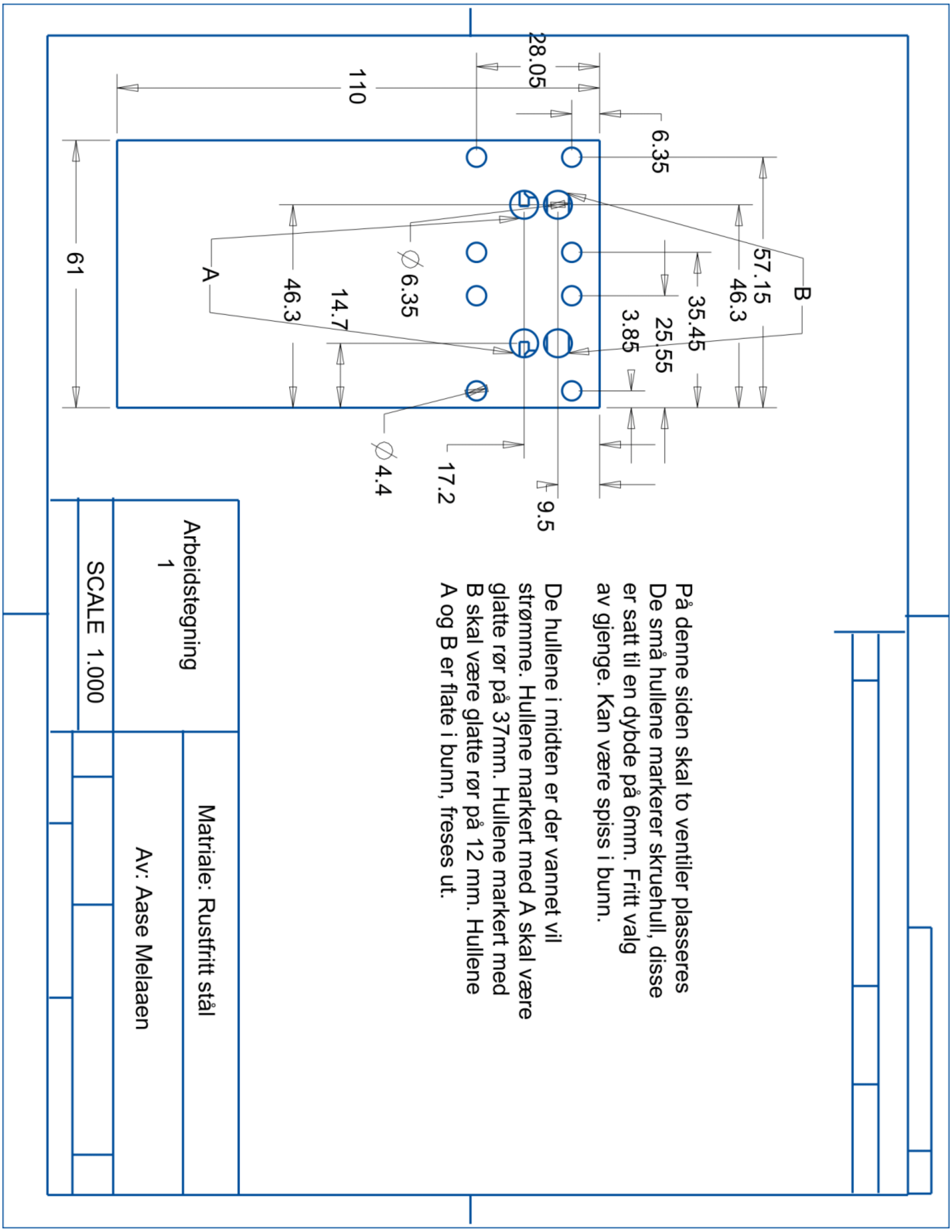
Warning!
The system designer and user have the sole responsibility for selecting products suitable for their special application requirements, ensuring their safe and trouble-free installation, operation, and maintenance. Application details, material compatibility and product ratings should all be considered for each selected product. Improper selection, installation or use of products can cause property damage or personal injury.

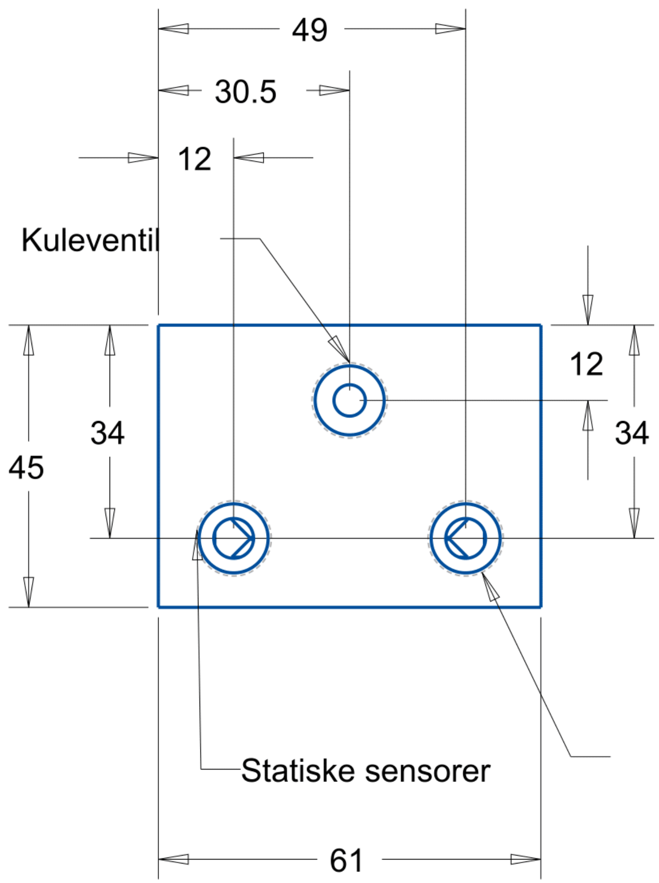
UCV UF, Rev.00, January 2014

ULTRA CLEAN VALVES

Appendix D – Construction work drawings

D.1 – Calibration tool



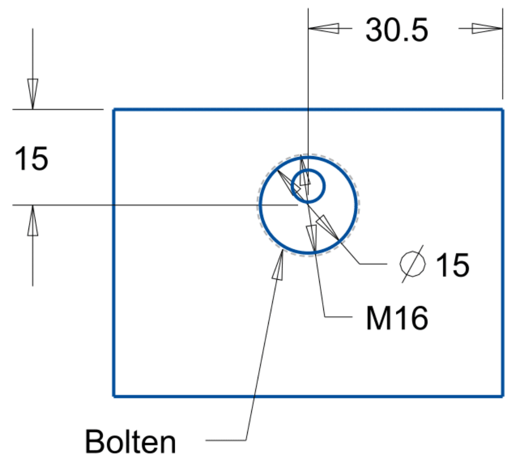


Det indre hullet til kuleventilen har en diameter på 5mm og er et glatt rør på 110mm. Det ytre hullet til kuleventilen er 6mm dypt og frest ut.

De indre hullene til de statiske sensorene har en diameter på 6,35mm og en dybde på 17,2. De ytre hullene er 8,5mm dype, hullene er frest ut.

Alle de tre hullene skal ha 1/4".

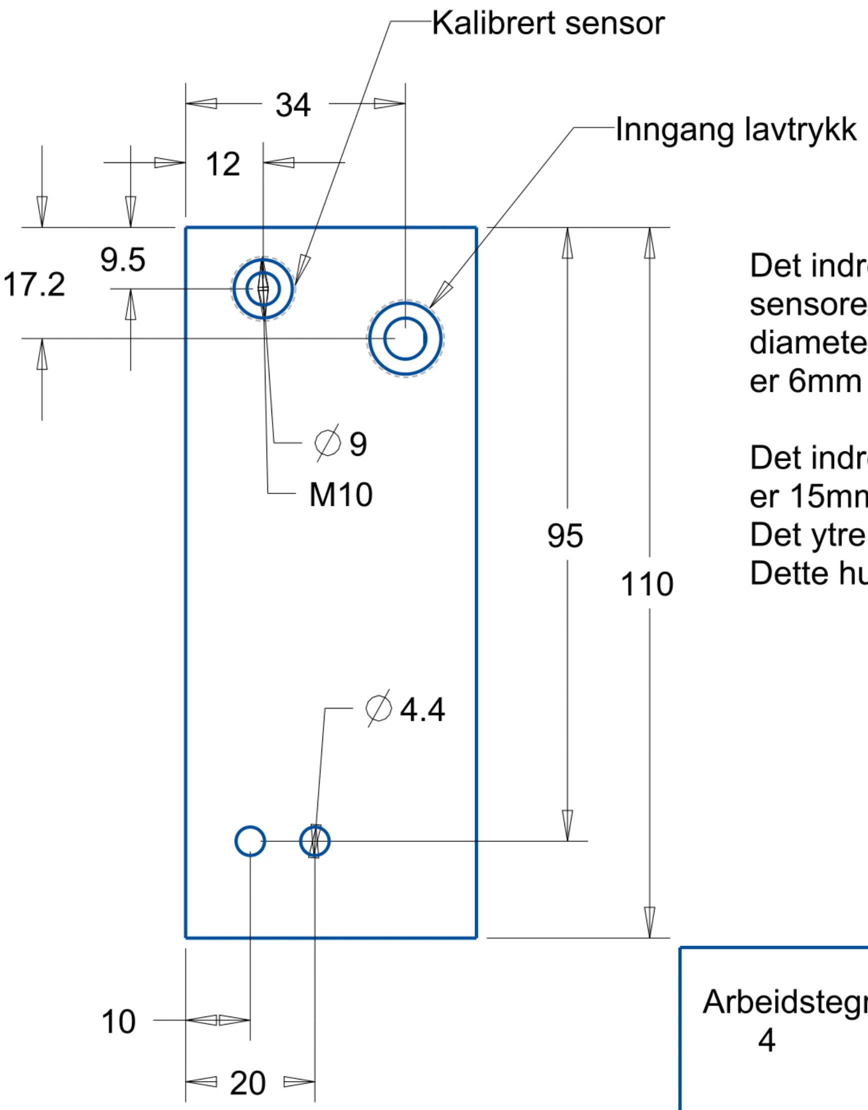
Arbeidstegning 2	Matriale: Rustfritt stål
	Av: Aase Melaaen
SCALE 1.000	



Dybden på hullet der bolten skal ha plass, er 98mm. Dette hullet skal freses ut.

Gjengene på bolten kan være valgfri

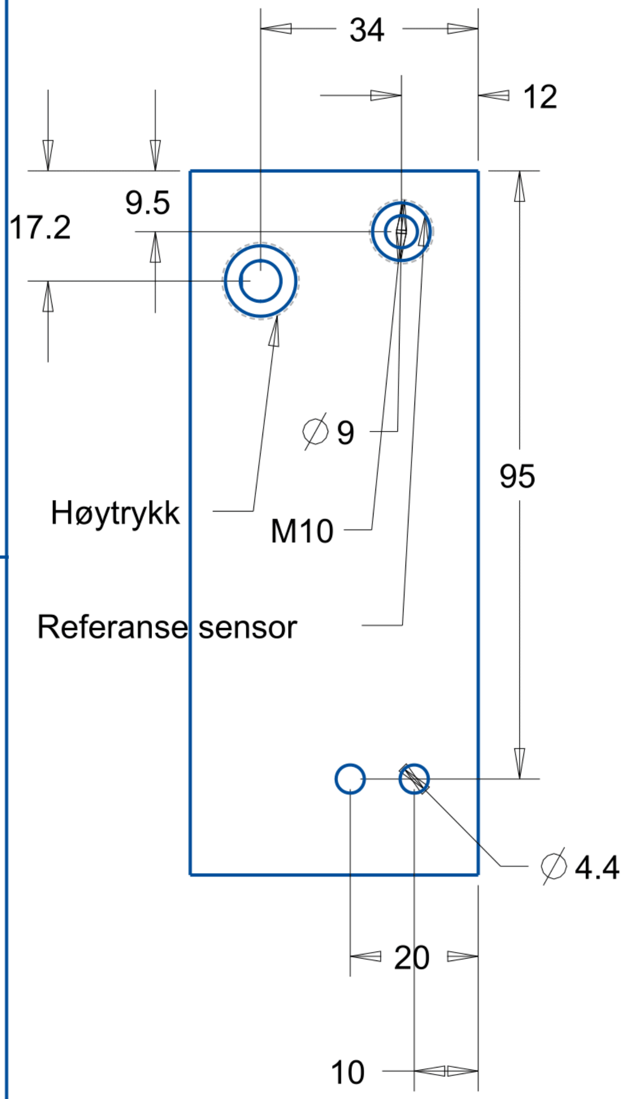
Arbeidstegning 3	Matriale: Rustfritt stål
	Av: Aase Melaaen
SCALE 1.000	



Det indre hullet ved den kalibrerte sensoren er 80mm langt, og 5mm i diameter. Det ytterste hullet er 6mm dypt, frest ut.

Det indre hullet ved lavtrykk ingengen er 15mm dypt, med en diameter på 6.35mm. Det ytre hullet er frest ut med dybde 8mm. Dette hullet skal være tilpasset et 1/4"

Arbeidstegning 4	Matriale: Rustfitt stål
	Av: Aase Melaaen
SCALE 1.000	

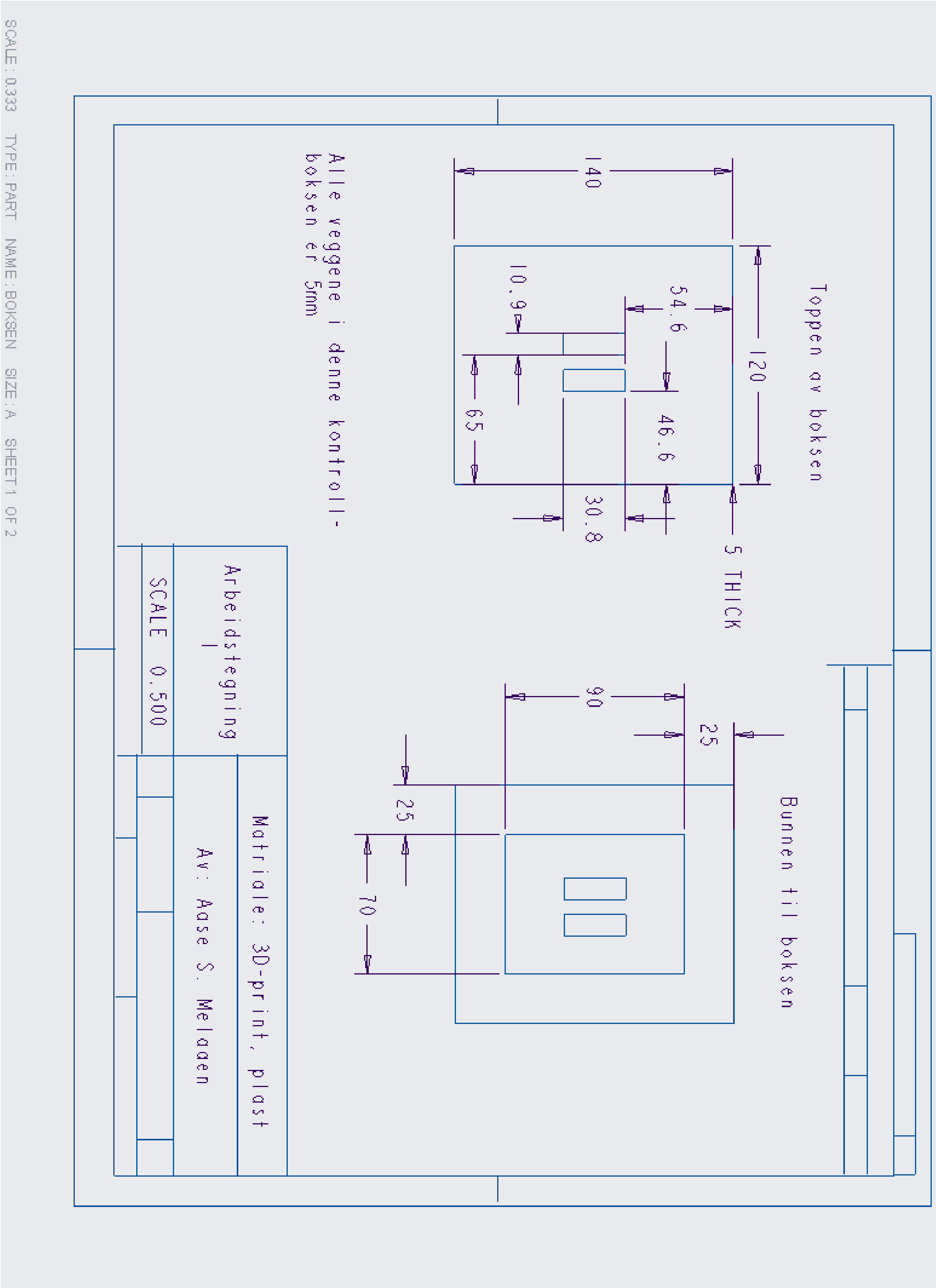


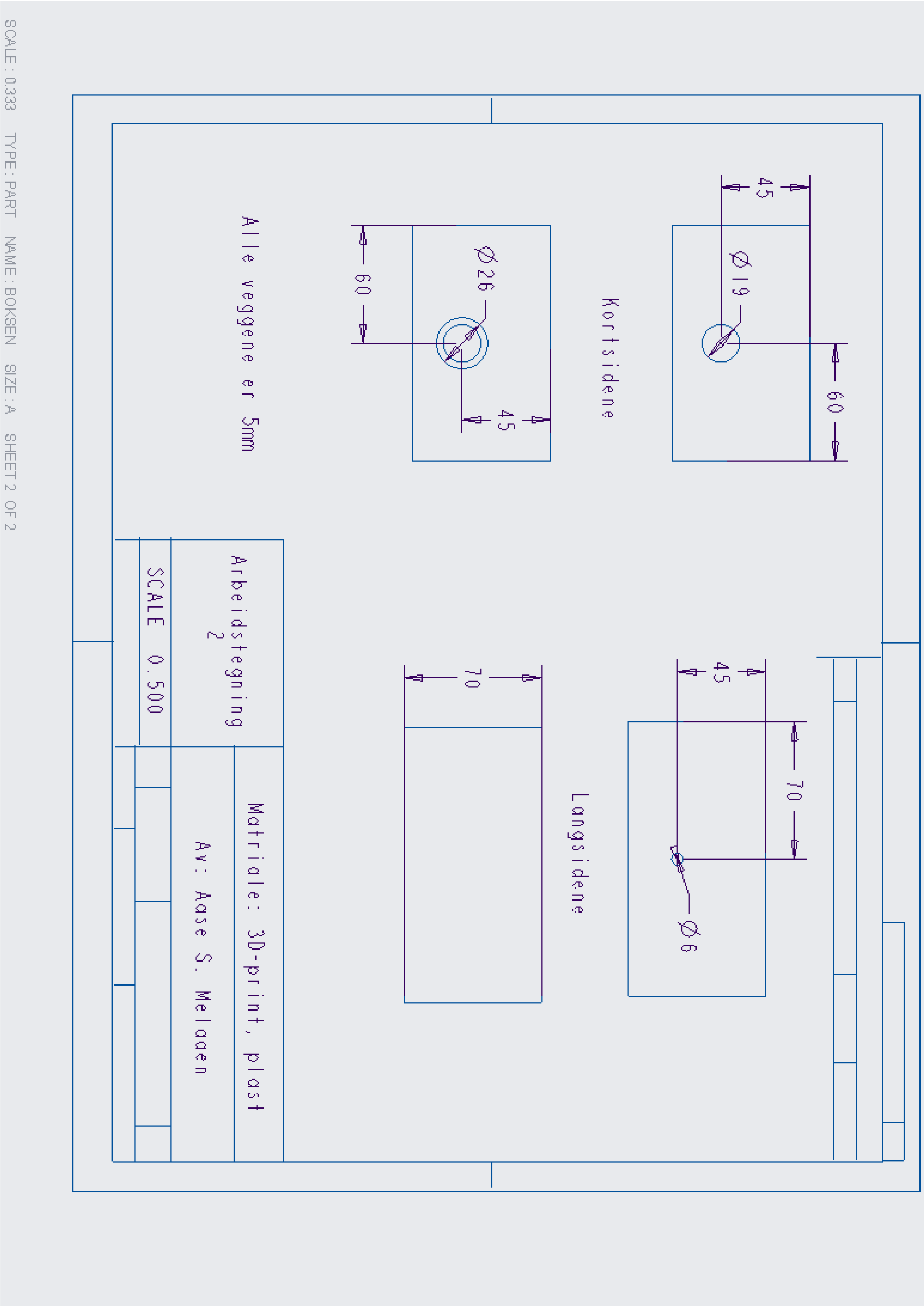
Det indre hullet ved referanse
sensoren er 80mm langt, og 5mm i
diameter. Det ytterste hullet
er 8mm dypt, frest ut.

Det indre hullet ved høytrykk ingengen
er 15mm dypt, med en diameter på 6.35mm.
Det ytre hullet er frest ut med dybde 8mm.
Dette hullet skal være tilpasset et 1/4"

Arbeidstegning 5	Matriale: rustfritt stål
	Av: Aase Melaaen
SCALE 1.000	

D.2 – Control-box




SCALE : 0.333 TYPE : PART NAME : BOKSEN SIZE : A SHEET 2 OF 2
Kortsidene
Ø19
45
60
Ø26
45
60
Alle veggene er 5mm
Langsidene
45
70
Ø6
70
Arbeidstegning 2
SCALE 0.500
Matriale: 3D-print, plast
Av: Aase S. Melaaen

Appendix E – Calibration reports, steady-state calibration

E.1 – UNIK 5000 PTX5072, 0bar to 10bar absolute

CALIBRATION REPORT

CALIBRATION PROPERTIES
Calibrated by: Aase Sørum Melaaen
Type/Producer: PTX 507
SN: 3725345
Range: 0-10 bar a
Unit: Pa

CALIBRATION SOURCE PROPERTIES
Type/Producer: Digital pressure indicator DPI 601
SN: 4539
Uncertainty [%]: 0,04

POLY FIT EQUATION:
Y= -248.88095162E+0X^0 + 124.98213249E+0X^1

CALIBRATION SUMARY:
Max Uncertainty : 0.039767 [%]
Max Uncertainty : 0.040529 [Pa]
RSQ : 1.000000
Calibration points : 70

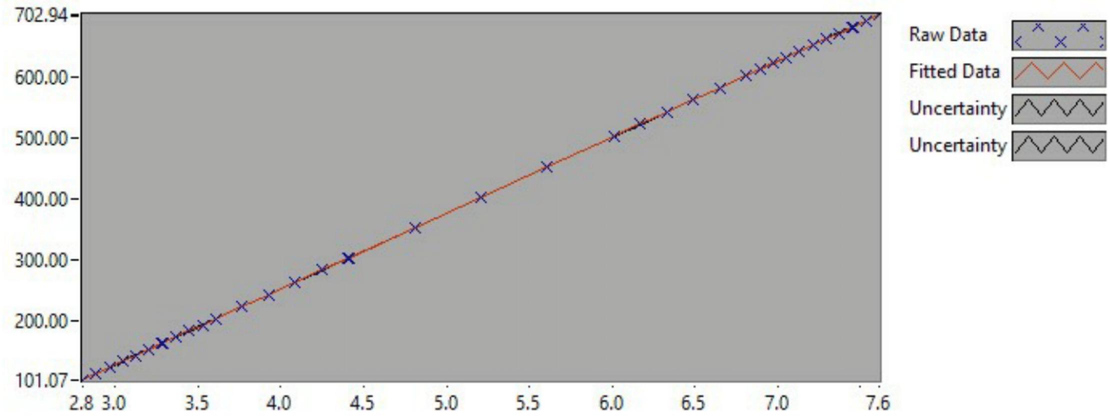


Figure 1 : Calibration chart (The uncertainty band is multiplied by 10)

____
Aase Sørum Melaaen

CALIBRATION VALUES

Value [Pa]	Voltage [V]	Best Poly Fit [Pa]	Deviation [Pa]	Uncertainty [%]	Uncertainty [Pa]
101.683000	2.803638	101.523720	0.159280	0.039757	0.040426
111.698107	2.884836	111.671950	0.026157	0.035387	0.039527
121.713214	2.965036	121.695539	0.017675	0.031766	0.038663
131.728321	3.046243	131.844975	-0.116654	0.028678	0.037777
141.743428	3.125258	141.720496	0.022933	0.026065	0.036946
151.758535	3.205355	151.731167	0.027369	0.023793	0.036108
161.773643	3.285705	161.773463	0.000179	0.021814	0.035290
171.788750	3.366368	171.854919	-0.066169	0.020065	0.034469
181.803857	3.446571	181.878842	-0.074986	0.018533	0.033693
191.818964	3.526371	191.852478	-0.033514	0.017152	0.032902
201.834071	3.606358	201.849403	-0.015332	0.015943	0.032179
221.864285	3.767208	221.952681	-0.088396	0.013836	0.030696
241.894499	3.927082	241.934092	-0.039593	0.012139	0.029363
261.924714	4.087713	262.010160	-0.085446	0.010720	0.028080
281.954928	4.248340	282.085615	-0.130687	0.009557	0.026945
301.985142	4.408548	302.108808	-0.123666	0.008601	0.025975
352.060677	4.808955	352.152504	-0.091826	0.006884	0.024237
402.136213	5.209107	402.164407	-0.028194	0.005870	0.023605
452.211748	5.609484	452.204269	0.007479	0.005364	0.024257
502.287284	6.010470	502.320454	-0.033170	0.005181	0.026022
522.317498	6.170648	522.339846	-0.022348	0.005169	0.026998
542.347712	6.330805	542.356532	-0.008820	0.005202	0.028211
562.377926	6.491250	562.409343	-0.031416	0.005228	0.029401
582.408141	6.652104	582.513226	-0.105086	0.005286	0.030786
602.438355	6.811288	602.408328	0.030027	0.005346	0.032208
612.453462	6.891970	612.492101	-0.038639	0.005392	0.033021
622.445569	6.971373	622.416061	0.029508	0.005423	0.033758
632.460676	7.051670	632.451857	0.008819	0.005469	0.034590
642.475783	7.131506	642.429834	0.045949	0.005504	0.035359
652.490890	7.211722	652.455394	0.035496	0.005561	0.036283
662.505997	7.291921	662.478945	0.027053	0.005591	0.037042
672.521104	7.372310	672.526052	-0.004948	0.005637	0.037911
682.536212	7.451558	682.430598	0.105614	0.005688	0.038826
692.551319	7.532446	692.540252	0.011067	0.005726	0.039656
702.566426	7.612429	702.536634	0.029792	0.005769	0.040529
702.566426	7.612119	702.497900	0.068525	0.005766	0.040511
692.551319	7.532555	692.553868	-0.002549	0.005733	0.039704
682.536212	7.452480	682.545902	-0.009690	0.005685	0.038803
672.521104	7.371702	672.450087	0.071017	0.005636	0.037902
662.505997	7.291613	662.440344	0.065653	0.005592	0.037049
652.490890	7.211902	652.477929	0.012962	0.005551	0.036221
642.475783	7.131607	642.442473	0.033310	0.005506	0.035377
632.460676	7.051643	632.448397	0.012279	0.005469	0.034590
622.445569	6.971884	622.480018	-0.034449	0.005425	0.033767

612.430462	6.891183	612.393812	0.036650	0.005395	0.033044
602.415355	6.811550	602.441130	-0.025775	0.005363	0.032308
582.385141	6.651365	582.420838	-0.035698	0.005290	0.030805
562.354926	6.491166	562.398771	-0.043845	0.005239	0.029464
542.324712	6.331077	542.390536	-0.065823	0.005209	0.028252
522.294498	6.170798	522.358493	-0.063995	0.005195	0.027134
502.264284	6.010271	502.295591	-0.031307	0.005193	0.026085
452.188748	5.609119	452.158723	0.030026	0.005361	0.024240
402.113213	5.208910	402.139752	-0.026539	0.005866	0.023587
352.037677	4.807399	351.958056	0.079621	0.006882	0.024228
301.962142	4.407029	301.918909	0.043232	0.008611	0.026001
281.931928	4.247516	281.982716	-0.050789	0.009566	0.026969
261.901714	4.086875	261.905425	-0.003711	0.010736	0.028117
241.871499	3.926797	241.898567	-0.027068	0.012143	0.029372
221.841285	3.765945	221.794946	0.046339	0.013837	0.030697
201.811071	3.606890	201.915791	-0.104720	0.015920	0.032129
191.795964	3.526467	191.864466	-0.068502	0.017163	0.032918
181.780857	3.446653	181.889068	-0.108211	0.018527	0.033679
171.765750	3.366532	171.875449	-0.109699	0.020072	0.034478
161.750643	3.281270	161.219111	0.531532	0.021849	0.035340
151.735535	3.202895	151.423722	0.311813	0.023813	0.036133
141.720428	3.126453	141.869839	-0.149410	0.026055	0.036925
131.705321	3.044517	131.629331	0.075991	0.028698	0.037797
121.690214	2.965847	121.796963	-0.106749	0.031752	0.038639
111.675107	2.884680	111.652560	0.022547	0.035402	0.039536
101.660000	2.803276	101.478473	0.181527	0.039767	0.040427

COMMENTS:

The uncertainty is calculated with 95% confidence. The uncertainty includes the randomness in the calibrated instrument during the calibration, systematic uncertainty in the instrument or property which the instrument under calibration is compared with (dead weight manometer, calibrated weights etc.), and due to regression analysis to fit the calibration points to a linear calibration equation.The calculated uncertainty can be used as the total systematic uncertianty of the calibrated instrument with the given calibration equation.

E.2 – UNIK 5000 PTX5072, 0bar to 5bar absolute

CALIBRATION REPORT

CALIBRATION PROPERTIES
Calibrated by: Aase Sørum Melaaen
Type/Producer: Sensotec
SN: 4347341
Range: 0-5 bar a
Unit: Pa

CALIBRATION SOURCE PROPERTIES
Type/Producer: Digital Pressure Indicator DPI 601
SN: 4539
Uncertainty [%]: 0.06

POLY FIT EQUATION:
Y= -125.31982553E+0X^0 + 62.50395279E+0X^1

CALIBRATION SUMARY:
Max Uncertainty : 0.066072 [%]
Max Uncertainty : 0.192385 [Pa]
RSQ : 0.999998
Calibration points : 31

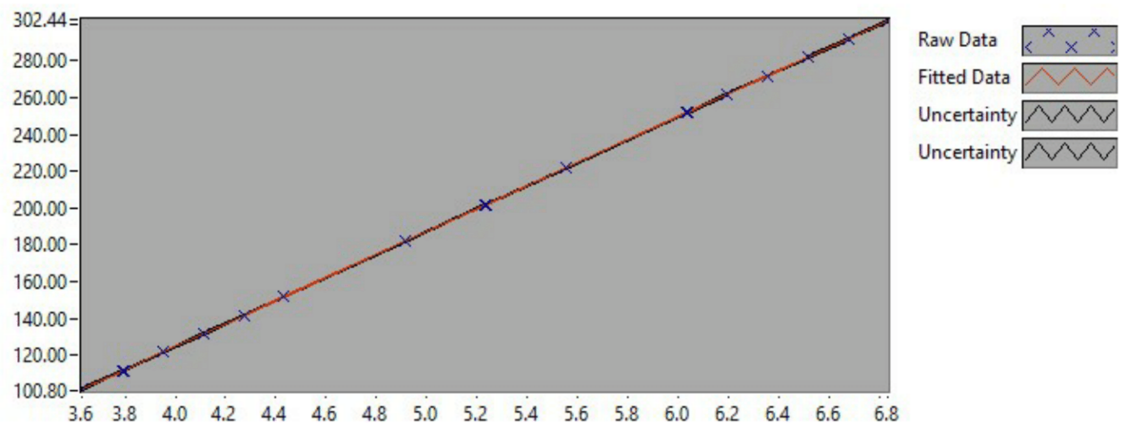


Figure 1 : Calibration chart (The uncertainty band is multiplied by 10)

____
Aase Sørum Melaaen

CALIBRATION VALUES

Value [Pa]	Voltage [V]	Best Poly Fit [Pa]	Deviation [Pa]	Uncertainty [%]	Uncertainty [Pa]
101.646000	3.629532	101.540292	0.105708	0.066041	0.090696
111.661107	3.792254	111.711050	-0.049943	0.056117	0.091733
121.676214	3.952206	121.708648	-0.032434	0.048018	0.093507
131.691321	4.111499	131.665114	0.026207	0.041328	0.095945
141.706428	4.272651	141.737745	-0.031317	0.035729	0.098957
151.721535	4.428578	151.483789	0.237747	0.031159	0.102576
181.766857	4.915698	181.930726	-0.163869	0.021761	0.116012
201.797071	5.234606	201.863741	-0.066670	0.018672	0.126805
221.827285	5.553328	221.785129	0.042157	0.017497	0.138640
251.872606	6.034738	251.875170	-0.002563	0.018090	0.157843
261.887714	6.193372	261.790375	0.097338	0.018628	0.164532
271.902821	6.354579	271.866452	0.036369	0.019280	0.171358
281.917928	6.518845	282.133737	-0.215809	0.020013	0.178312
291.933035	6.677819	292.070227	-0.137193	0.020737	0.185326
301.948142	6.833443	301.797367	0.150775	0.021437	0.192385
301.948142	6.832365	301.729970	0.218172	0.021424	0.192372
291.933035	6.676390	291.980927	-0.047893	0.020721	0.185311
281.917928	6.514749	281.877742	0.040186	0.019976	0.178279
281.917928	6.514736	281.876929	0.040999	0.019976	0.178279
271.902821	6.356142	271.964169	-0.061348	0.019298	0.171372
261.887714	6.194444	261.857419	0.030294	0.018640	0.164541
251.872606	6.036150	251.963422	-0.090816	0.018104	0.157853
221.827285	5.554354	221.849227	-0.021942	0.017494	0.138638
201.797071	5.234101	201.832194	-0.035123	0.018675	0.126807
181.766857	4.913576	181.798093	-0.031236	0.021770	0.116017
151.721535	4.432355	151.719871	0.001665	0.031106	0.102539
141.706428	4.272564	141.732341	-0.025912	0.035729	0.098957
131.691321	4.112007	131.696860	-0.005539	0.041316	0.095936
121.676214	3.952006	121.696151	-0.019937	0.048021	0.093509
111.661107	3.794048	111.823164	-0.162056	0.056069	0.091696
101.646000	3.628440	101.472017	0.173983	0.066072	0.090719

COMMENTS:

The uncertainty is calculated with 95% confidence. The uncertainty includes the randomness in the calibrated instrument during the calibration, systematic uncertainty in the instrument or property which the instrument under calibration is compared with (dead weight manometer, calibrated weights etc.), and due to regression analysis to fit the calibration points to a linear calibration equation.The calculated uncertainty can be used as the total systematic uncertianty of the calibrated instrument with the given calibration equation.

Appendix F – Calibration report, Kistler 601C

KISTLER
measure. analyze. innovate.

Kalibrierschein
Calibration Certificate

Type **Kistler 601CBA00001.5** **Serial No. 5102357**

Bearbeiter Calibration Technician	**Datum** Date
A. Mändli	03. Feb. 2017

Referenzgeräte Reference Equipment	**Typ** Type	**Serie Nr.** Serial No.
Gebrauchsnormal Working Standard	Kistler 601CB	4821404
Ladungskalibrator Charge Calibrator	Kistler 5395A	1621210

Umgebungstemperatur Ambient Temperature °C	**Relative Feuchte** Relative Humidity %
23	45

Messergebnisse Results of Measurement

Kalibrierter Bereich Calibrated Range bar	psi	**Empfindlichkeit** Sensitivity mV / bar	mV / psi	**Linearität** Linearity ≤ ± % FSO
0 ... 1,5	0 ... 22	3118	215,0	0,11

Messverfahren Measurement Procedure

Das Kalibrierobjekt wurde nach den Vorschriften der Kalibrieranweisung CPC9951PD kalibriert.
The calibration object was calibrated according to the requirements of calibration instruction PC9951PD.

Bestätigung Confirmation

Das oben durch die Seriennummer identifizierte Gerät entspricht der Vereinbarung der Bestellung und hält die Herstelltoleranzen gemäss den Spezifikationen der Datenblätter ein, sofern nicht anders auf dem Kalibrierschein vermerkt. Das Kistler Qualitätsmanagement System ist nach ISO 9001 zertifiziert. Das Dokument erfüllt die Anforderungen von EN 10204 Abnahmeprüfzeugnis "3.1". Die aufgeführten Referenzgeräte sind auf nationale Normale rückgeführt. Das Dokument wurde elektronisch erstellt und ist daher ohne Unterschrift gültig.
The equipment identified by Serial No. complies with the agreement of the order and meets the manufacturing tolerances specified in the data sheets, unless otherwise specified on the calibration certificate. The Kistler Quality Management System is certified per ISO 9001. This document fulfils the requirements of EN 10204 Inspection Certificate "3.1". The reference equipment is traceable to national standards. The document was issued electronically and is therefore valid without signature.

Seite page **1/1**

Kistler Instrumente AG
Eulachstrasse 22
8408 Winterthur
Switzerland

Tel. +41 52 224 11 11
Fax +41 52 224 14 14
info@kistler.com

ZKB Winterthur BC 732
Swift: ZKBKCHZZ80A
Account: 1132-0374.628

IBAN: CH67 0070 0113 2003 7462 8
VAT: 229 713
ISO 9001 certified

www.kistler.com

Appendix G – Risk assessment

NTNU HSE	Hazardous activity identification process	Prepared by	Number	Date
		HSE section	HMSRV2601E	09.01.2013
		Approved by		Replaces
		The Rector		01.12.2006

Unit: *Department of energy and process engineering* **Date: 08.05.2017**

Line manager: Ole Gunnar Dahlhaug

Participants in the identification process (including their function)**: Ole Gunnar Dahlhaug** (Supervisor)**, Einar Agnalt** (Co-supervisor)**, Aase Sørum Melaaen** (Student)

Short description of the main activity/main process: Master project for student Aase Sørum Melaaen. Calibration and Uncertainty Analysis of Pressure Sensors used for Dynamic Measurements

Is the project work purely theoretical? (YES/NO): NO *Answer "YES" implies that supervisor is assured that no activities requiring risk assessment are involved in the work. If YES, briefly describe the activities below. The risk assessment form need not be filled out.*

Signatures: *Responsible supervisor:* Ole G. Dahlhaug *Student:* Aase S. Melaaen

ID nr.	Activity/process	Responsible person	Existing documentation	Existing safety measures	Laws, regulations etc.	Comment
1	Use of the high pressure tank when testing the calibration system developed	ASM	X	Use of safety goggles		

Unit: *Department of energy and process engineering* **Date: 08.05.2017**

Line manager: Ole Gunnar Dahlhaug

Participants in the identification process (including their function)**: Ole Gunnar Dahlhaug** (Supervisor), **Einar Agnalt** (Co-supervisor), **Aase Sørum Melaaen** (Student)

Short description of the main activity/main process: Master project for student Aase Sørum Melaaen. Calibration and Uncertainty Analysis of Pressure Sensors used for Dynamic Measurements

Signatures: *Responsible supervisor:* Ole G. Dahlhaug *Student:* Aase S. Melaaen

Activity from the identification process form	Potential undesirable incident/strain	Likelihood: Likelihood (1-5)	Consequence: Human (A-E)	Environment (A-E)	Economy/ material (A-E)	Risk Value (human)	Comments/status Suggested measures
Test of calibration system with use of the high pressure tank	Water leakage	3	A	A	A	A3	
Test of calibration system with use of the high pressure tank	Fire in electric motor	1	B	C	D	B1	
Test of calibration system with use of the high pressure tank	Pneumatic hose cracks	2	A	A	A	A3	

Likelihood, e.g.:
1. *Minimal*
2. *Low*
3. *Medium*
4. *High*

Consequence, e.g.:
A. *Safe*
B. *Relatively safe*
C. *Dangerous*
D. *Critical*

Risk value (each one to be estimated separately):
Human = Likelihood x Human Consequence
Environmental = Likelihood x Environmental consequence
Financial/material = Likelihood x Consequence for Economy/materiel

5. Very high *E. Very critical*

Potential undesirable incident/strain
Identify possible incidents and conditions that may lead to situations that pose a hazard to people, the environment and any materiel/equipment involved.

Criteria for the assessment of likelihood and consequence in relation to fieldwork
Each activity is assessed according to a worst-case scenario. Likelihood and consequence are to be assessed separately for each potential undesirable incident. Before starting on the quantification, the participants should agree what they understand by the assessment criteria:

Likelihood

Minimal 1	Low 2	Medium 3	High 4	Very high 5
Once every 50 years or less	Once every 10 years or less	Once a year or less	Once a month or less	Once a week

Consequence

Grading	Human	Environment	Financial/material
E Very critical	May produce fatality/ies	Very prolonged, non-reversible damage	Shutdown of work >1 year.
D Critical	Permanent injury, may produce serious serious health damage/sickness	Prolonged damage. Long recovery time.	Shutdown of work 0.5-1 year.
C Dangerous	Serious personal injury	Minor damage. Long recovery time	Shutdown of work < 1 month
B Relatively safe	Injury that requires medical treatment	Minor damage. Short recovery time	Shutdown of work < 1week
A Safe	Injury that requires first aid	Insignificant damage. Short recovery time	Shutdown of work < 1day

The unit makes its own decision as to whether opting to fill in or not consequences for economy/materiel, for example if the unit is going to use particularly valuable equipment. It is up to the individual unit to choose the assessment criteria for this column.

Risk = Likelihood x Consequence
Please calculate the risk value for "Human", "Environment" and, if chosen, "Economy/materiel", separately.

About the column "Comments/status, suggested preventative and corrective measures":
Measures can impact on both likelihood and consequences. Prioritise measures that can prevent the incident from occurring; in other words, likelihood-reducing measures are to be prioritised above greater emergency preparedness, i.e. consequence-reducing measures.

MATRIX FOR RISK ASSESSMENTS at NTNU

CONSEQUENCE						
	Extremely serious	E1	E2	E3	E4	E5
	Serious	D1	D2	D3	D4	D5
	Moderate	C1	C2	C3	C4	C5
	Minor	B1	B2	B3	B4	B5
	Not significant	A1	A2	A3	A4	A5
		Very low	Low	Medium	High	Very high
		LIKELIHOOD				

Principle for acceptance criteria. Explanation of the colours used in the risk matrix.

Colour	Description
Red	Unacceptable risk. Measures must be taken to reduce the risk.
Yellow	Assessment range. Measures must be considered.
Green	Acceptable risk Measures can be considered based on other considerations.