NTNU – Trondheim
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A Study on Acoustic Logging Techniques in Oil and Gas producing Wells

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Problem Description

Acoustic logging is a cost effective method for periodic well integrity studies. An acoustic survey will easily detect whether a gas lift valve is fully closed or not without any form of well intervention. This test can save significant time since it possible to manipulate the valve and recheck it with the acoustic instrument several times until it operates properly. If proper operation is not achieved, the decision to pull the valve can be made with minimum delay.

Objectives

- The student should start by describing the background for this thesis, and explain the current challenges when it comes to analyzing acoustic surveys.
- Give a brief explanation on the gas lift technique and give some examples on different applications for acoustic measurements.
- Provide a mathematical background on wave dynamics in order to get a better theoretical understanding
- Take a look at the frequency content in acoustic signals to better understand what happens when a pressure pulse is introduced into a well.
- Strong reflections from elements located near the surface can be a great challenge because the reflection from the liquid level often disappears in the other reflections. It's desirable that the student takes a closer look at this issue, and how it affects the acoustic signal.
- Design a small scale version that can be used for acoustic testing and explain how this can be related to a real sized oil well.
- It is desirable that the student use the small scale version to investigate different scenarios in order to get a better understanding on pressure wave propagation.
- Discuss the results

Preface

This thesis was written during the fall of 2013 as part of the study program leading to a Master of Science in Engineering Cybernetics at Norwegian University of Science and Technology (NTNU). The thesis is written for Scanwell AS and is a continuation on my project work in the spring of 2013. The project work covered the basics behind gas lifted wells and how it was possible to use an acoustic approach in order to verify well integrity. In this process, a database consisting of a vast amount of acoustic measurements were used. It was actually the big range in quality of these surveys that motivated the work in this thesis.

This thesis has provided me with a very good understanding on the dynamics of acoustic wave propagation. This has helped me a lot in order to better understand many of the challenges in acoustic measurements and why some of the surveys turn out the way they do. Furthermore, I hope that this thesis will contribute in the process of overcoming many of the difficulties the operators have when they are offshore and conduct leak surveys for the client.

First and foremost, I would like to thank *Olaf Ellingsen* and my supervising counselor *Morten Kvernvold* in Scanwell AS. Thank you for giving me the opportunity to write this thesis for your company. This is very much appreciated. I would also like to thank the two of you for letting me spend Scanwell's money to buy high pressure hoses for my experimental testing in the lab. I hope it was some well spent money. At NTNU, I would like to thank my supervisor *Tor Onshus* for both help with structural planning and for our monthly telephone meetings we had around my difficulties. This was of great help to me.

Further, I would like to thank *Sam Hussin* for being very helpful and assisting me in the lab with the assembling and disassembling of all the hoses and connections for the different test scenarios. You saved me a whole lot of time. Last but not least, I would like to thank *Hanne, Øystein, Torgeir, Roy, Cezar, Iraj* and *Per* for a good supportive working environment at Scanwell.

Abstract

Gas lift is an artificial lift technique used in reservoirs with an inadequate pressure. The main idea behind the gas lift technique is to inject gas with low density into the production pipe so that the fluid mixture becomes lighter. By doing this, a higher production rate can be obtained. However, this also introduces high-pressure combustible gas into the annulus, which again constitutes a major safety risk. In relation to this, acoustic surveys can be used to either verify barrier integrity or reveal any potential weaknesses in the barriers. Since the operation is carried out from the surface, this reduces the overall risk since there is no need for well intervention. Additionally, the operation can be performed multiple times which allows for monitoring the current state of the well.

In this thesis, a mathematical explanation on pressure wave propagation is provided. When an acoustic survey is performed, a pressure pulse is introduced into the well by utilizing a differential pressure between the well and the chamber on the acoustic equipment which contains atmospheric pressure. The introduced pressure pulse will result in reflected waves whenever it reaches a discontinuity in form of a cross sectional area change or a sudden change in density between two media. These waves will then travel in the opposite direction and get recorded by the microphone on the surface. The dynamics of wave propagation causes the reflected waves to be either positive or negative in magnitude. The latter is exploited when analyzing the acoustic signal afterwards by looking in the well barrier schematic and link the corresponding reflections and elements together. The positive and negative pressure waves are referred to as upkicks and downkicks in this thesis. An upkick means a reflected wave propagating with a higher pressure than the ambient pressure whilst a downkick means a reflected pressure wave propagating with a lower pressure than the ambient pressure.

A frequency analysis is also performed on the acoustic signals from wells with an annular safety valve installed. A representation where the frequency domain is combined with the time domain is suggested and the method is used to analyze shots containing strong reflections. The active frequencies are linked together with the physical layout of the well and a thorough explanation is provided. The problem regarding resonance frequencies and strong harmonic multiples is also addressed and a proposal on how these can be attenuated is presented.

Furthermore, a small scale version of a gas lift well is designed and a detailed description on how this can be related to a real sized gas lift well is given. Different scenarios are investigated, and the goal is to address the challenges operators face on a daily basis. The results serves as a good overview on how different factors affect the acoustic signal and they can also help to get a better understanding on the acoustic principle.

Sammendrag

Gass løft er en kunstig løfte teknikk som blir brukt i sammenheng med reservoar som har utilstrekkelig trykk. Hovedideen bak gassløft teknikken er å injisere gass med lav tetthet inn i produksjonsrøret slik at den gjennomsnittlige tettheten reduseres. Ved å gjøre dette, er det mulig å oppnå en høyere produksjonsrate. En konsekvens av dette er derimot at ringrommet vil bli fylt med lettantennelig gass, noe som introduserer en stor risiko faktor. Akustiske målinger kan dermed bli brukt til enten å verifisere barriere integritet, eller å avsløre potensielle svakheter i barrieren. Siden selve operasjonen kan bli utført fra overflaten, vil dette redusere den samlede risikoen siden det ikke er nødvendig med brønn intervensjon. I tillegg kan operasjonen bli utført flere ganger, noe som også muligjør overvåking av den gjeldende tilstanden av brønnen.

I denne avhandlingen er en matematisk beskrivelse av trykkbølger gitt. Når en akustisk måling blir utført blir en trykk puls introdusert nedover i brønnen ved å utnytte et differensial trykk mellom brønnen og kammeret på det akustiske utstyret som har atmosfærisk trykk. Den introduserte pulsen vil resultere i reflekterte bølger som vil gå motsatt vei hver gang den treffer på en diskontinuitet i form av endring i tverrsnitt eller en plutselig endring i tettheten på transmisjons mediumet. Bølgene vil da gå oppover igjen og bli registrert av mikrofonen på overflaten. Bølge dynamikken fører imidlertidig til at de reflekterte bølgene enten kan være positive eller negative. Det sistnevnte blir utnyttet når det akustiske skuddet blir analysert ved å sammenligne de reflekterte bølgene med de faktiske elementene funnet i brønn barriere skjemaet. De positive og negative bølgene blir referert til som "upkicks" og "downkicks" i denne avhandlingen. Ved et "upkick" menes det en bølge som inneholder et høyere trykk enn det systemet har, imens ved et "downkick" menes det en bølge som har et lavere trykk enn det systemet har.

En frekvens analyse har også blitt gjort på signaler fra brønner som bla.a har en annulær sikkerhetsventil installert. En representasjon hvor både frekvens domenet og tids domenet blir kombinert blir foreslått og metoden blir brukt til å analysere skudd med sterke refleksjoner i. De aktive frekvensene blir linket opp mot det fysiske designet av brønnen og en grundig forklaring blir gitt. Problemet som angår resonans frekvenser og sterke harmoniske multipler blir også addressert og et forslag til hvordan disse kan bli dempet blir presentert. Videre ble også en små skala versjon av en gass løft brønn designet, og en detaljert forklaring på hvordan denne kan bli relatert til en gassløft brønn blir gitt. Forskjellige scenarioer blir undersøkt, og hovedmålet er å addressere de utfordringene som operatører møter på en daglig basis. Resultatene fungerer som en god oversikt over hvordan ulike faktorer påvirker det akustiske signalet og de kan også hjelpe til å forstå det akustiske prinsippet litt bedre.

Contents

Nomenclature

ADC	Analog to Digital Converter
ASCSSV	Annular Surface Controlled Sub Surface Valve
ASV	Annular safety valve
GLV	Gas Lift Valve
ID	Inner Diameter
ODE	Ordinary Differential Equation
PDE	Partial Differential Equation
PSD	Power Spectral Density
STFT	Short Time Fourier Transformation

Chapter 1

Introduction

The following chapter is based on my previous work on well integrity and gas leak valve testing. The work was carried out during my project assignment in the spring of 2013 at NTNU [1].

1.1 Motivation

Today, failure in downhole barriers such as completion, tubing, casing or cement is a growing problem in The North Sea. Along with ageing wells not only comes the challenges with maintaining well integrity, but also inadequate reservoir pressure develops with time. Without sufficient reservoir pressure, it's not possible to obtain the needed differential pressure in order to extract the oil. In fact, the average extraction rate worldwide lies between 20-30%. Needless to say, there's great potential when it comes to the extraction rate and vast amount of money to be made if this rate is increased. However, in some fields in The North Sea the extraction rate is as high as 60% which shows that it is possible to use new technology such as the gas lift technique in order to extract more oil from the existing fields.

However, when a well is running on gas lift the annulus now contains high pressurized gas instead of heavy fluid. This clearly increases the risk and sets strict requirements to the well integrity. Well integrity can in its simplest definition be defined as a condition of a well in operation that has full functionality and two qualified well barrier envelopes, [2]. Any deviation from this state, is either a minor or major well integrity issue. It's important that failures in the barriers are addressed at an early stage to reduce the risk to personnel, equipment and the environment. Unfortunately, there are many disasters caused by loss in well integrity. To illustrate the importance of well integrity, the gas leak on the Elgin platform can be used as an example. 238 workers were evacuated from the Elgin platform 25 march 2012, when a gas leak was discovered. The leak caused the operator Total to miss out on almost $ 130 million in income as well as high repair costs. Actually, it took Total almost a year to stop the leak and at the height of the incident, about 200 000 cubic meters of gas was escaping every day, [3]. Furthermore, it can take them up to 2 years to return to the output of the platform prior to the gas leak. Hence, it's rather safe to say that a loss in production is much more costly than to establish robust preventive routines to avoid such events. Besides a lower income, these events also have great impact on the environment. Especially in times where climatic changes are paid a lot more attention to, the oil and gas industry is under a lot of pressure from many environmental organizations.

The zero philosophy is a term the government in Norway introduced. The main thought behind this term is that accidents don't happen, they are caused by something. Therefore, every accident can be prevented so the ultimate goal is zero injuries and accidents. Some people say that this approach contributes to under-reporting of adverse events. Nevertheless, continuous monitoring of the well barriers is a crucial part when it comes to revealing potensial weaknesses in well integrity. Furthermore, by revealing potential dangers, one reduce the amount of risky practises performed by unwary workers.

1.2 The gas lift technique

The most common way to enhance the extraction rate of hydrocarbons is to introduce artifical lift into the well. The most economic and widely used one is the gas lift technique. Gas lift valves can be applied in both large oil reservoirs where oil extraction becomes more difficult with time, as well as smaller reservoirs with lower pressure. The gas lift technique is introduced to a well by injecting gas into the production pipe so that the fluid mixture becomes lighter. The injection of gas increases the total volume of the mixture, thereby reducing the overall average density. Whilst a reduced overall density will result in a lower pressure gradient, a larger volume will introduce a greater flow speed. Hence, as long as the volume expansion dominates the reduction of average density, a net pressure gradient will be obtained which again will result in a higher production rate.

The gas lift technique is dependent on an extra gas source from which lift-gas can be injected. The pressurized gas is then pumped into the annulus, close to the well head. Further, the pressure will cause the gas to flow downward the annulus all the way down to the gas lift valve. The gas lift valve is preferably located near the bottom, in order to have greater effect. The gas will then flow into the tubing and create an artificial lift.

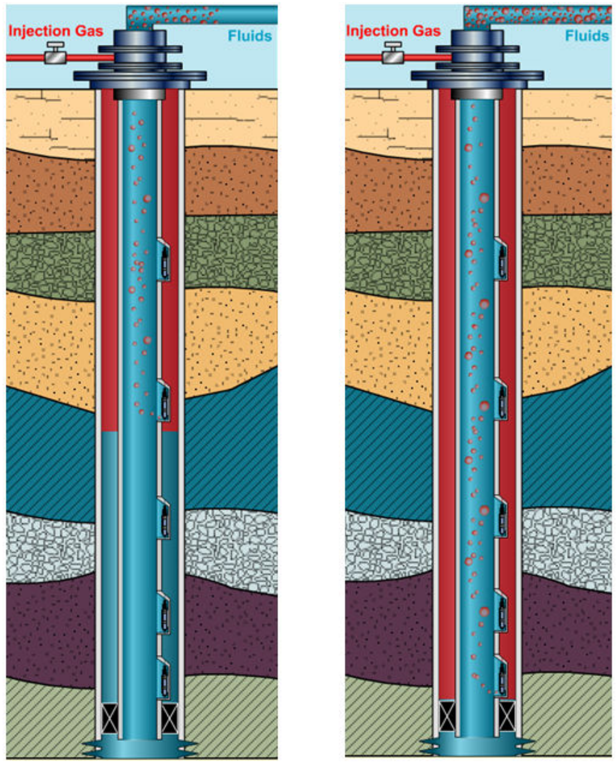


Figure 1.1: Gas lift principle with two different injection points

1.3 Acoustic logging

1.3.1 Monitoring integrity

When the gas lift technique is applied to an oil well, there are several changes to both the layout of the well as well as the well barriers. For instance, gas lift valves are installed with a wireline tool into a side pocket mandrel and according to NORSOK D-010, they are part of the primary barrier. This is because with gas in the annulus, the safety barrier that completion fluid otherwise provides, is lost. A proper functioning gas lift valve is a one-way valve which means that it allows gas to pass from the annulus through to the tubing, and at the same time, prevents oil from passing through to the annulus. The latter, is the very reason why acoustic logging is so important when it comes to monitoring the integrity of the well. If the valve is malfunctioning and hydrocarbons begin to flow into the annulus, an undesired accumulation of high-pressure combustible gas can be created and in a worst case scenario this can lead to a blowout. Therefore, maximum allowable leak rate for oil, gas and water are regulated by Norsok D-010 and API RP 14B, [4] [5]. An elaboration concerning standards and regulations can be found in [1].

The well barriers consist by definition of a number of elements which together comprise the different barrier envelopes. While these particular elements can be discussed, it's not possible to test them individually. Fortunately, this is not a major issue, as most investigations of accidents in the past, confirm that it's normally a long chain of events that lead to a blowout. This means that sufficient well integrity has to be seen as a whole, and not as a series of individual elements.

The traditional way of doing this was to bleed down the pressure, and then wait and measure a possible pressure buildup. Especially on wells with big volumes, reducing the pressure is very time costly. In addition, if a pressure buildup occurs, it's impossible to say where the problem is located. Acoustic logging on the other hand, is a big step toward optimising production uptime and minimise the time to verify system integrity. The principle behind this technique is that an acoustic gun is used to generate a single pressure pulse that propagates down the annulus in high speed. The pressure pulse is generated by utilizing a differential pressure between the well and a chamber in the gas gun. The generated wave propagates downward and will get reflected by either solids or liquids. The greater the change in diameter, the larger the amplitude of the reflected wave.

- A reduction in cross sectional area is seen as a downkick
- An increase in cross sectional area is seen as an upkick
- Fluid level gives a large kick and lets no energy through.

Summarized, this means that it is possible to analyze the well from the well head and all the way down to the gas lift valve, as depicted in figure 1.2. In other words, it enables the operator to pinpoint any possible weaknesses in the safety barriers.

Figure 1.2 illustrates a very interesting example from an acoustical point of view. The shots in the plot are those performed before bleed down and after pressure buildup. Indicated in black and red color, respectively. By looking at the shot before bleed down, we notice that there are two different downhole markers caused by side pocket mandrels at 1450 meters and 2550 meters. Additionally, the liquid level can be seen at about 3000 meters. Furthermore, we look at the shot performed after pressure build up and notice the same downhole marker as we saw in the first shot, located at 1450 meters. However, in this shot the strong reflection from the liquid level shows up at a depth of 2000m. What this means is that after the pressure was bled down, liquid started to flow through the leaky GLV in the lowest side pocket mandrel. The leak in this case was so big that the liquid level actually rose more than a kilometer up in the annulus. As a result, the liquid level moved past the whole second side pocket mandrel which is also the reason why it's impossible to see the corresponding response in this signal.

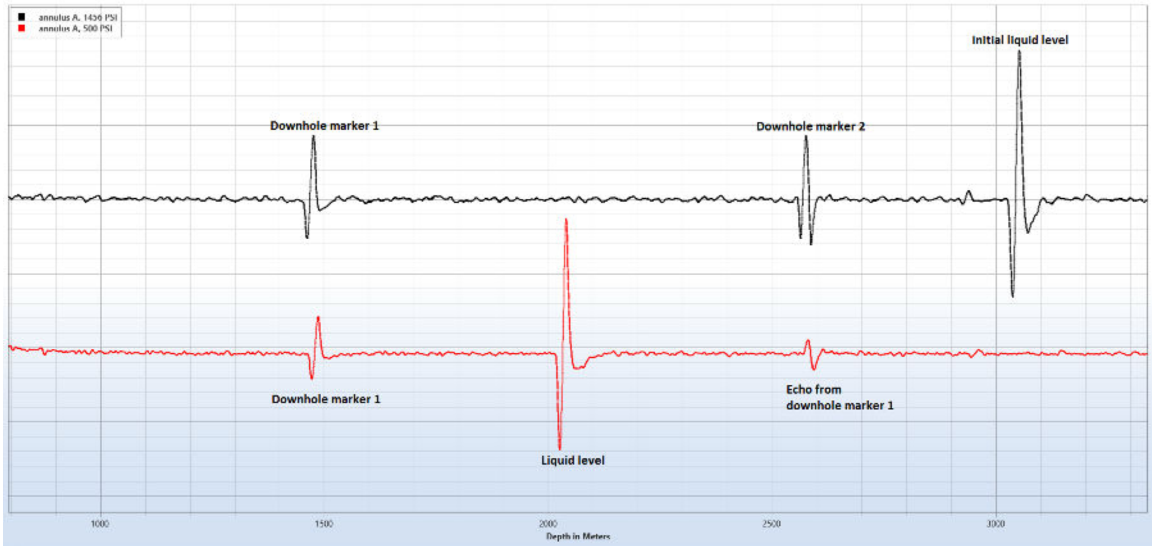


Figure 1.2: Example of an acoustic signal which also reveals a severe leak

1.3.2 Performance indication

Integrity verification is not the only application that acoustic logging can be used for. Knowing the actual liquid level depth, can also give the operating company a good indication of the well's performance. Figure 1.1 depicts two different scenarios that can be the case in a gas lift well. The subfigure to the right, shows a normal operating gas lift well which is lifting from the lowest GLV. Furthermore, gas injection through the lowest GLV is the most optimal depth to lift at in a gas lift well. The reason for this is that the higher pressure the gas is exposed to, the more it will be compressed. Hence, less lift gas is needed in order to produce at a certain rate. Unfortunately, lifting from the lowest GLV is not always the case in many gas lift wells. Even though the operator thinks they are lifting from the lowest GLV, they sometimes lift from a leaky dummy valve placed in a side pocket mandrel further up. Sometimes they even lift through a tubing leak without even realizing it. What the two latter scenarios have in common, is gas flowing into the tubing causing the pressure to drop in the annulus. As a consequence, the compressors on the surface may not be able to push the gas all the way down to the lowest GLV. The latter is depicted in the left subfigure, where the lift gas is being injected throgh a leaky valve in the second side pocket mandrel. This is obviously not optimal, since the gas will be less compressed due to a lower pressure. Usually, they therefore end up injecting an enormous amount of gas which barely improves the production rate at all.

Acoustic logging can therefore be used in order to locate the liquid level. If the liquid level is found to be much further up than what the operator thought, this can indicate that the well has some performance issues that should be dealt with.

1.4 Annular safety valve

Wells running on gas lift, has a large inventory of lift gas in annulus A. This high pressure gas constitues a rather large quantity of energy. An accidental release of this to the atmosphere followed by a subsequent ignition, could lead to disastrous consequences for both personnel and platform. Therefore, the NORSOK D-010 standard rev3, Section 7.3 - Completion activites, states that :

> "An ASCSSV should be installed in the completion string for all wells where the A-annulus is used for gas lift unless there is any other downhole device that is qualified as a well barrier in addition to what is found in the wellhead area".

The requirement for safety valves is that they shall be located at least 50 meters below the seafloor. Hence, ASV's are usually installed at 70-150 meters below and ensure that only a fraction of the gas in the annulus can escape. The valve is designed in such a way that hydraulics keep the valve open at all times, and if the hydraulic control of the ASV is lost, it will close immediately. However, there is always the chance that the ability to maintain the ASV open, is lost (e.g a leak in the operating piston). The latter is very important to find out as soon as possible, as the consequence of a closed ASV, is the impossibility to test both the annulus- and GLV integrity.

In figure 1.3, a simplified sketch of the ASV is shown. It's not very difficult to see that such a valve, will worsen the signal quality. In the previous section, it was mentioned that a reduction in cross sectional area was seen as a downkick in the acoustic graph. However, in this case the reduction in cross sectional area is so big that most of the energy from the pressure pulse gets reflected back up again. The second subplot in 1.4, shows the frequency spectrum of the signal in the first subplot. The multiple resonance peaks located at the lower frequencies is due to the ASV, and the power from these peaks are stronger than the rest of the signal. This is a major problem today when it comes to acoustic logging in offshore wells with big volumes and ASV's installed. Instead of getting upkicks and downkicks from elements located further down the well, the signal is dominated by strong echoes from the ASV.

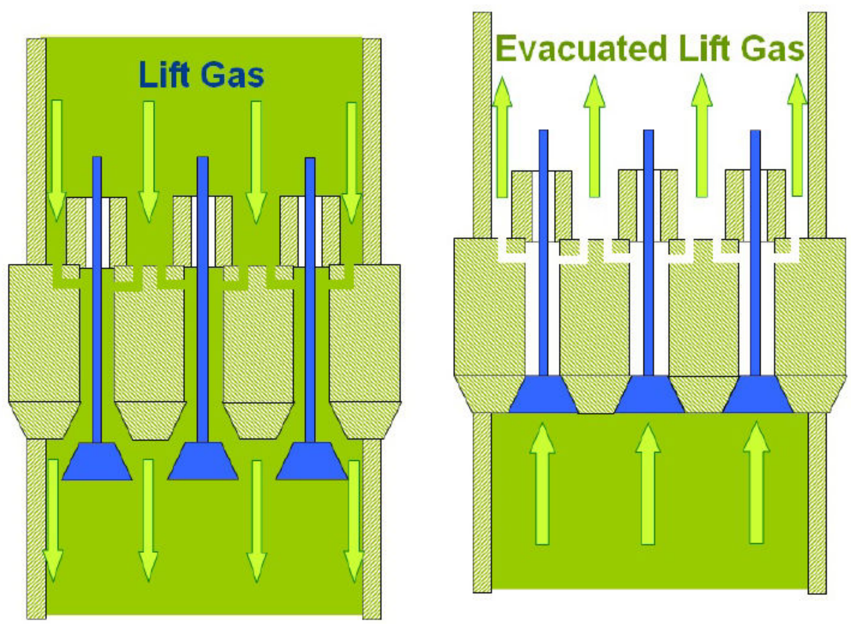


Figure 1.3: ASV in opened and closed position

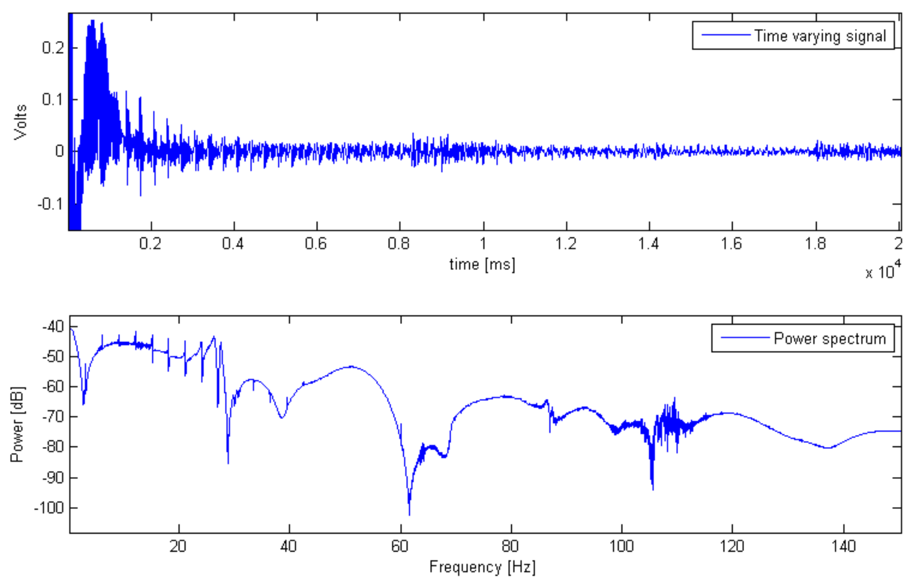


Figure 1.4: Acoustic logging from a well with ASV installed.

Chapter 2

Mathematical modeling of wave dynamics

2.1 Differential pressure and displacement

The main principle behind acoustic logging is the fact that a differential pressure released into a tube will produce a pressure pulse propagating downhole causing reflections whenever it reaches a discontinuity. In [6], an explanation of the correlation between pressure and displacement is given, and a derivation based on Newton's laws are provided. In order to better understand what happens when the shooting valve on the acoustic gun is released, an adapted description along with the equations in [6] will be given:

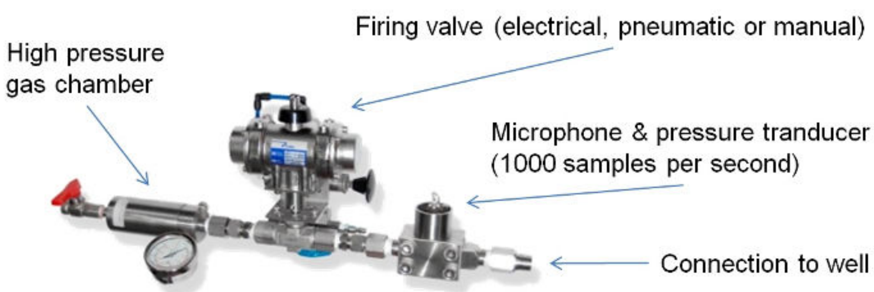


Figure 2.1: Acoustic gas gun

In figure 2.1, a picture of the acoustic gas gun is presented. Before we go into greater detail, we notice the gas chamber, firing valve and the connection to the well. This is where the differential pressure occurs whenever there exists a pressure exceeding the atmospheric pressure in the connection to the well. To describe the relationship between the parameters, the following mathematical formula can be used:

$$F = (p_1 - p_2)A \tag{2.1}$$

Normally when an implosion shot is to be fired, we have $p_1 = p_{chamber} = p_{atm}$, $p_2 = p_{well}$ and A is the area of the surface on contact.

Furthermore, Newton's second law is applied to get another expression for the force F:

$$F = ma \tag{2.2}$$

Figure 2.2 depicts a discretisized model, where dx represents a small displacement in our system.

Let y describe an average displacement of the element. Consequently, the acceleration can be described as the second derivative with respect to time:

$$a = \frac{\partial^2 y}{\partial t^2} \tag{2.3}$$

Now, let $x_2 = x_1 + dx$ describe the length of our element. The mass m, in equation 2.2 is then given by:

$$m = \rho V = \rho A(x_2 - x_1) \tag{2.4}$$

As a result, we now have two expressions describing the force F:

$$(p_1 - p_2)A = \rho A(x_2 - x_1)\frac{\partial^2 y}{\partial t^2} \tag{2.5}$$

Equation 2.5 can then be rearranged to cancel A and reverse the order of p_1 and p_2:

$$\frac{p_2 - p_1}{x_2 - x_1} = -\rho\frac{\partial^2 y}{\partial t^2} \tag{2.6}$$

By looking at small distances in the latter equation as $x_2 - x_1 \to 0$, this gives us the relationship between the differential pressure and acceleration:

$$\frac{\partial p}{\partial x} = -\rho\frac{\partial^2 y}{\partial t^2} \tag{2.7}$$

Hence, at the instant when the firing valve is turned, the pressure in the well will exert a force to the left into the chamber. An acceleration will occur and thus, the pulse will propagate downhole.

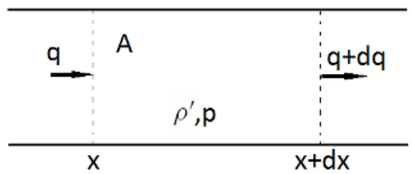


Figure 2.2: Volume element for hydraulic transmission line.

2.2 Transmission line model

The dynamics of transmission lines are important in several applications such as electrical lines for signal transmission, systems with hydraulic drives or gas and oil pipelines. To understand the dynamic properties in these systems, a comprehensive theory of transmission line dynamics can be used to mathematically describe the dynamic properties in i.e acoustic waves propagating in a tube. The transmission medium is a material substance such as solid, liquid or gas that can propagate energy waves. When it comes to wells running on gas lift, natural gas is the transmission medium and the energy waves are pressure pulses propagating both down- and upstream. Sound is by definition a mechanical wave that is an oscillation of pressure transmitted through some medium, this means that the absence of a transport medium as in vacuum makes it impossible to perform acoustic measurements.

2.3 PDE Model

A partial differential equation (PDE) is an equation that can be used to describe many phenomena such as sound, heat, fluid or flow. In contrast to ordinary differential equations (ODEs) which deals with functions of a single variable and its derivatives, PDEs involve functions and their partial derivatives. This makes it possible to model multidimensional systems.

As just stated, a hydraulic transmission line is a pipe consisting of a transmission medium which makes it possible for energy waves to propagate. Section 4.5 in [7] contains a thourough explanation on hydraulic transmission lines and is also the basis for the following PDE model.

The pipe is of length L and has a cross section of area A, and the length coordinate along the pipe is denoted x. The pressure of the medium is $p(x,t)$, the volumetric flow is $q(x,t)$, the density is $\rho(x,t)$,and the bulk modulus is β. These parameters are depicted in figure 2.2.

The following model is found from mass balance and the momentum balance (4.5.2 in [7]).

The model for a hydraulic transmission line can be written as the partial differential equations:

$$\frac{\partial p(x,t)}{\partial t} = -cZ_0 \frac{\partial q(x,t)}{\partial x} \tag{2.8}$$

$$\frac{\partial q(x,t)}{\partial t} = -\frac{c}{Z_0}\frac{\partial p(x,t)}{\partial x} - \frac{F[q(x,t)]}{\rho_0} \tag{2.9}$$

where the friction $F = F(q)$ is a function of the volumetric flow q. The acoustic velocity c and the line impedance Z_0 are defined by:

$$c = \sqrt{\frac{\beta}{\rho_0}},\ Z_0 = \frac{\rho_0 c}{A} = \frac{\sqrt{\rho_0 \beta}}{A} \tag{2.10}$$

Since we are more interested in the dynamics of the pressure pulses and how they behave in discontinous sections , we ignore the friction term in equation 2.9. Hence, $F = 0$ and the transmission line model becomes:

$$\frac{\partial p(x,t)}{\partial t} = -cZ_0 \frac{\partial q(x,t)}{\partial x} \tag{2.11}$$

$$\frac{\partial q(x,t)}{\partial t} = -\frac{c}{Z_0}\frac{\partial p(x,t)}{\partial x} \tag{2.12}$$

Without any further elaboration on Laplace transformation, we can use this transformation on equation 2.11 and 2.12 and represent the transmission line model as:

$$\frac{\partial q(x,s)}{\partial x} = -\frac{Ts}{LZ_0} p(x,s) \tag{2.13}$$

$$\frac{\partial p(x,s)}{\partial x} = -\frac{Z_0 \Gamma(s)^2}{LTs} q(x,s) \tag{2.14}$$

where $T = L/c$ is the propagation time, $\Gamma(s)$ is the wave propagation operator and Z_0 is the line impedance.

Furthermore, equation 2.13 and 2.14 can be combined so the Laplace transformed model can be written as a wave equation in pressure or flow as given by the two equations:

$$L^2 \frac{\partial^2 p(x,s)}{\partial x^2} - \Gamma(s)^2 p(x,s) = 0 \tag{2.15}$$

$$L^2 \frac{\partial^2 q(x,s)}{\partial x^2} - \Gamma(s)^2 q(x,s) = 0 \tag{2.16}$$

The wave equation is an important second-order linear PDE for the description of waves such as sound waves. Solutions for this equation are only valid inside a specified region, and initial conditions are necessary to describe the value and velocity for the wave as well as boundary conditions for solutions representing the waves.

Without further explanation, the transmission line can be modeled with the wave variables

$$a(x,s) = p(x,s) + Z_c(s)q(x,s) \tag{2.17}$$

$$b(x,s) = p(x,s) - Z_c(s)q(x,s) \tag{2.18}$$

Since we have assumed a frictionless model, the solutions for the wave variables are given by:

$$\Gamma = Ts,\ Z_c = Z_0 = \frac{\rho_0 c}{A}$$

$$a(x,s) = e^{\frac{-x}{L}Ts}a(0,s) \tag{2.19}$$

$$b(x,s) = e^{-\frac{L-x}{L}Ts}b(L,s) \tag{2.20}$$

It's important not to confuse the latter two equations with some sort of exponential functions, as this is how delay is represented in the Laplace domain. Actually, a describes a wave moving in the positive x direction from distance $x = 0$ and b describes a wave moving in the negative x direction at distance $x = L$.

Furthermore, the boundary conditions for the wave variables are given by

$$a(0,s) = a_1(s) \tag{2.21}$$

$$b(L,s) = G_L(s)a(L,s) \tag{2.22}$$

where

$$G_L(s) = \frac{Z_L(s) - Z_c}{Z_L(s) + Z_c} \tag{2.23}$$

The unit for both $Z_L(s)$ and Z_c in 2.23 is mass flow rate per unit area, so $G_L(s)$ would represent the dimensionless reflection coefficient.

2.4 Reflection of waves

When either a positive or negative pressure pulse propagates in a pipe and reaches a closed end, the wave will get reflected back in phase. This particular scenario is the simplest case and the most intuitive for people to understand. However, there are several different scenarios when it comes to how a wave behaves when it encounters different conditions. This can be an increase or decrease in cross sectional area or the boundary between two media which differs in density. For most people, the dynamics for wave propagation can be confusing because it doesn't necessarily reflect dynamics that people are used to on a daily basis. The example in [8], illustrates this pretty well.

> "If we walk down a corridor and out of an open door at the end, we do not experience a force sending us back in the other direction upside-down."

The fact that a positive acoustic pressure pulse can be reflected as either a negative- or positive pressure pulse, shows that the meaning of the word reflection, not necessarily involves what most people might associate with this word.

2.4.1 Acoustic impedance

Acoustic impedance is a term that is used in order to understand what happens when an acoustic wave reaches either a change in cross sectional area or a change in density between two media. Actually, there are two kinds of acoustic impedance and they differ slightly in how they are defined. First off, we have the specific acoustic impedance z. It characterizes the relationship between the acting sound pressure and the resulting particle velocity, thus a characterization of the medium itself, [9]. To put it differently, the specific acoustic impedance z, is the opposition of a medium to wave propagation. Mathematically, this is expressed as the ratio of sound pressure p to particle velocity u:

$$z = \frac{p}{u} \tag{2.24}$$

The specific acoustic impedance z, is a physical property that does not depend on the amount of substance for which it is measured. This can be confirmed by looking at equation 2.24, which only consists of pressure and velocity.

Secondly, the acoustic impedance with symbol Z is defined as the ratio of acoustic pressure p to acoustic volume flow U.

In [10], a one dimensional wave passing through an aperture with area A is considered. Furthermore, volume flow U is defined as the volume passing per second through the aperture. Hence, if the flow moves a distance $dy = u\,dt$, the volume passing through is $A\,dy$, so:

$$U = \frac{dV}{dt} = A\frac{dy}{dt} = Au \tag{2.25}$$

The acoustic impedance Z is the ratio of sound pressure to volume flow, so in the one dimensional case, we get the following relationship:

$$Z = \frac{p}{U} = \frac{p}{Au} = \frac{z}{A} \tag{2.26}$$

where z is the specific acoustic impedance. In contrary to the specific acoustic impedance, Z is dependent on the area A.

The two latter equations in section 2.2 are worth noticing. $G_L(s)$ is the transfer function which defines the relationship between the incident wave and the reflected wave. In the time domain, this particular equation defines the reflection coefficient at a discontinuity. In other words, it tells how much of the original wave that gets reflected in the opposite direction. Besides providing information about both the incident wave and the reflected wave, it also indirectly describes how much of the wave that continues to propagate.

2.4.2 Discontinuities

2.4.2.1 Change in cross sectional area

When an acoustic survey is to be carried out in an offshore well, the gas lift injection is stopped and the conditions are more or less stationary. By looking at smaller sections of the well, we can disregard the effect increasing temperature has on the acoustic velocty. Thus, the pressure and acoustic velocity will remain the same throughout this section. An interesting case to look at, will therefore be a section that contains a discontinuity. There exists several discontinuities in a well, and they originate from different casing sizes, sidepocket mandrels and gas-liquid interfaces. The common denominator for these, is a sudden change in cross section. Even though the gas-liquid interface has a big change in density rather than cross section, the sudden change from low- to high density will act as an infinite decrease in cross sectional area. Figure 2.3 contains an illustration of a discontinuity. As just stated, when we look at small section around the discontinuity, we can neglect other factors such as increasing temperature hydrostatic pressure.

In the previous section acoustic impedance was elaborated on, and an equation was presented. Thus, by looking at equation 2.26, one can see that the acoustic impedance will change whenever a sudden change in cross sectional area occurs. In order to illustrate the dynamics being active, the equations in section 2.3 in [11] is going to be used together with figure 2.3 which illustrates the discontinous joint. There are two different relations which are used as the basis. To begin with, we have that the pressure immediately to the left of the discontinous joint, is equal to the pressure immediately to the right of the discontinuous joint. In other words, the sum of the wave variables given in equation 2.19 and 2.20 are the same for both sides. Hence, if the variables $c(x, s)$ and $d(x, s)$ describes the waves in the second section, we have the following relationship:

$$p(x,s) = a(x,s) + b(x,s) = c(x,s) + d(x,s) \tag{2.27}$$

Hereby, these variables are denoted as a, b, c and d. Since the only wave in the second section is the transmitted wave c, this means that there is no reflected wave in this section, which results in $d = 0$. We end up with the following expression:

$$a + b = c \tag{2.28}$$

Furthermore, we have the same volume velocity on each side of the change in cross section. By using equation 2.26 we get the following expression for the volume flow:

$$U_1 = \frac{a-b}{Z_{1L}} \tag{2.29}$$

$$U_2 = \frac{c-d}{Z_{2L}} \tag{2.30}$$

By plugging in the line impedance $Z_{1L} = \frac{\rho_0 c_0}{A_1}$, $Z_{2L} = \frac{\rho_0 c_0}{A_2}$ from 2.10 into the equation $U_1 = U_2$, we get:

$$\frac{A_1(a-b)}{\rho_0 c_0} = \frac{A_2(c-d)}{\rho_0 c_0} \tag{2.31}$$

We cancel $\rho_0 c_0$ from the equation and recall that $d = 0$ and $c = a + b$ to obtain the following expression:

$$A_1(a-b) = A_2(a+b) \tag{2.32}$$

This can be rewritten as:

$$a(A_1 - A_2) = b(A_1 + A_2) \tag{2.33}$$

By dividing this expression with A_2 and rearranging the variables, we arrive with the final expression for the reflection coefficient $\frac{b}{a}$:

$$R = \frac{\frac{A_1}{A_2} - 1}{\frac{A_1}{A_2} + 1} \tag{2.34}$$

In fact, the expression for the reflection coefficient, is in the exact same form as the transfer function in equation 2.23. As this transfer function describes the relationship between the incident and the reflected wave, we see that the change in impedance is fully dependent upon the ratio of the two cross sections. From equation 2.22, we see that the bigger change in cross section, the bigger the reflection coefficent will become and the bigger the amplitude of the reflected wave. Another interesting property to notice, is that the reflection coefficient will never go beyond the interval $[-1,1]$. This makes sense, as the amount of

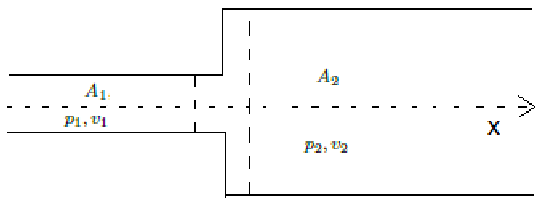


Figure 2.3: Discontinuity in a well where A_1, p_1, v_1 and A_2, p_2, v_2 are cross sectional area, pressure and velocity in first and second section, respectively.

energy in the incident wave defines the upper and lower limit of the reflected wave.

The same way we eliminated the transmitted wave c, it is possible to eliminate the reflected wave b in order to obtain the transmission coefficient:

$$T = \frac{2\frac{A_1}{A_2}}{\frac{A_1}{A_2} + 1} \tag{2.35}$$

The relationship between the two latter equations is defined by the following expression:

$$R + T = 1 \tag{2.36}$$

In other words, the energy from the incident wave that is not reflected at a discontinuity continues to propagate downhole.

Further, three key values of equation 2.34 will be looked closer into.

Firstly, we can consider the case where $A_2 \gg A_1$. This corresponds to a long pipe with an open end. Hence, $lim\ \frac{A_1}{A_2} \rightarrow 0$ as $A_2 \rightarrow \infty$ and the we get:

$$R = \frac{0 - 1}{0 + 1} = -1 \tag{2.37}$$

To put it differently, whenever a wave encounters an increase in cross sectional area, we get a reflected wave which is inverted as compared to the incident wave. For illustrating purposes, equation 2.22 will be repeated:

$$b(L, s) = G_L(s)a(L, s)$$

In the latter example $G_L(s)$ will take the value -1, and the reflected wave $b(L, s)$ will be inverted.

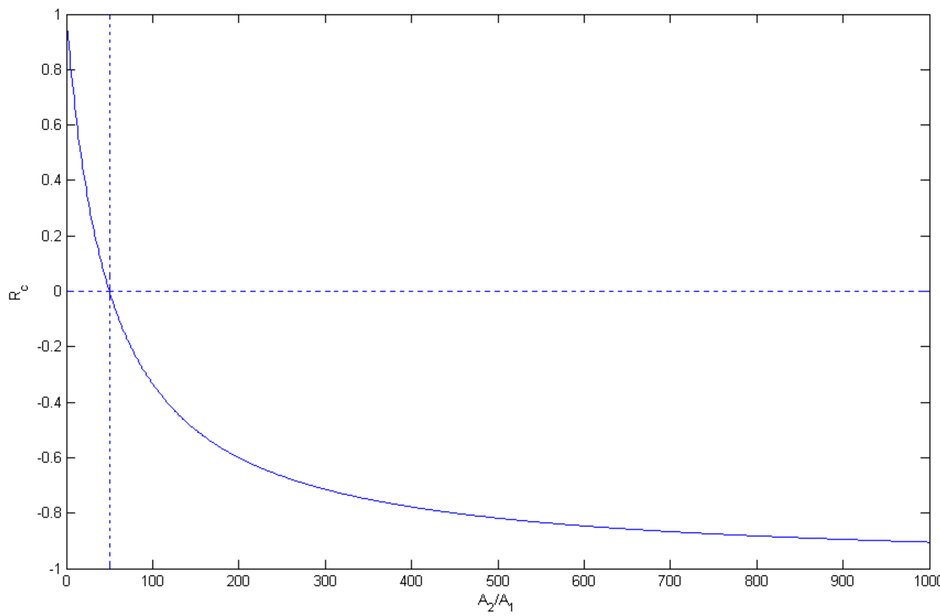


Figure 2.4: Relationship between cross sectional ratio and reflection coefficient

Secondly, we have the case whenever the pulse encounters a decrease in cross sectional area. This is the case whenever the pulse reaches the liquid level. Since the liquid level has such a higher density as compared to the gas, this can be modeled as an infinite decrease in cross sectional area.

What this means is that $A_1 \gg A_2$, and $lim \frac{A_1}{A_2} \rightarrow \infty$ as $A_2 \rightarrow 0$.

$$R = \frac{\infty - 1}{\infty + 1} \approx 1 \tag{2.38}$$

Thus, the reflection coefficient will take the value 1, and the reflected pulse will be in phase as compared to the incident wave.

Lastly, we concider the case when there are no changes in cross sectional area. In this case $A_1 = A_2$ and $\frac{A_1}{A_2}$=1. By looking at the reflection coefficient, the numerator will take the value 0 resulting in $R = 0$, which implies no change in impedance and no reflected wave.

$$R = \frac{1 - 1}{1 + 1} = 0 \tag{2.39}$$

Figure 2.4 shows the reflection coefficient with respect to the ratio of A_1 and A_2, as seen in figure 2.3. The start of the x axis corresponds to the case where $A_2 \rightarrow 0$, i.e the liquid level. Further, A_2 increases along the x axis, while A_1

remains fixed. The intersection between the dashed horizontal- and vertical line is the point where $A_1 = A_2$. In this case we see that the reflection coefficient equals 0, as stated earlier. Another interesting case will be when $A_2 = 2A_1$ or $A_2 = \frac{1}{2}A_1$. Without any further analysis, it would seem that we would lose 50% of the original signal in the reflection. However, by investigating the graph in figure 2.4 more closely, it tells us that by either doubling or halving the cross section, only $\frac{1}{3}$ of the transmitted signal will be "lost" in the reflection. The latter tells us that the amount of energy in the reflected wave, is not proportional to the change in cross sectional area.

2.4.2.2 Change in density

Up to this point, different parts of an acoustic survey have been covered. A mathematical description on both how the propagating pulse is introduced to the system and how discontinuities in cross section causes different kind of reflected waves have been provided. The last scenario is then what happens when the pressure pulse reaches the liquid level. The discontinuity in this case, is not the change in cross section but rather a big change in density. This is depicted in figure 2.5. In order to understand what happens at the discontinuity, we recall the equation for the line impedance:

$$Z_L = \rho_0 c_0 \tag{2.40}$$

The full derivation is given in section 4.4.1 in [12], but only the final solution will be given here. Actually, the derivation is more or less similiar to what is presented in section 2.4.2.1 up until equation 2.31. The equation will be on the same form, but the variables will take different values. Immediate to the left of the liquid level we have the variables ρ_1, c_1 and immediate to the right we have ρ_2, c_2. When it comes to the area, this will remain the same and we get $A_1 = A_2 = A$. This gives us the following:

$$\frac{A(a-b)}{\rho_1 c_1} = \frac{A(c-d)}{\rho_2 c_2} \tag{2.41}$$

The same conditions apply for the wave variables in this equation as for equation 2.31, but instead of cancelling the impedance, we cancel the area A.

We get:

$$\frac{a-b}{\rho_1 c_1} = \frac{a+b}{\rho_2 c_2} \tag{2.42}$$

This can be rewritten as

$$\rho_2 c_2 (a-b) = \rho_1 c_1 (a+b) \tag{2.43}$$

We then separate the wave variables

$$(\rho_2 c_2 - \rho_1 c_1)a = (\rho_2 c_2 + \rho_1 c_1)b \tag{2.44}$$

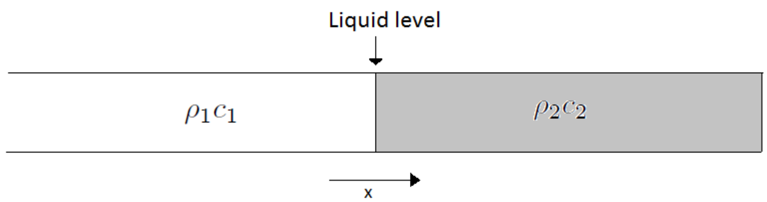


Figure 2.5: Sudden change in density

Now it is possible to solve for the reflection coefficient, which is the ratio between the reflected wave b and the incident wave a:

$$R = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1} \tag{2.45}$$

The transmission coefficient is obtained similarly:

$$T = \frac{2\rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1} \tag{2.46}$$

When looking at both the reflection and transmission coefficient, we notice that they are expressed in the exact same form as presented in the latter section. The only difference is that the reflection coefficient in equation 2.34 describes the reflections caused by change in cross sectional area and equation 2.45 describes the reflection as the acoustic pulse hits the interface between two media. In a gas lift well, the liquid level in both the annulus and tubing is the gas-liquid interface. The density and velocity in the gas will in this case be much lower than the density and velocity of the liquid. Thus, $\rho_1 c_1 \ll \rho_2 c_2$ will result in $R \to 1$ and $T \to 0$. This explains why the reflection from the liquid level is the most powerful reflection throughout a shot and why it's always in phase with the incident wave.

2.4.3 Specific acoustic impedance

In equation 2.15 and 2.16, it was proven that a solution of the transmission line model could be described as a wave equation. Furthermore, d'Alembert's formula is a general solution to the one-dimensional wave equation

In this equation the first and second term represents waves travelling in positive and negative x-direction. Further, c represents the wave velocity or phase velocity.

$$p(x) = a(x + ct) + b(x - ct) \tag{2.47}$$

In this equation the first and second term represents waves travelling in positive and negative x-direction. Further, c represents the wave velocity or phase velocity.

We let $k = \frac{\omega}{c}$, where k is the wave number and ω is the angular frequency. The latter expression is then solved with respect to the variable ω and then plugged into equation 2.47 to get the following expression for the particle displacement:

$$y = Asin(kx - \omega t) \tag{2.48}$$

where A is the amplitude, k is the wave number and $\omega = 2\pi f$ is the angular frequency.

From [6], we also have that $p(x) = -\kappa \frac{\partial y}{\partial x}$ where κ is the adiabatic bulk modulus.

We now have the equation for the displacement, and we notice that the pressure and the velocity is the differentiation of the displacement with respect to distance and time, respectively.

This gives us:

$$p(x,t) = -\kappa Akcos(kx - \omega t) \tag{2.49}$$

$$u(x,t) = \frac{\partial y}{\partial t} = -\omega Acos(kx - \omega t) \tag{2.50}$$

We now recall the expression for the the specific acoustic impedance to obtain the final expression:

$$z = \frac{p}{u} = \frac{\kappa k}{\omega} \tag{2.51}$$

The latter equation has an interesting property which is worth noticing. When the frequency increases, the impedance will decrease exponentially. In other words, low frequencies will produce the highest impedance and higher frequencies will produce less impedance. This matches very well with the results obtained in section 5.5 and 5.6 in [1]. In [1], it was seen that the amplitude carrying frequencies for the liquid level response and downhole marker response, was the very lower ones.

2.4.4 Interference of pressure waves

One of the great benefits with acoustic surveys, is the possibility to perform a leak test on a well without actual interfering with it. The acoustic gun is installed on the wellhead, with the microphone as a part of the assembly. Hence, by introducing pressure pulses downhole, the microphone can record everything from the surface. However, whenever there is only a single recording device

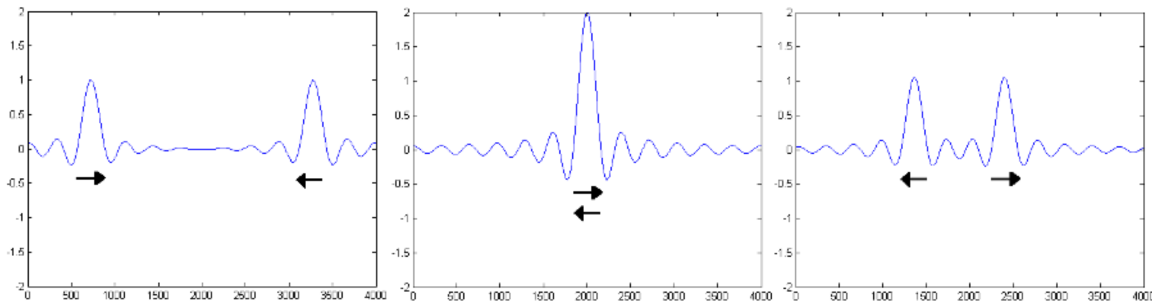


Figure 2.6: Constructive interference illustrated with sinc functions

on top, there are some unfortunate conditions that can occur downhole. These conditions can make it very difficult for the operator to analyze the data afterwards. Therefore, we will have a closer look at two scenarios that can occur when there are several pressure pulses propagating in a well.

2.4.4.1 Constructive interference

Pressure pulses propagating in gas, can intersect without affecting each other. This particular property is very powerful as it makes it possible to get good acoustic data from elements of interest, despite echoes and noise present downhole in the system. Figure 2.6 depicts a scenario where two pressure pulses travelling in opposite directions intersect. The arrows beneath the pulses indicate the direction of propagation. In this case, we have two upkicks, which means that the two pulses are in phase. Thus, when they intersect the result is a superposition of the two waves with a total amplitude equal to the sum of the two. However, a consequence of this is that reflections can be camouflaged in other reflected waves. This scenario can occur whenever a reflected wave reaches an element at the exact same moment as an echo pulse propagates downward. The echo will then produce a reflection wave which propagates upward in phase with the other wave. The two waves will then appear as one single wave and it can be very difficult for the operator to see.

2.4.4.2 Destructive interference

Another scenario that can occur is destructive interference which is depicted in figure 2.7. Destructive interference can occur whenever a reflected wave propagates upward, and reaches a valve like the ASV at the exact same moment as an echo pulse propagate downwards. If the two waves travelling upward are out of phase, the amplitude of the two waves will cancel each other, which will result in a big decrease in amplitude. Hence, if two waves with opposite

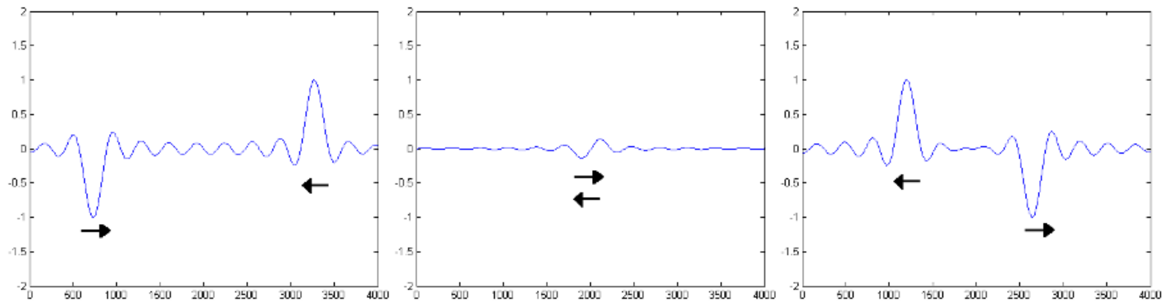


Figure 2.7: Destructive interference illustrated with sinc functions

magnitude cancel each other, it will be impossible for the operator to see on the surface.

Chapter 3

Signal interpretation

In [13], pressure pulse technology is elaborated on, and different applications for this technique are discussed. However, this technique has many similarities to an acoustic approach since both are based on propagating pressure pulses. Utilizing transient pressure pulses are an efficient way to monitor oil wells, either it's on-demand measurements on liquid level or long-term monitoring of well integrity since a lot of information can be obtained by analyzing the pressure profile versus time/depth. With high-quality pressure transducers and computer-based data acquisition systems, it has become possible to record the data contained in rapid pressure transients. In other words, because of the high sampling rate it is possible to see the reflected pressure transients caused by irregularities and physical discontinuities downhole in the well.

However, the quality of the data received on the surface varies a lot depending whether the well has a safety valve installed close to the surface or not. In [1], the Ekofisk M-25 well was used as an example. The data from this well is very difficult to interpret as it has a very large volume in combination with a shallow annular safety valve. The result is then a graph which is very difficult to understand when it is presented with respect to time. When this is the case, it may be more meaningful to view it with respect to frequency.

3.1 Fourier transformation

The Fourier transformation is widely used within many fields in signal processing, and the technique can be applied for all time varying signals. Very briefly, the time and frequency domains are alternative ways of representing a signal, and the Fourier transform is the mathematical relationship between these two representations. Throughout this thesis, only an explanation on how this technique can be used in order to improve the acoustic interpretation will be given. The interested reader will be referred to [14] where a full derivation of the transformation is given, along with detailed descriptions of its properties.

When the acoustic signal is recorded, the analog to digital converter listens to the continuous signal and discretize the signal at a specified sample rate. As for the ADC converter on the acoustic gun, this has a sample rate of 1000 samples per second. Furthermore, this corresponds to a frequency range from 1Hz to 500Hz. The frequencies contained in a digital signal describes the dynamics of the signal in the time domain. Morover, the signal in the frequency domain gets written as the sum of simple waves where the amplitude for these waves are calculated. Consequently, a higher sampling rate enables the possibility to capture faster dynamics in the signal, so that the discretized signal will be more similar to the real continuous signal. Similar as the ADC has an anti aliasing filter which prevents distorting of the signal due to frequencies above 500Hz, we will also have to filter the signal in order to remove unwanted parts of the signal.

In [1], it was described how it is possible to calculate a power spectral density in order to see which frequencies are active in a signal. This can be useful when a cutoff frequency is to be chosen for filtering purposes. Figure 1.4, shows an example of a signal and its corresponding PSD. A higher amplitude shows that there are active dynamics in the time varying signal with this particular frequency. However, since this is a PSD for the whole signal, it doesn't tell us exactly when this takes place. This is helpful to some extent, but it would be more helpful if it was possible to relate the frequency changes in the signal to the time domain.

3.2 Short time Fourier transformation

The short time fourier transformation, hereby abbreviated STFT, is a fourier related transform used to determine the sinusoidal frequency and phase content of local sections of a signal as it changes over time, [15]. A full derivation of this, can be found in chapter 7 in [16]. Digitally sampled data in the time domain, is broken into chunks of data which usually overlaps. The function to be transformed, which in our case is the acoustic signal, is multiplied by a window function which is non-zero for only a short period of time. This particular window function can vary in both type and length so that it can be optimised for different applications. However, by varying the width of the window, we get a tradeoff between time resolution and frequency resolution, [16]. What this means is that a wide window size will give great frequency resolution but poor time resolution, whilst a narrow window will give poor frequency resolution but a good time resolution. For this very reason, it is important to choose a window function that will give you good resolution for the parameters you are most interested in. Furthermore, when an appropriate window has been chosen, the acoustic signal is fourier transformed to calculate the magnitude of the frequency spectrum for each chunk. This principle is depicted in figure 3.1.

Here one can see an example of a time varying signal and a window function denoted by blue and red color, respectively. The non-zero part of the window function, will then define the part of the data that will be fourier transformed.

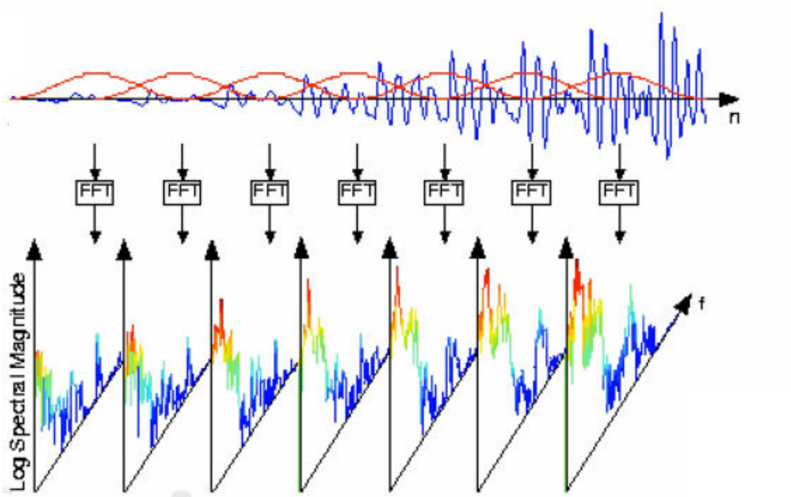


Figure 3.1: STFT principle

The resulting PSD for that time span will then correspond to a vertical line in the image. These lines define a measurement of magnitude versus frequency for a specific moment in time. The spectrums are then laid side by side to form a image, or a three dimensional surface. This is a three-dimensional plot of the energy in the frequency content as it changes over time. In this format the x axis represents time, the y axis is frequency and the z axis is the intensity of each point in the image which again represent the amplitude of a particular frequency at a particular time, [15]. The intensity on the z axis is directly correlated with the amplitude of the frequencies within that band and the colorbar shows the relationship. Furthermore, the intensity is measured in decibel, and the relationship between the color and decibel is given by the colorbar next to the plot. Decibel (dB) is a logarithmic unit which makes it possible to conveniently represent very large, or small numbers. The unit is used to express the ratio between two values of a physical quantity. Anyhow, it can be very difficult for people to understand the logarithmic scale and it's easy to underestimate the actual change in power. A rule of thumb is that a change in voltage ratio by a factor of two is approximately a 6dB change. Similarly, a change in voltage by a factor of 10 is equivalent to 20dB change. The latter should help to understand not only the range of the colorbar, but also the sensitivity for this representation.

The plot in figure 3.2, shows both the time varying signal and its corresponding spectrogram representation. To calculate this, the spectrogram function in Matlab was used. The spectrogram is the result after applying STFT to a time varying signal, as depicted in figure 3.1. Since we now have both the time- and frequency domain in the same plot, it is easier to understand what happens when we filter the acoustic signal. In fact, this representation can help to make sure that we choose an appropriate cutoff frequency in our filter. By looking at the spectrogram in 3.2, we first notice the big turquoise area with an approximate power of $-120dB$. This is the high frequent noise in the signal and no useful information is found in this part of the signal. Furthermore, we recall from the previous chapter that it was the lowest frequencies that produced the highest impedance. The area with dark red color located around 12 and 15 seconds in the lowest frequency band, indicates the side pocket mandrel and the liquid level in the Ekofisk A-02 well.

Figure 3.3 depicts the same acoustic shot, just from a different angle. From this angle it is clearer to see the amplitude carrying frequencies in the signal. The fact that both the response from the side pocket mandrel and the liquid level is found in the very lower frequency band tells us that the majority of the frequencies carry no information at all.

3.3 Resonance frequency

In order to be able to perform an acoustic survey, the acoustic gun has to be attached to the well somehow. Unfortunately, it's not possible to install it at the place that best suit your needs. Most often, the gun is attached to the well through either a manifold or a hose. The length and the actual setup varies from well to well. A consequence of this is that there will be a very big change in cross section at the point between the section where the gun is attached and the annulus. With this in mind, we recall the section on discontinuities in the previous chapter. There it was shown that we would get a reflected wave whenever a change in cross sectional area occured. The transition between the connection hose and the actual annulus A is such a discontinuity. The cross sectional area is much bigger in the annulus compared to the connection, so this will act as an open end. Furthermore, the shooting valve will act as a closed end since it's turned 180 degrees (closed - open - closed) when the acoustic shot is fired. Hence, when the tube is excited with a pressure pulse, this will be reflected back and forth with its own natural frequency. This particular frequency is called the resonant frequency and the system will oscillate with greater amplitude here than at other frequencies. The reason why the amplitude is stronger at this frequency, is because the open end causes a 180 degrees phase change in the reflected wave. The latter will produce constructive interference between the incident- and the reflected wave as described in section 2.4.4.1. Furthermore, the constructive interference will produce standing waves inside the tube. In other words, the waves will superposition and create standing waves with a higher amplitude. The standing wave behaviour is depicted in figure 3.4. The reconance frequency which is also called the fundamental frequency, can be seen in figure 3.3 at approximately $70Hz$. Additionally, one can see more of these lines with greater amplitude higher up in the frequency band. Those frequencies are called the harmonics of the fundamental frequency, and are an integer multiple of the fundamental frequency.

In order to compute the resonant frequencies, we will use the equation for wavelength and apply this to our case.

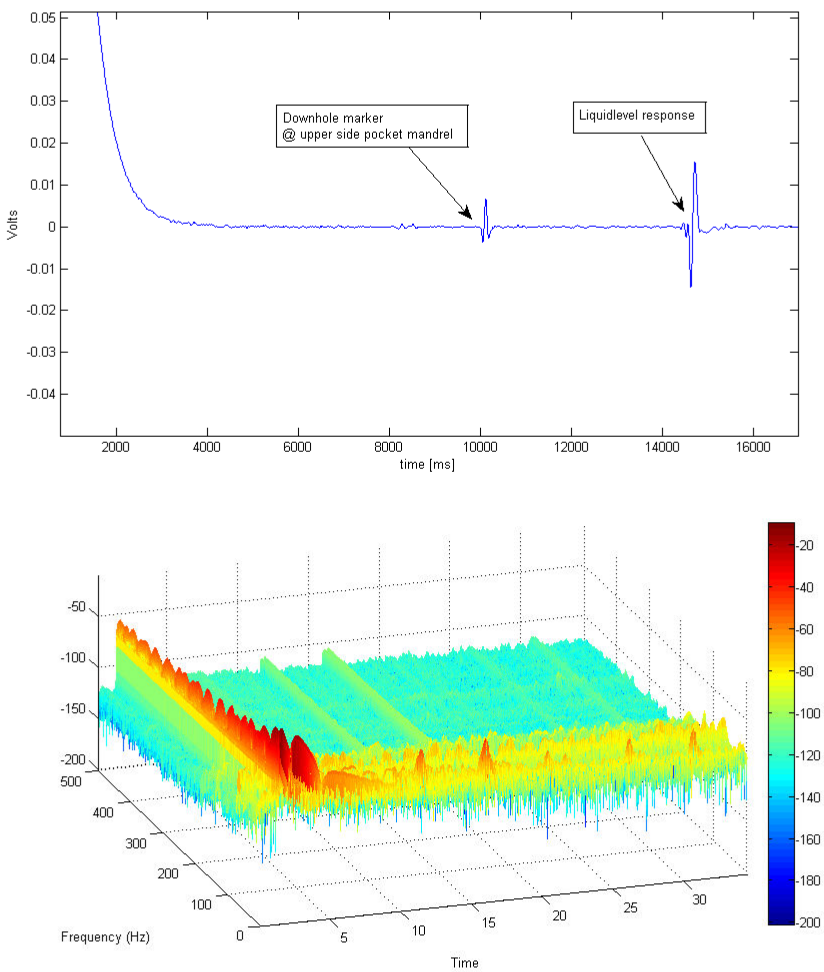


Figure 3.2: Time varying signal and Spectrogram representation of Ekofisk A-02 well

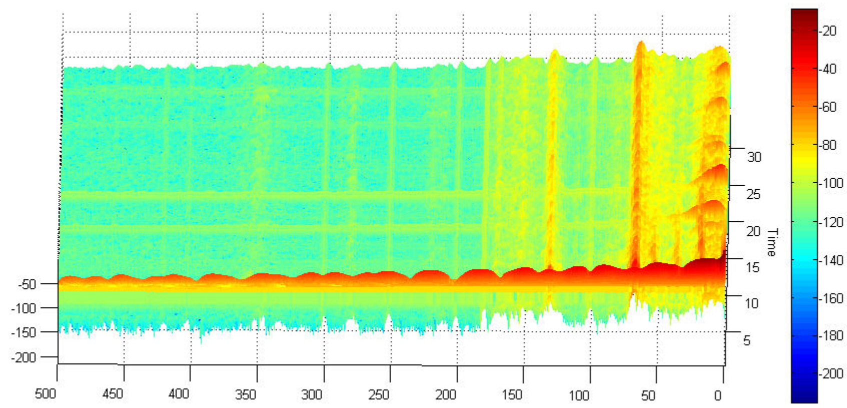
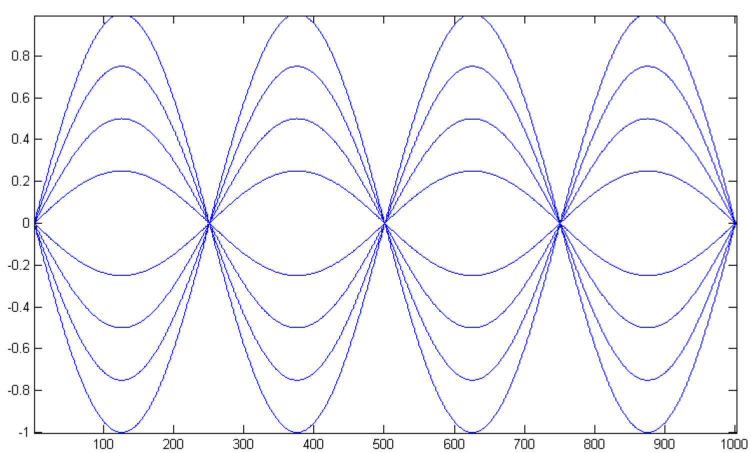


Figure 3.3: Illustration of pressure waves in the frequency band



impedance

Figure 3.4: Standing waves

Firstly, we have the relationship between wavelength, acoustic velocity and frequency:

$$\lambda = \frac{v}{f} \tag{3.1}$$

Secondly, we solve this equation with respect to the frequency and plug in for the wavelength λ.

In a closed system, the first resonance frequency has the wavelength $2L$, where L is the length of the pipe. However, since our system has an open end, this produces a reflection with 180 degrees phase change so the wavelength becomes $4L$.

This gives us the following:

$$f_{resonance} = \frac{(2n-1)v}{4L} \tag{3.2}$$

where n is the resonance number, v is the acoustic velocity and L is the tube length.

If we use some default values together with the fundamental frequency in figure 3.3, we get the following:

$$L = \frac{350m/s}{4 \cdot 70Hz} \approx 1.25m$$

This estimated length matches very well with the reality. Usually, the equipment is connected to a hose or a manifold, with an approximately distance of 1 meter to the annulus.

It's now possible to use the estimated length L, and compute some harmonic frequencies.

$$f_1 = 70Hz$$

$$f_2 = 140Hz$$

By looking at figure 3.3, one can see that these frequencies matches pretty good with those in the spectrogram. Similarly, one can see more of these lines in the frequency band. The reason for the other resonant frequencies could be several connections in the manifold each with its own natural frequency. Even though the resonance frequencies are high compared to the amplitude carrying frequencies from the elements downhole, equation 3.2 shows some interesting properties. Namely, the resonant frequencies will vary with both the acoustic velocity and the tube length. This can be verified by looking at different shots in different wells. However, the section which has one open end will be more sensitive to changes in tube length than those with two closed ends because of the phase change in the reflection. Since we want the resonant frequency not to interfere with the amplitude carrying frequencies, the connection length should therefore be as short as possible.

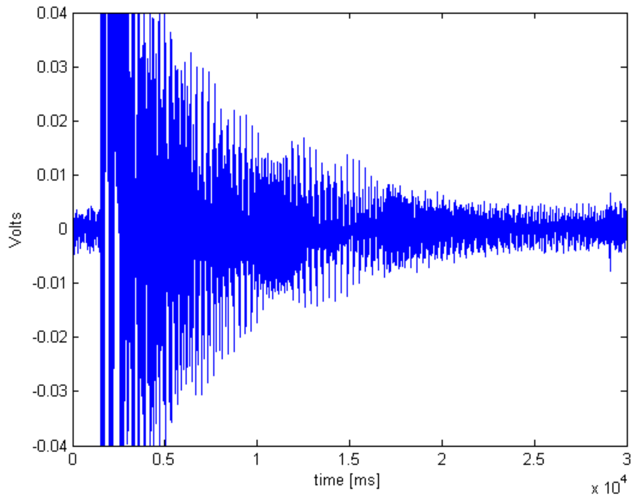


Figure 3.5: Acoustic signal from the Ekofisk M-25 well with a shallow ASV

3.4 Reflections and echoes

A shallow ASV in the annulus, assures a lot of reflections and echoes in the upper part of the well. Since strong repeating echoes are considered as noise, this worsens the signal to noise ratio. Hence, by looking at the signal afterwards, it's not too straightforward to understand what happened to the initial pulse. What started off as a single pressure pulse resulted in a messy signal with no distinct peaks. An interesting question would therefore be what actually happens from the microphone's point of view. As seen in section 2.4.4, pressure pulses move freely past each other so there will be a lot of activity for the analog to digital converter. One also need to take into acount that if the signal is to be filtered, it needs to be transformed into the frequency domain. Since all of the dynamics in the signal will be presented as a combination of different frequencies, the cutoff frequency for the filter being used will decide how much of the total information that will be attenuated. A great challenge in many cases will therefore be how to choose a reasonable cutoff frequency, and still be able to see the reflections from the elements downhole.

3.4.1 Case I: Ekofisk M-25

A good example to illustrate the challenges just mentioned, would be any acoustic survey from the Ekofisk M-25 well. The well barrier schematic for this well can be found in appendix A. This particular well has an ASV located at 350ft combined with a big annulus volume. A larger cross section in the annulus together with the same opening in the ASV, means that a smaller part of the

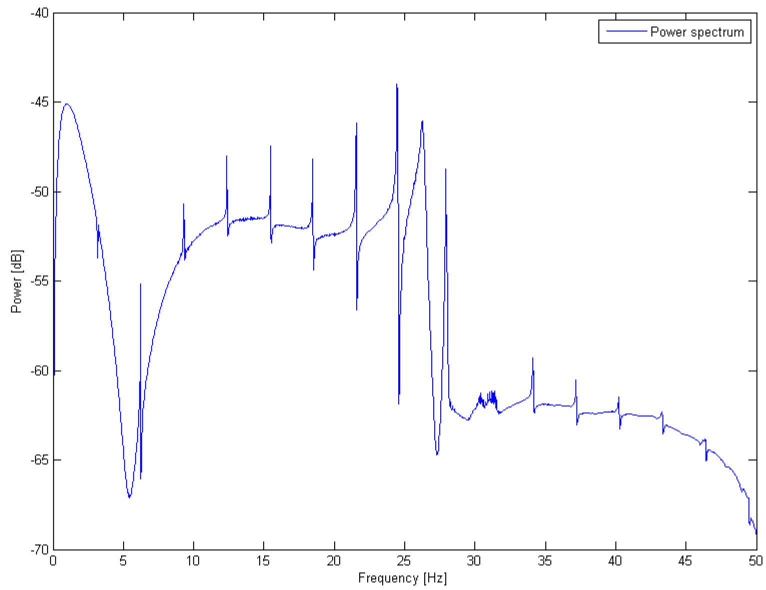


Figure 3.6: PSD representation of the signal in figure 3.5

signal will get past the safety valve. When the power of the transmitted signal is poor, it is preferable that there is as little activity in the upper part of the well as possible. Unfortunately, figure 3.5 proves otherwise. In this situation, care must be taken when filtering the signal, since it's not too clear what we are looking at. In order to analyze this a bit closer, the signal will be transformed into the frequency domain. The resulting PSD can be seen in figure 3.6.

Suddenly the confusing signal in figure 3.5, is organized in an orderly manner in terms of frequency. The dynamics in the signal is much more clearer and it is now possible to understand what is going on. We notice that all of the peaks in this case, has a fixed length between them. In other words, these are the harmonics of the fundamental frequency caused by the strong reflection from the ASV. To put it the same way as in the latter section, these are an integer multiple of the lowest resonance frequency. By taking into account that the ASV is located only $350ft$ from the surface, this also explains why these harmonics are so strong compared to the rest of the signal. This is clearly a challenge in regards to be able to distinguish the actual signal from the resonance frequency.

Furthermore, the spectrogram in figure 3.7 depicts both the strong harmonics in the lower frequency band, and the higher resonance frequencies caused by the small section between the annulus and the acoustic gun. Obviously, we would want to attenuate the lower resonance frequencies in order to increase the signal to noise ratio. After all, the amplitude carrying frequencies from the elements

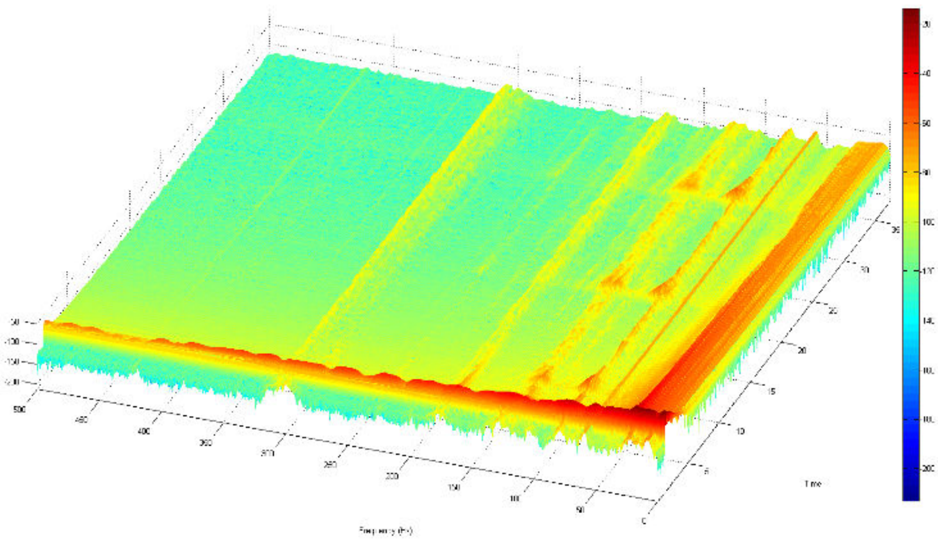


Figure 3.7: Spectrogram representation of the Ekofisk M-25 signal.

downhole, are located in the lower part of the frequency band.

3.4.2 Case II: Ekofisk X-19

Another example will be used in order to show that it is actually possible to get a good shot even though there is an ASV located in the well. The well being used in this example is the Ekofisk X-19. The well barrier schematic for this well, can be found in appendix B. This particular well has an ASV installed at $700ft$ which means that the ASV is located at twice the depth as compared to the M-25 well. Consequently, the corresponding resonant frequency caused by the ASV should be half the value when comparing the two PSD's in figure 3.6 and 3.9. Even though it can be difficult to locate the first natural frequency in the PSD, it's possible to tell from the harmonic components that the expectation actually is correct. Also in this PSD there is a fixed length between the harmonics, which means that they are an integer multiple of the fundamental frequency. However, the fact that they are much closer to each other verifies that the initial resonant frequency is lower in this signal. By looking at the PSD's a bit more closely, one can see that this signal has approximately 10 harmonics within a 10Hz range, whereas the M-25 signal has approximately 5 harmonics within the same range. The latter confirms that all of the peaks in the PSD's are caused by resonant frequencies in the upper part of the well. Furthermore, one can see the strong resonant frequency at approximately 55Hz due to the first section where the gun is attached.

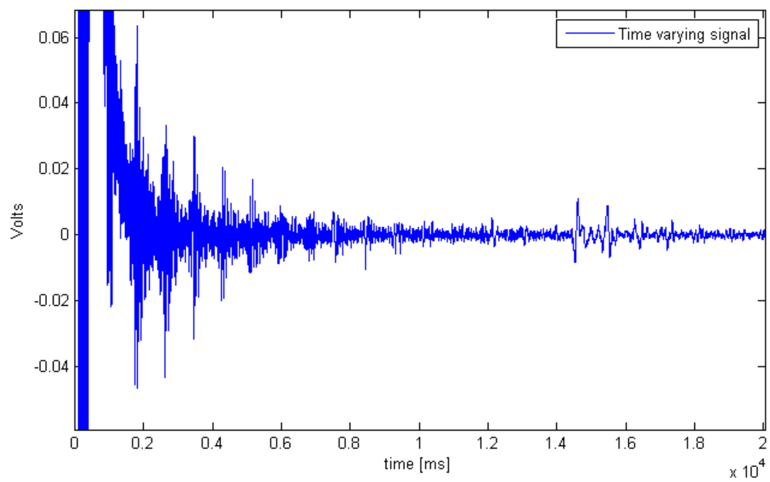


Figure 3.8: Acoustic signal from the Ekofisk X-19

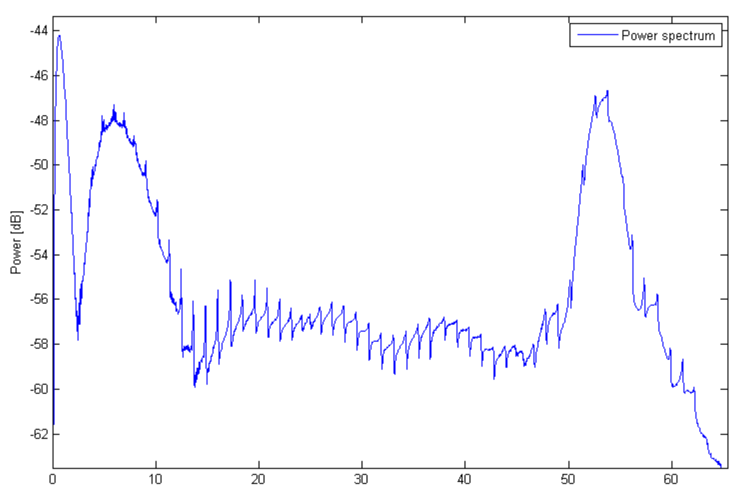


Figure 3.9: PSD representation of X-19

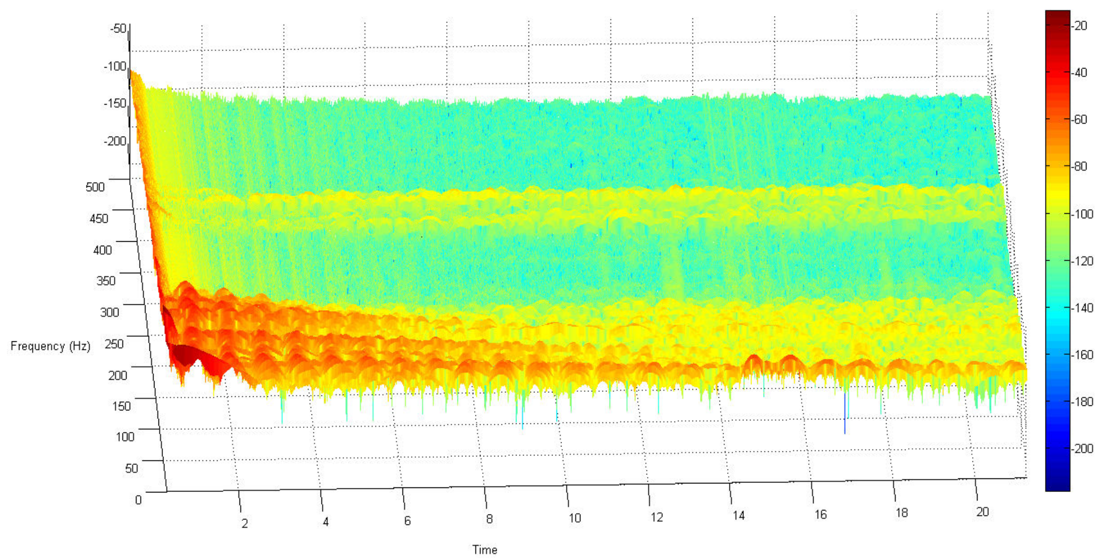


Figure 3.10: Spectrogram representation Ekofisk X-19 well.

The spectrogram representation of the X-19 shot, clearly shows the response from the liquid level after around 15 seconds. Furthermore, it is visible in both the frequency and time domain despite the fact that there still are ASV echoes present in the signal.

3.5 Harmonics

When acquiring the acoustic signal offshore, the data collected is in a continuous format. Since continuous signals can't be directly represented in digital computers, it needs to be transformed into a digital format by the use of an analog to digital converter. The result is then a digitalized signal consisting of a finite number of equally spaced samples. Since we now have a signal of finite length, it is possible to apply Fourier analysis on the signal. The motivation for the Fourier transform comes from the study of Fourier series, where complicated periodic functions in the time domain can be written as the sum of simple sine and cosine waves.

Chapter 11 in [14] states that if a signal is periodic with frequency f, the only frequencies composing the signal are integer multiples of f, i.e, f, $2f$, $3f$, $4f$, etc. These frequencies are called harmonic frequencies where the first frequency f is called the fundamental frequency. Thus, if we have a perfectly periodic signal with no noise present, this will only consist of the fundamental frequency f. However, if the periodic signal gets distorted in any way, the frequency domain of the signal will be composed by the fundamental frequency plus harmonics. In fact, any continuous periodic signal can be represented as a summation of harmonics. Furthermore, the harmonics can be of any amplitude, depending on the shape of the periodic signal, but usually they become smaller as they increase in frequency.

The latter is directly related to our acoustic approach. In the acoustic signal case, the strong reflection from the ASV will correspond to the fundamental frequency. Furthermore, the initial pressure pulse introduced to the well is not a perfect periodic signal. In addition, the section above the ASV will affect the shape of the pulse even more. Hence, the result seen from the microphone and thus the analog to digital converter will be a distorted periodic signal. This explains all the peaks seen in figure 3.6 and 3.9

3.6 Comparison of the two cases

The biggest difference between the two spectrograms is the fact that the magnitude of the resonant frequencies decay a lot faster in the X-19 well compared to the those in the M-25 well. This makes it possible to see both the downhole markers and the liquid level. To put it differently, the amplitude from the liquid level is greater than the amplitude of the ASV echoes in that neighborhood. Hence, the signal acquired from the X-19 well, has a better signal to noise ratio. It is however possible to catch a glimpse of the response which most likely is caused by the liquid level in the M-25 signal too. This response can be seen as the yellow line along the frequency axis after approximately 18 seconds. In view of the strong harmonics from the ASV, this response seems a lot weaker than the response from the other well. However, the reason why the liquid level response looks that much weaker, is due to the fact that the resonance frequencies remain strong throughout the whole signal. As a result, the signal to noise ratio is very poor in this signal. Nevertheless, reflections from the elements in the Ekofisk M-25 well, will be weaker than those from Ekofisk X-19 due to the larger cross section in the annulus. The reason for this is that the larger the cross section, the lower the acoustic impedance that opposes its motion will be.

The two examples just elaborated on, shows the importance of understanding what you are looking at when you analyze an acoustic signal. Some wells has an ASV installed, and as we just have seen, this has great impact on the frequency content in the signal. For this very reason, digital filters must be used with great care. The lowpass filter is the most common filter to use when a signal is to be filtered. As for the X-19 well, a lowpass filter is a good choice in order to emphasize the response from the elements of interest while at the same time, attenuate the high frequent noise. However, by using a lowpass filter on the M-25 well, we will attenuate everything except the harmonic frequencies. Thus, all we are looking at is the resonance frequencies which completely dominate everything in this frequency band. The lowpassed signals from these two cases will therefore serve as a very good example on how different the outcomes can be after a signal is filtered with the same lowpass filter. It also shows very well the relationship between how much of the signal that gets reflected and how

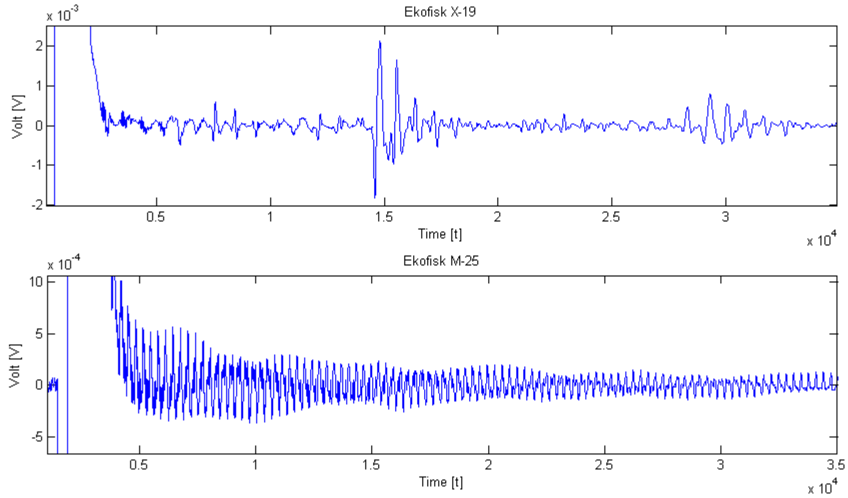


Figure 3.11: Comparison between the two lowpassed signals.

this affects the power of the harmonic frequncies.

3.7 Attenuation of the resonance frequencies

3.7.1 Check valve as part of gun assembly

Figure 3.11 shows two different outcomes for the acquired data in gas lifted wells with an ASV installed. Both signals contain resonant frequencies, but the harmonics in the first signal are much weaker. This makes it possible to distinguish between the echoes and the actual signal that we are interested in. As for the M-25 case, since the ASV is located so close to the surface, this generates strong reflections with sharp edges. The sharper the edge, the higher frequency is needed in order to represent it. This is the very reason why the amplitude of the harmonics is higher in the M-25 signal.

Therefore, attenuation of the ASV echoes will yield in a better signal to noise ratio. One way to accomplish this would be to install a check valve (one-way valve) in the gas gun assembly. By adding a check valve between the shooting valve and the microphone, strong echoes originating from a shallow ASV would be absorbed into the chamber. In this way, when the pressure pulse propagates down to the ASV, some part of the signal will continue and a lot of it would reflect back up to the surface and get recorded by the microphone. Anyhow, since we now have introduced a check valve into our gas gun assembly, some of the reflected pressure pulse will be absorbed by the one way valve instead of being reflected back down again. Thus, by removing energy from the system, this could reduce the power of the strong harmonic frequencies which again would increase the signal to noise ratio.

Chapter 4

Experimental testing

As mentioned in the previous chapter, an acoustic survey is carried out from the surface. There is no well intervention involved in the process and everything is recorded by the microphone placed on the acoustic gas gun. Hence, when a signal is received, this can either be good or bad depending on the current conditions. If the signal is of good quality, reflections from elements in the well will easily be distinguished and they will match good with the well barrier schematic. On the other hand, if the signal is of poor quality, it can be difficult to locate the different reflections. It might be caused by wider reflections with smaller amplitude, dominating repeating echoes with high amplitude or it could be a weak signal corrupted by noise. Consequently, it will be very difficult to analyze the current state of the well. In addition, if the initial quality of the collected data is poor, it won't help to process the data afterwards through various filter techniques.

With this in mind, the only way to acquire better data is to optimise the way the acoustic survey is carried out. What this means is that the execution of a leak investigation needs to be adapted accordingly to the current conditions. In order to improve the data quality in the surveys, it's also necessary to understand what might worsen it as well. This can vary from well to well depending on the layout of the well. Unfortunately, there are no procedures as of today that defines how an acoustic survey should be carried out for wells with different properties. Besides the fact that it is very costly in terms of money to shut down a well, there are also many uncertainties present in the system. The latter factors shows that an offshore installation is not a suitable place to perform acoustic testing.

Length	Number of hoses	Inner diameter
$100m$	2	1/2”
$20m$	4	1/2”
$10m$	1	1”

Table 4.1: Hoses used in experiment

4.1 Small scale version

Nevertheless, in order to acquire better data as well as interpreting it better, better and more customized procedures are needed. However, in the process of improving the procedures, better knowledge on how different factors influence the acoustic shot is needed. Therefore, one needs to get rid of all the sources of uncertainties, and try to reproduce the acoustic surveys which is carried out offshore. A small scale version of this will enable us to test many different cases in a controlled environment. Furthermore, the acoustic data will be more detailed and accurate as the system is noise free. Another very important fact to remember is that when acoustic surveys are carried out in order to verify system integrity, unknown hidden weaknesses in the barriers can be revealed. Hence, it is possible to stop them before they develop into a safety hazard. From the operator's point of view, more exposure of abnormal events can help them identifying potential risks as they show up in the acoustic data. After all, people are good at what they are exposed to on a daily basis, but it is also very important that they know what to look for in order to detect weaknesses as early as possible.

In order to perform small scale testing, it is necessary to put together components that reflect the behaviour of an offshore well. Throughout this chapter, a description of the small scale version and the different testing scenarios will be presented.

4.1.1 Casing

One of the things that make acoustics so powerful, is the possibility to depict all the components inside a well on a graph, without the use of wireline. Due to the high acoustic velocity, the casing will need to be long enough so that reflections don't intersect with each other. Usually, the offshore wells are several thousand meters deep, so this is never a problem. In the small scale version on the other hand, we need to make sure that the length of the “casing” is long enough so that it is possible to distinguish the different reflections. Therefore, a variety of rubber hoses with significant length was used in order to simulate the casing.

Figure 4.1, shows an example where two 100m hoses are installed on a reel. These hoses represent the transmission line described in chapter 2 and act as the tube where the pressure pulses propagate back and forth.

Figure 4.1: Hoses representing the casing in the offshore well

4.1.2 Annulus pressure

A well running on gas lift, has a large inventory of gas lift in the casing. Whenever the wells are producing, the annulus contains high pressurized gas. Furthermore, when a well is to be leak tested, the annulus is bled down to approximately half of the pressure in the tubing. Therefore, it is the pressure in the tubing that ultimately decides how much it is necessary to decrease the pressure in the annulus. The reservoir pressure has a direct impact on the tubing pressure, so different wells will have different conditions. A consequence of this, is that the operator will have to perform leak testing and adapt to both high pressure, and low pressure. As seen in chapter 2, the pressure has a direct impact on the reflected waves, so for testing purposes, we will need to be able to regulate the pressure in our small scale version. To do this, nitrogen bottles was used together to increase the pressure in the hoses. Furthermore, a regulator was applied in order to control the pressure to the desired level. The setup for this can be seen in figure 4.2. The nitrogen bottle is attached at the end of the hose, making it possible to inject nitrogen into the hoses to increase the pressure. The nitrogen will then represent the transmission medium described in chapter 2.

4.1.3 Liquid level

During normal operation the lift gas will flow from the injection point on the surface, down the annulus and then through the GLV. Oil, water and other fluids will therefore stabilize below the GLV forming the gas-liquid interface. When the pressure in the annulus is bled down the new differential pressure will try to move liquid and gas from the tubing to the annulus. The gas-liquid interface will then either move upwards or remain at the same level depending

Figure 4.2: Nitrogen tank and a regulator, used to inject gas and regulate the pressure in the hoses.

on whether the GLV is leaking or not. In an acoustic graph, the liquid level can be seen as the reflection with the biggest amplitude, since the whole pulse will get reflected due to the big change in density between the gas and the liquid. In order to simulate the liquid level in the smale scale version, a valve was installed at the end of the hose. Hence, when the valve is closed, this would resemble the case when $A_2 \rightarrow 0$, meaning that the entire wave will get reflected. The setup for this can be seen in figure 4.3. Next to the liquid level valve, a pressure gauge was installed. The only purpose for this was to fine tune the pressure in the hoses.

4.1.4 Annular safety valve

The annular safety valve and its importance is described in the introduction of this thesis. This particular valve plays a significant role when it comes to the overall safety on the platform. For this very reason this is something that just need to be dealt with, despite the fact that it makes the acoustic interpretation a lot harder. The echoes that arises when the incident wave reaches the ASV, is also one of the reasons why it was decided to create a small scale version in the first place. The main thought was to introduce something into the system that would create strong reflections. In this relation, two different kind of restrictions were introduced. Firstly, a needle valve was installed between the hoses. By doing this, it was possible to vary the restriction and see the influence it had

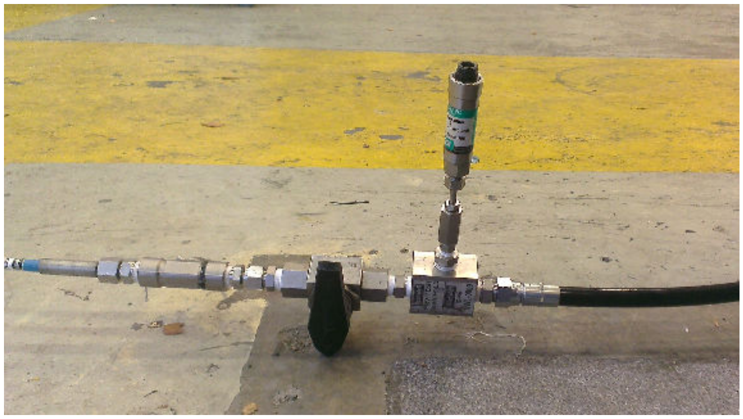


Figure 4.3: Ball valve acting as the liquid level

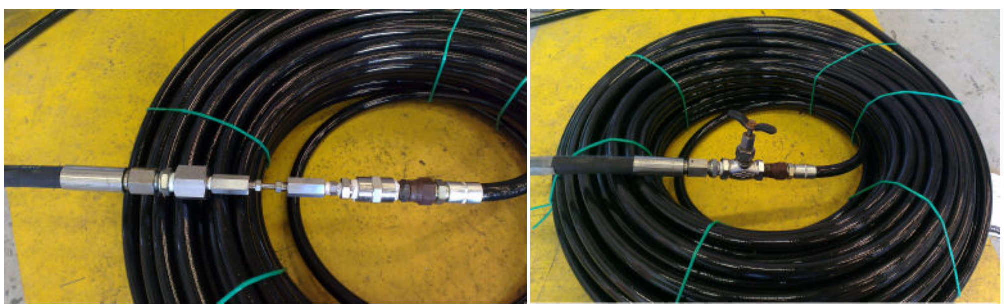


Figure 4.4: Small tubing and needle valve acting as ASV

on the result. In light of chapter two, this would equal to a fixed A_1 whilst A_2 would vary from 0 all the way up to $A_2 = A_1$. Secondly, a very small tubing piece was put between the hoses. The size of the tubing was chosen so that the ratio between the hose and the tubing, would resemble the ratio between the opening in the ASV and the casing in an offshore well. The needle valve and the tubing are depicted in figure 4.4

4.1.5 Downhole markers

A commonly used method in order to calculate the acoustic velocity is to use a downhole marker located at a known depth. Normally, these downhole markers take form as a side pocket mandrel and is characterized as a temporarily change in cross section. Since the exact depth can be found in the well schematic and the elapsed time is known, it is straightforward to compute the velocity. As for the small scale version, the connections between the hoses could be used as downhole markers. The connection has a slightly bigger area enough to result in a small upkick. However, since the experiments are carried out in a controlled

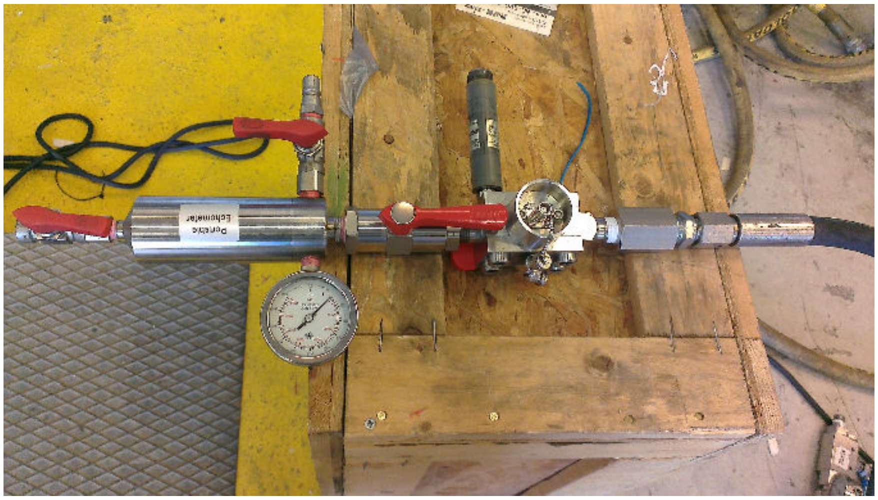


Figure 4.5: Acoustic gun

environment, it is possible to use the liquid level as a downhole marker. After all, this is the reflection with the biggest amplitude, and it is then possible to use the connections between the hoses to verify that the acoustic velocity is correct.

4.1.6 Acoustic gun

The acoustic gun is attached on top of the hoses, similar to how it is connected to a well. Figure 4.5 shows the acoustic gun and how it's connected to the hose. When an acoustic shot is performed, the hose is pressurized whereas the chamber will have atmospheric pressure. At this time, the shooting valve will be closed. Hence, by quickly turning the shooting valve, the differential pressure will cause the pressure pulse to accelerate and propagate downhole. It can also be noticed that the microphone is placed on the downhole side of the shooting valve. Hence, it will record all the reflections throughout the shot regardless of the position of the shooting valve.

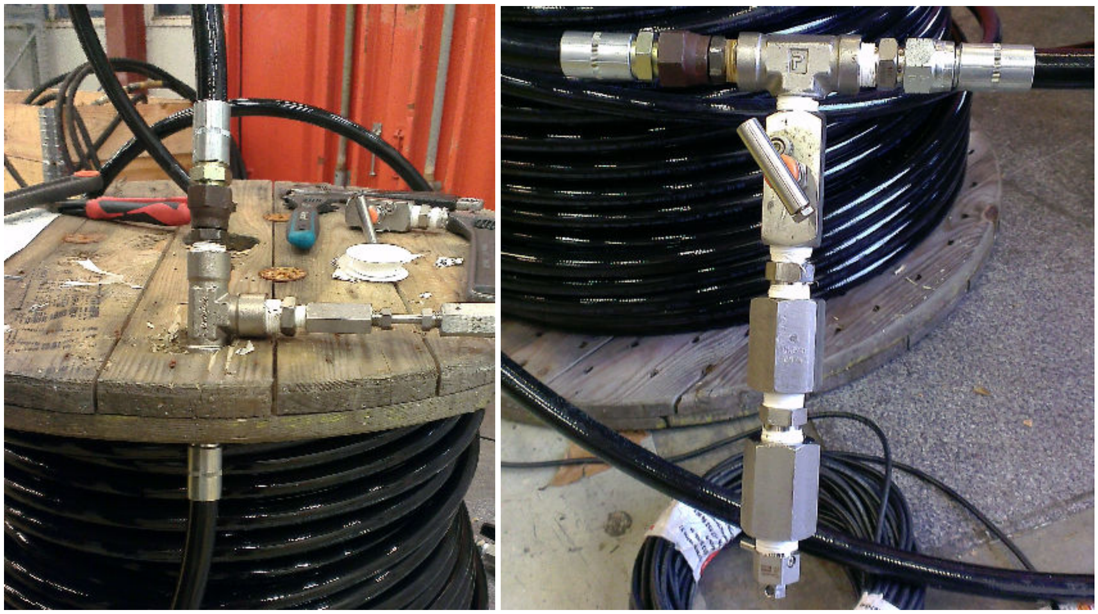


Figure 4.6: T-connection representing tubing leak.

4.1.7 Tubing leak

Occasionally, tubing leaks are found in offshore wells. Tubing leaks usually take form as a pinhole in the tubing and can be caused by either corrosion or mechanical damage. Communication between the annulus and tubing in form of a pinhole is obviously very undersirable, and should be detected as soon as possible before it develops into a safety hazard. Luckily, one doesn't experience tubing leaks too often. This is exactly why it is so important that the operator carrying out the acoustic surveys, knows what a tubing leak looks like in the acoustic signal. In order to simulate a tubing leak in our small scale version, a T-connection was used between the hoses. Immediately after the T-connection, on the T-branch that is, a needle valve was used in order to reduce the cross section significantly relative to the casing hose. A needle valve would also enable us to manipulate the opening on this branch. The setup for this can be seen in figure 4.6

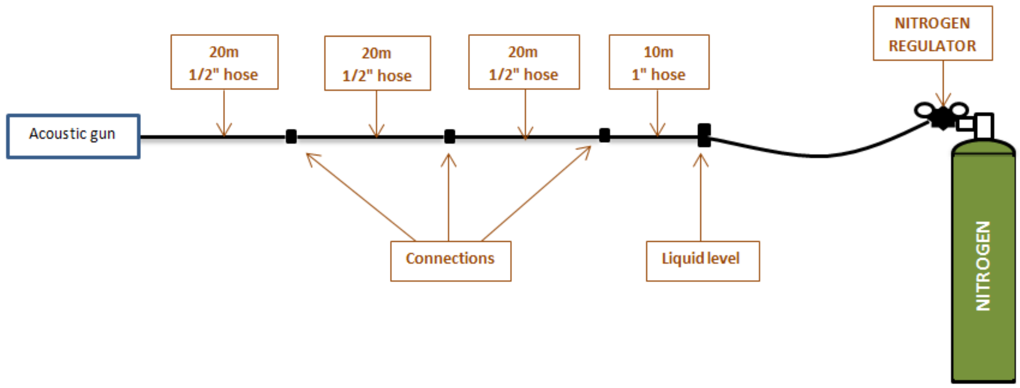


Figure 4.7: Initial test setup

4.2 Initial test setup

Even though the same principle is applied in this case, the cross section in the hoses are significantly smaller than the cross section in the tubing or casing for most offshore wells. Hence, we have a significant change in both length and volume which again influences the frequency content in the signal. Hence, it is needed to make a setup with different components to see that we get a satisfying result which is possible to interpret. Therefore, several hoses were used to get reflections from different components in the setup. As seen in figure 4.7, both the cross section and length of the hoses was varied in order to see how the different changes influenced the signal. The 1" hose was introduced so that we could get an upkick in our signal followed by the downkick from the liquid level.

Thus, a result agreeing with the initial expectations for this particular setup, would mean that the dynamics obtained from a small scale version would reflect the actual dynamics from a normal sized oil well.

4.3 Restriction in the setup

As of today, there exist a vast amount of oil rigs in the North Sea, and most of these are customized when it comes to structural design and layout. Consequently, there exists many different ASV's which differs in both size and design. Relevant examples for this could be a small annulus volume combined with an ASV with big cross section in the opening, or it could be a big volume combined with an ASV with a small opening. Needless to say, this gives many challenges when it comes to acquiring the best possible acoustic data. More knowledge on how acoustic waves behave in regards to different pressures and restrictions can help to understand how an acoustic survey should be carried out, in order to get the best possible data. Thus, the scenarios that would give a better understanding would be constant pressure whilst the restriction varies, and a fixed

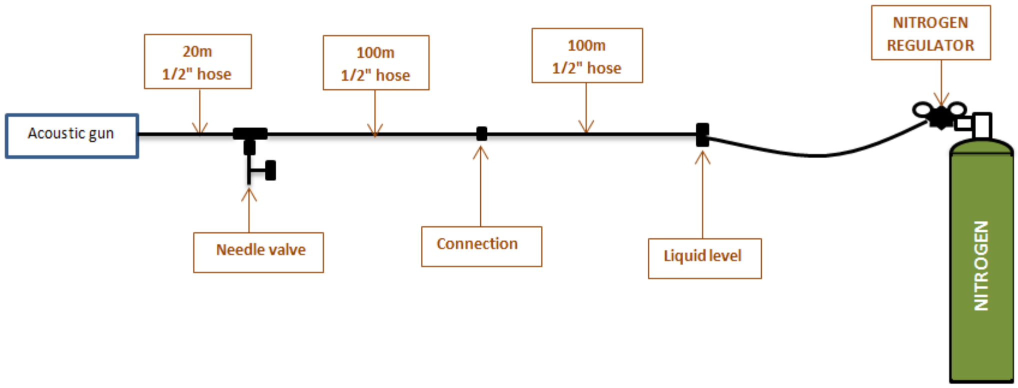


Figure 4.8: Needle valve acting as ASV

restriction whilst the pressure is regulated.

4.3.1 Needle valve as restriction

As we have seen earlier, a change in cross section will cause a reflected wave to travel upward from the point of reflection. However, when the reflected wave reaches the top of the well, it will not only be recorded by the microphone, it will also reach a closed end and get reflected back down again. The pressure wave is now an echo which travels back and forth in the well. These echoes make it a lot harder to interpret the acoustic signal and they provide no useful information. Hence, it is of great interest to understand how these echoes behave for different changes in cross sectional area . Usually, the ASV in a well is located at approximately $350ft$ or $700ft$. Consequently, this affects how frequent the echoes occurs in the signal. In our small scale setup, the needle valve is located after $20m$, as depicted in figure 4.8. The depth of the ASV versus the GLV depth is about 1/10, so it isn't too far off the ratio for oil wells.

In order to control the ratio of area change in the small scale setup, a needle valve was used. The needle valve used, had 10 half turns between fully opened and fully closed. By setting the pressure to a fixed value, it was possible to see how an increasing area change affected the echo waves by increasing the amount of turns on the spindle. A fully opened needle valve would then act as no restriction at all, whilst a fully closed needle valve would act as a defect ASV where the hydraulic opening pressure has failed.

4.3.2 Small tubing as restriction

As most acoustic problems arise from big restrictions in the casing, it is area reductions that are most interesting to study. The previous scenario was investigated so that we could get a better understanding on how the reflected waves behave for different area reductions. Anyhow, in an offshore well, the casing already has a fixed cross section together with an ASV that has a fixed opening area. What this means is that it is not the physical design of the system that is varied, but rather the pressure of the transmission medium. Therefore, we introduced a very small tubing piece between the hoses so that we could simulate the actual area change the operator experience when carrying out acoustic surveys on some offshore wells. Furthermore, the tubing piece had an inner diameter of $2,3mm$ whilst the hose had an inner diameter of 12.3mm. The reduction in area is then calculated to be:

$$\frac{A_{tubing}}{A_{hose}} = \frac{\pi \cdot 1.15^2}{\pi \cdot 6.35^2} = 3.28\%$$

What this means is that when the pressure pulse reaches the tubing piece, it will experience a 96.72% reduction in the cross sectional area.

With this setup it is then possible to vary the pressure, and see how different pressures in the same setup affects the reflected waves. They actual layout was identical to the previous case, except that the needle valve was replaced with the small tubing piece.

4.4 Microphone placed at the liquid level

In many situations, it would have been preferable to place the microphone downhole in the well. The ideal situation would be to carry out the acoustic survey from beneath the ASV so that we could get rid of all difficulties. Needless to say, this is not possible on an offshore installation and the operator therefore needs to make the best out of it. Nevertheless, by getting more knowledge on the transmitted pressure pulse on the other side of a significant restriction, it can help in order to make the right decisions on the surface. Therefore, a second microphone was installed just next to the liquid level valve. It was decided to put the microphone here so that we would get the same conditions as on top. This would make it possible to record the pulse after it had propagated through the small tubing piece. Hence, the reflection recorded by the microphone next to the liquid level can be compared to the liquid level response on top. The only difference between these two reflections would then be one propagation through the restriction. The setup for this is illustrated in figure 4.9.

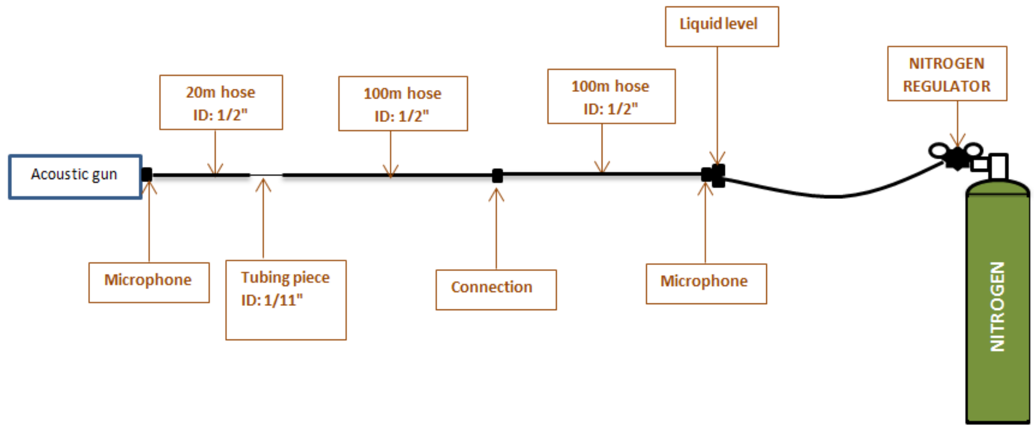


Figure 4.9: Microphone at liquid level

4.5 External chamber

When looking at reports on acoustic surveys that have been performed on different wells in the past, the people intepreting the data have had great difficulties when it comes to locating the liquid level. This is an issue even though most of the ASV echos already have died out in the signal. The reason for this in many cases is that the total energy left in the transmitted pulse is too small after a major part of the initial pressure pulse got reflected at the ASV. Therefore, it was decided to try to replace the chamber on the gun with a bigger one. Hence, one could try to increase the amount of energy contained in the pressure pulse. The latter would hopefully provide better acoustic conditions in wells with a large annulus volume.

Figure 4.10: Gas bottle used as chamber for the acoustic gun

Figure 4.11: 90 degrees connection

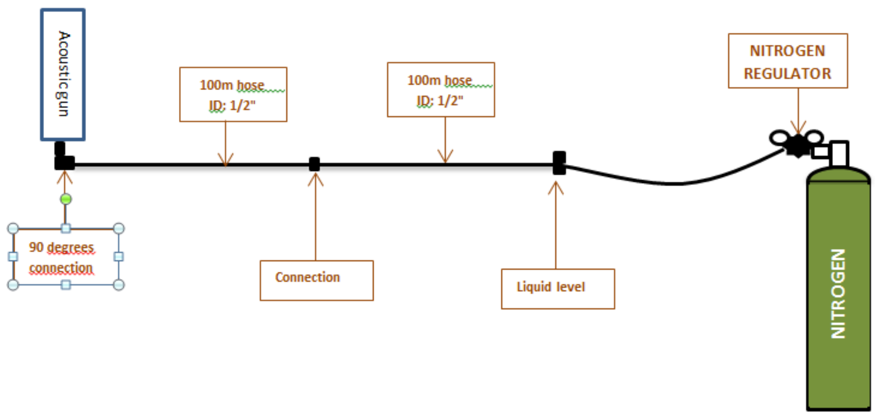


Figure 4.12: Acoustic gun connected perpendicular to the hose.

4.6 Perpendicular shot

In a majority of the cases when the gas gun is to be connected on the well head, it is installed on a manifold. Manifolds are used so that additional pressure gauges and measurement devices can be installed. However, having the acoustic gun attached to the manifold means that the gun will be placed perpendicular to the line that goes into the annulus. In other words, there will be a 90 degrees turn immediate after the gas gun. It is therefore preferable to find out if this has any affect on the acquired data in any way. To address this potential problem, a 90 degrees connection was introduced into the system. This connection can be seen in figure 4.11. Furthermore, the rest of the system was designed as simple as possible in order to minimise the amount of reflections. The exact layout for this scenario is illustrated in 4.12.

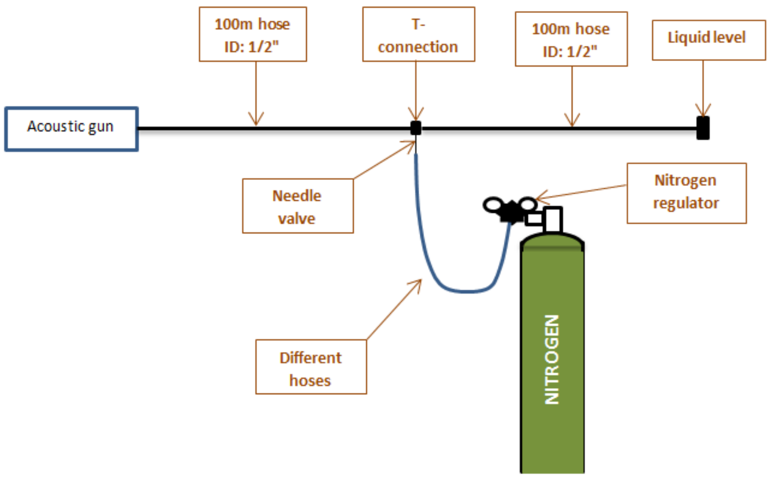


Figure 4.13: Leak through pinhole

4.7 Leak through pinhole

In order to simulate a leak in the tubing, an additional branch was introduced into our system. This branch was connected perpendicular to the other hoses by the use of a T-connection between the 100m hoses. Furthermore, all other restrictions were removed from the system in order to get a clearer signal. In this way it would be easier to see what effects a potential leak between the barriers would have on the acoustic signal. The layout for this scenario is depicted below. In order to simulate a tubing leak in our small scale version, a T-connection was used between the hoses. Immediately after the T-connection, on the T branch that is, a needle valve was used in order to reduce the cross section significantly relative to the casing hose. The setup for this can be seen in figure4.6.

Figure 4.14, shows how an actual pinhole could look like. A hole like this would definitely introduce communication between the tubing and the annulus, and is therefore concidered as a tubing leak. To clarify, a hole in the tubing won't cause a leak if the pressure on both sides are the same. However, whenever the pressure is different between the tubing and annulus, this will result in a flow through the hole. In other words, a leak through the primary barrier when dealing with high pressurized gas, introduces a major safety risk. Yet another consequence would be reduced overall performance of the well, since less gas will flow through the unloading valve at the bottom.

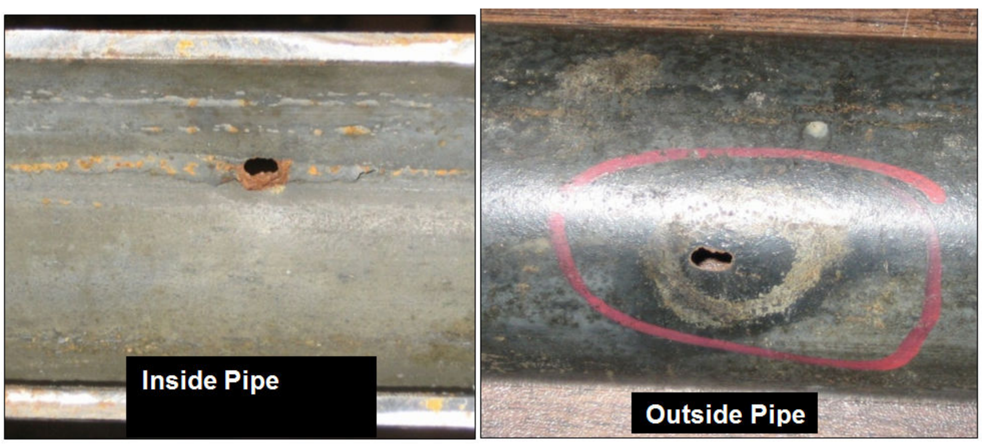


Figure 4.14: An actual pinhole in tubing

Chapter 5

Results

In this chapter, the results obtained from the experiments which is described in the previous chapter will be presented. Furthermore, the name on the sections correspond to those in the previous chapter where the description was provided. Voltage along the y axis and depth along the x axis is something all plots have in common. The acoustic velocity is calculated by using the liquid level as a downhole marker, while reflections from connections between the hoses are used to verify the velocity. However, the acoustic velocity isn't paid too much attention to, since it's the qualitative aspect to this that is the main focus for this study.

5.1 Initial test setup

As mentioned in the description for this test scenario, the main goal for this setup is to verify that the small scale version can produce good acoustic results that can resemble those signals acquired from a real sized oil well. Thus, if the result complies with the initial expectations, this would mean that other test scenarios would be valid as well. The result for this case can be seen in figure 5.1. The annotations in the plot indicates the beginning of the connection between the 4 hoses. As expected, we can see downkicks originating from the connections between the first three $\frac{1}{2}$ inch hoses after 20m, 40m and 60m. The reason for the downkick and the subsequent upkick is because the connection is attached inside the end of the hose. This causes the cross section to decrease slightly. Furthermore, the actual connection between the hoses has a slightly bigger cross section, which causes the upkick. When it comes to the 4th connection, this is the transition between the $\frac{1}{2}$ inch hose and the 1 inch hose. In light of chapter two, we recall equation 2.34 which describes the reflection coefficient. Since $A_2 > A_1$, this will result in a negative coefficient. In other words, we will get a reflected wave with opposite magnitude with respect to the incident wave. Since we introduce a negative pressure pulse into the system, this will cause a positive pressure pulse to be reflected from this point. Hence, the big upkick

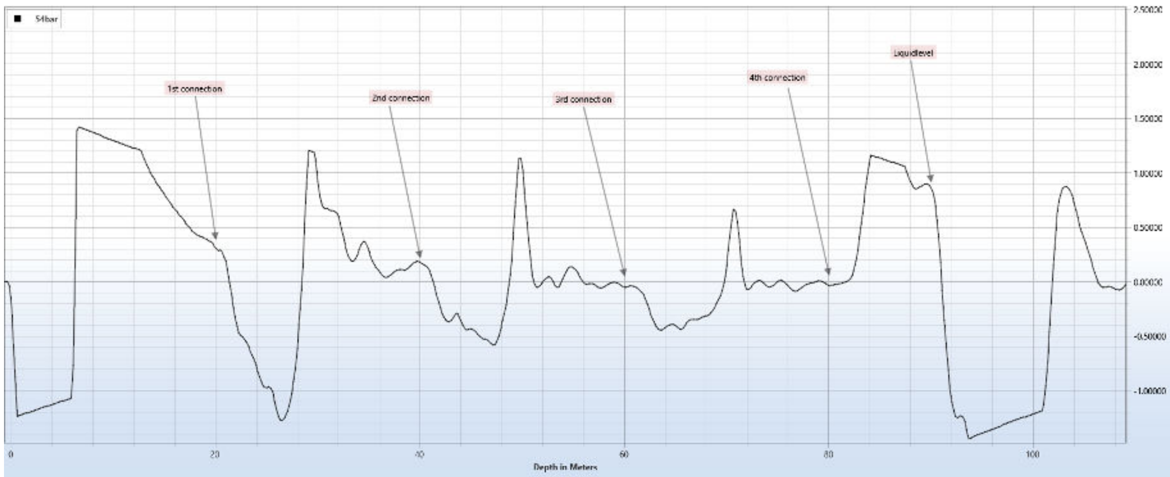


Figure 5.1: 90 meters of hose for testing purposes

in the graph at 80 meters. We also notice that the top on this reflected wave is capped. The reason for this is simply because the microphone has a limited range. Thus, whenever the signal goes outside this range, the signal will get saturated. However, this doesn't pose any particular problems, so we will not pay any further attention to that. Lastly, the response from the liquid level valve shows up after 90 meters. In this case, the reflected wave shows up before the response from the 4th connection has died out. This causes the liquid level response to start before the signal reaches the base line at $0V$. The latter can happen in offshore situations as well.

Considering that the results in this test setup was according to the expectations, further testing was performed.

5.2 Needle valve as restriction

In this setup, a needle valve was introduced in order to generate stronger reflections into the system. Throughout this section, the needle valve will be referred to as the ASV. The benefit with a needle valve as restriction is the possibility to vary the opening area by turning the spindle. Hence, by keeping the pressure at a constant level, it is possible to see how the degree of restriction affects the reflected waves. The result from this test is depicted in figure 5.2. As can be seen in the upper left box, the spindle was varied between fully opened, 75% closed, 95% closed and 98% closed. In the latter case, it was barely an opening through the valve at all.

When looking at the result, there are som interesting properties worth noticing. First, we notice the correlation between the amplitude of the reflections and the corresponding opening through the needle valve. As expected, the echoes become stronger as the restriction becomes bigger. In both the black and blue signal, we can see the initial reflection after approximately $20m$ caused by the needle valve. Further, one ASV echo can be seen after around $40m$. The next reflection is the downkick located after $120m$ followed by the subsequent ASV echo after $140m$. The latter occurs when the echo pulse reaches the same connection, which also explains why there is exactly one ASV length between them. Lastly, we can see the strong reflection after $220m$ which is the liquid level.

In the red and green shot, it's apparent that the opening through the ASV has become significantly smaller. The ASV echoes are much stronger in both of these shots, which indicate that a major part of the signal gets reflected at the restriction. Especially in the green signal, we can see that the ASV echoes lasts throughout the whole signal. To put it differently, the bigger the reduction in cross sectional area, the less will the amplitude decrease in the echoes since a bigger part of the signal gets reflected every time.

Another aspect in the signal that corroborates the correlation between the amount of energy being reflected and the amplitude on the echoes, is the response from the liquid level. The amplitude of the liquid level response is actually inversely proportional to the amplitude of the echoes. What this means is that the more energy that gets reflected from various restrictions, the less energy will remain in the pressure pulse when it gets to the liquid level. This is especially evident in the green signal, where the echoes are so powerful that it's almost impossible to spot the liquid level. In other words, there are almost no energy left in the signal when it reaches the liquid level. The black signal on the other hand contains none of these echoes, meaning that the major part of the initial pressure pulse gets reflected at the liquid level. In chapter 2, these dynamics was explained mathematically by the use of the reflection coefficient and the transmission coefficient. The greater reduction in cross sectional area, the bigger the reflection coefficient and the smaller the transmission coefficient will become. The results for this scenario are therefore consistent with the theory on wave propagation.

The black signal and the green signal in figure 5.2 represent two very different shots. While the green signal contains strong periodic reflections, the black signal doesn't have this at all. It would therefore be very interesting to compare the frequency content in these two signals. For this reason, the corresponding PSD's for the two signals can be seen in figure 5.3. Immediately, we notice big differences in the frequency content for the two signals. As for the blue signal where the needle valve is fully open, there is no particular frequency that stands out from the others. This is reasonable since there are no strong periodic reflections in the time domain. However, the red signal corresponds very well with the theory on harmonics frequencies presented in section 3.5. The strong reflections in the time domain, have been decomposed into a fundemental frequency together with a series of harmonics components. Since these shots were carried out in a controlled environment with known acoustic velocity, we can therefore check what depth the fundamental frequency corresponds to.

We start with the reciprocal relationship between frequency and time:

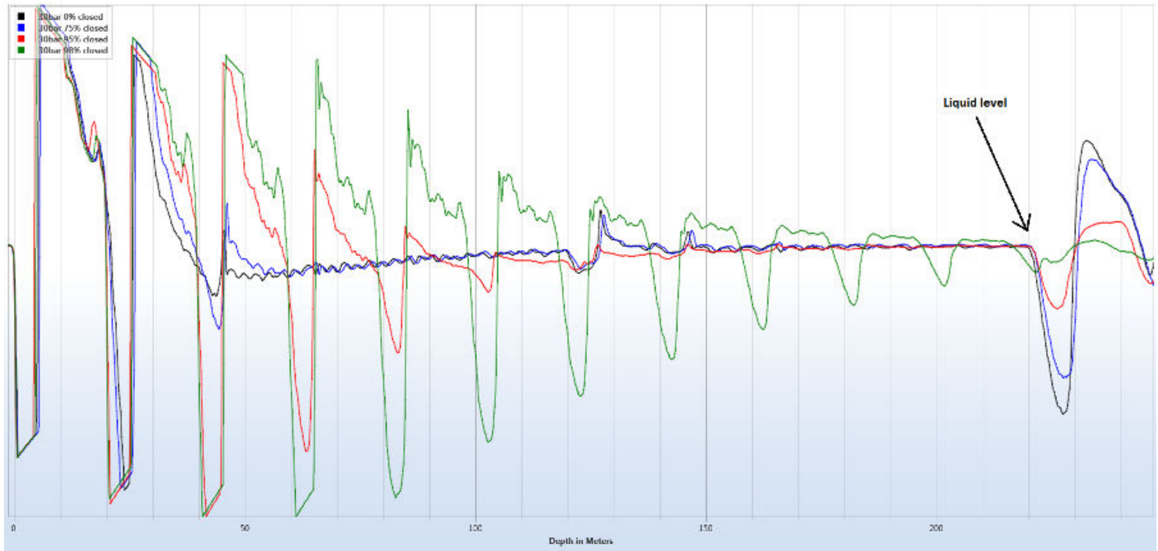


Figure 5.2: Comparison between different opening areas in needle valve while the pressure was kept at 30 bar

$$f = \frac{1}{t} \tag{5.1}$$

By solving for frequency we can plug this into the expression for depth d:

$$d = \frac{v}{f} = \frac{352m/s}{8.824Hz} = 39.89m \tag{5.2}$$

Furthermore, since equation 5.2 represents the round trip distance, we need to divide this number by 2. Thus, the element located at $\frac{39.89m}{2} = 19.95m$ causes the pressure pulse to propagate back and forth at the fundamental frequency. Since the needle valve is placed after 20m, it is therefore proven that it is in fact the ASV that causes the strong resonant frequencies we see in the acoustic surveys i.e the Ekofisk M-25 well.

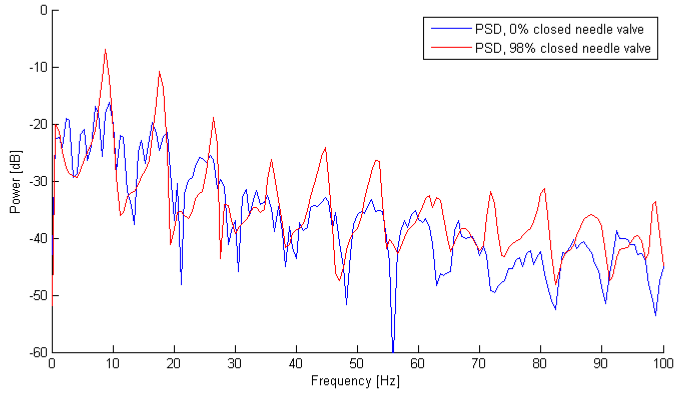


Figure 5.3: PSD's for the black and green signal

5.3 Small tubing as restriction

One of the uncertainties when using a needle valve, is that it is impossible to know exactly how big the actual opening is, except at the extreme positions when it's fully closed or fully open. For this reason, it was decided to replace the needle valve with a small tubing piece. By doing this, we could calculate the exact area reduction in this particular section. As seen in section 4.3.2, the total area reduction was calculated to be 96.72%, which is a significant reduction. A setup like this would therefore really put the acoustic principle to test. By having a fixed restriction we could vary the pressure and see how this would affect the result. The result is depicted in figure 5.4.

The results for this test scenario are very interesting. As can be seen, there are much less variations in regards to how strong the echoes are. Furthermore, the shape of the echoes is more or less the same in contrast to what was the case in the previous section. The only thing distinguishing the echoes apart is the amplitude. We can clearly see that a higher pressure causes a greater amplitude. To support this, we recall the specific acoustic impedance that was elaborated on in chapter 2. Since the equation is very relevant in this case, it is presented below one more time:

$$z_{specific} = \frac{p}{u}$$

As can be seen from the equation, the specific acoustic impedance will increase as the pressure increases. Even though the acoustic velocity will increase to some extent, it will increase less than the pressure so the end result will be a greater impedance. The latter can be verified by looking at the relationship between pressure and acoustic velocity for natural gas found in [17]. An increase in impedance due to higher pressure can therefore be seen as reflections with greater amplitude in figure 5.4.

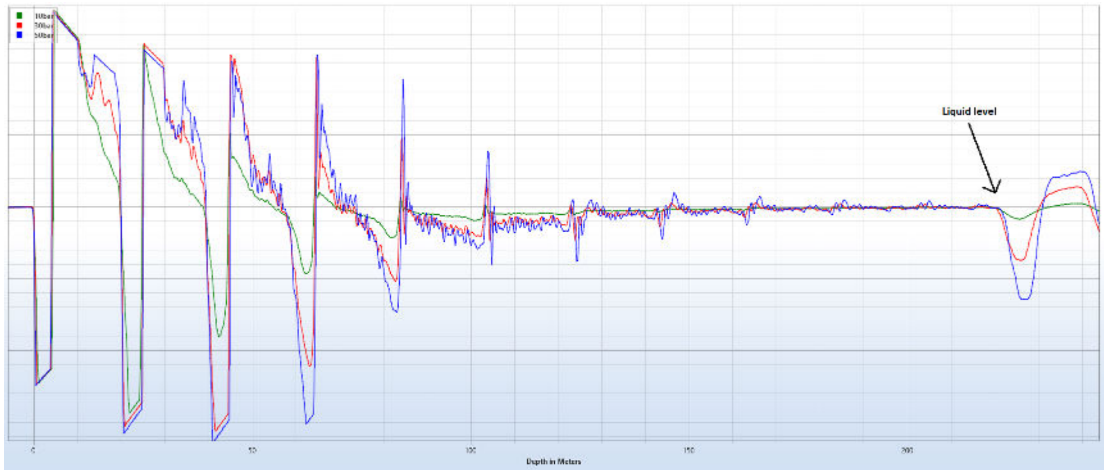


Figure 5.4: A comparison between 10bar, 30bar and 50bar together with a fixed restriction.

An overview of the acoustic velocity in natural gas with 0.6 specific gravity which is found in [17] can also be seen in Appendix C.

Prior to the testing, it was also discussed whether it was possible to saturate the restriction or not. A consequence of the latter would be that after a certain pressure was reached, additional pressure would only contribute to stronger reflections from the restriction. In order to investigate this further, we therefore increased the pressure stepwise for every test. In none of the tests we managed to saturate the restriction. This can be confirmed by looking at the liquid level response which increased in amplitude every time we increased the pressure. The reason why saturation of the pressure pulse never is achieved, is simply because there are no increase in velocity for the pressure pulse as it propagates past the restriction. In fact, the pulse already propagates at sonic velocity which is dependent upon the transport medium and the current conditions. Hence, the pulse will not experience any change in acoustic velocity and will therefore propagate with the same velocity regardless of the cross section. The only effect a change in cross section has on the pressure pulse, is a decrease in amplitude defined by the incident wave and the reflection coefficient. A higher pressure will therefore only yield in a greater amplitude for the pressure waves.

5.4 Boundary behaviour

Throughout the testing we also tried to install the microphone in between the 100 meter hoses so that we could record the pressure pulse as it propagated past the microphone. When we did that, we became aware of another interesting feature. Namely, the response we got from the microphone on top, was bigger

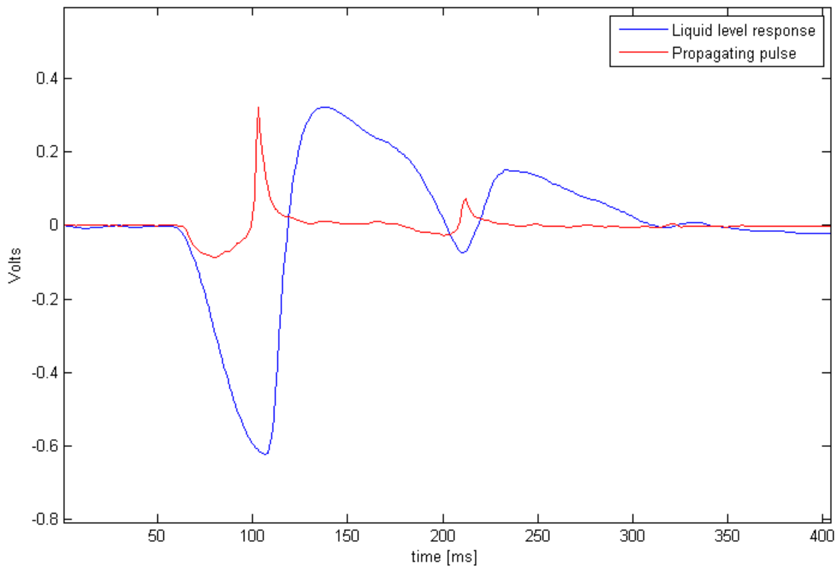


Figure 5.5: Comparison between the liquid level response on top and the propagating pressure pulse

in amplitude than the amplitude of the propagating pulse we recorded between the hoses.

In order to understand why this is the case, we need to know what happens to the pulse when it gets reflected by a boundary. The two boundaries in our case will be the liquid level at the bottom and the closed shooting valve on the acoustic gas gun. The boundary will then represent the interface between the two media. Since the microphone is located next to the boundary, it is actually the reflection of the pressure pulse as it hits the boundary that we see int the plot afterwards. As we saw in equation 2.45 in the section on reflections due to a sudden change in density, whenever the pressure pulse reaches a media with a higher density, the reflected wave will be in phase with the incident wave. Put differently, since the transmission media in the immediate neighborhood of the end is free to move, it will cause both the upkick and downkick in the pressure wave to increase in size at the boundary. This is due to the fact that the last particle of the transmission medium is free to move, and it will therefore move along with the wave and stretch out the pulse. Thus, the signal to noise ratio will increase. It is the same principle as when you hold one end of a rope and move it so that you introduce a propagating wave in it. Hence if the other end is free, it will move along the wave and increase the amplitude.

The result for this is can be seen in figure 5.5 whilst a simplified sketch of the reflection phenomena is depicted in figure 5.6

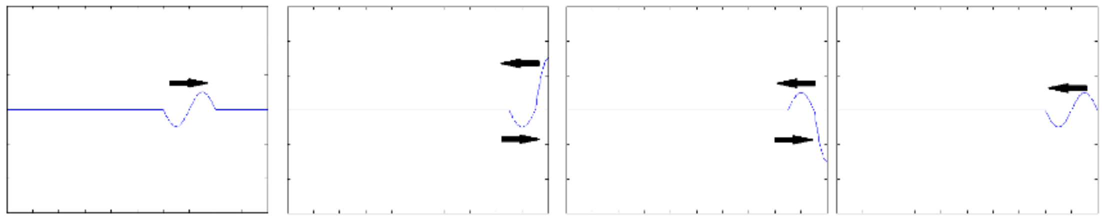


Figure 5.6: A pressure wave encounters a free end

5.5 Microphone at liquid level

One way to get a better understanding of the acquired signal on the surface, is to gain more knowledge on how the signal behaves as it propagates downhole past restrictions. In order to investigate this, a second microphone was introduced next to the liquid level as shown in figure 4.9. It was then possible to record the pressure pulse the same way it gets recorded at the top. For each test, two acoustic shots were performed. The first shot was carried out as usual whilst in the second shot the microphone cord was connected to the second microphone. By doing it this way, the pressure pulse had already propagated past the restriction before it got recorded by the microphone at the liquid level. Thus, what we are actually looking at in this section, is the pulse as it propagates back up again. Therefore, we are only looking at the liquid level response in the signal from the microphone on top. By comparing these two, it is then possible to see how a restriction affects the pulse and hopefully also a verification of the theory already presented.

Figure 5.7 shows the result before and after the restriction in both the time and frequency domain. Indicated in blue and red color, respectively. Naturally, the blue signal has the biggest amplitude since this is before the restriction. The red colored transmitted signal, which is after the restriction, appears as a scaled version of the blue signal. The relationship between the incident wave,transmitted wave and the transmission coefficient is described matehematically in equation 2.35. In order to support this, the corresponding PSD for both signals was computed as well. This can obviously be seen in the right subfigure. Once again, we can see the harmonic components due to the subsequent echos after the first reflection. In addition, we can see that the red signal is an attenuated version of the blue signal containing the same frequency components. This proves that whenever the pressure pulse reaches a restriction, some of the energy in the pulse will be lost in the transmitted wave. To put it differently, everytime the pressure pulse reaches a discontinuity, the amplitude of the transmitted wave will be reduced. Hence, if the pressure in the well is low both the propagating pressure pulse and the trasnmitted pulse will become smaller. If there is a lot of noise present in the signal as well, this can make it very difficult to differentiate between the noise and the actual signal. This can become a problem when you shoot acoustics in a well with an ASV installed

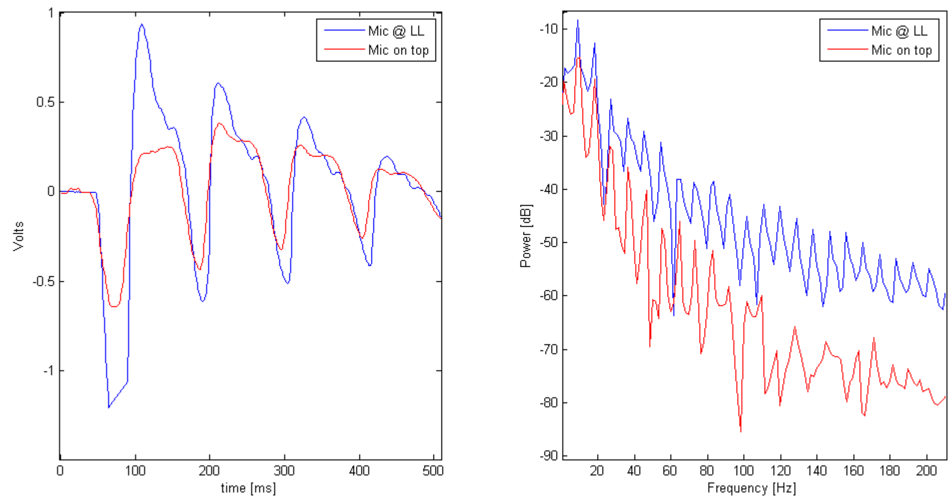


Figure 5.7: Comparison between the pulse reflected at the liquid level and the liquid level response recorded on top

after the pressure is bled down in the annulus.

5.6 External chamber

In the pursuit of a greater pressure pulse, the original chamber was replaced with the big gas bottle depicted in figure 4.10. In this way, there would be a much bigger volume on the other side when the shooting valve was opened. By carrying out multiple tests with both the regular chamber and the gas bottle as chamber, it is possible to compare the results and see how the type of chamber influences the acquired signal. In addition to the tests already mentioned, a similar test was carried out with the regular chamber. However, instead of having atmospheric pressure in the chamber prior to the shot, about half of the pressure in the system was used in order to create a smaller differential pressure. This was accomplished by opening and closing the shooting valve so that we would get the same pressure in the chamber as in the system. Then the gauge installed on the chamber was used so that we could bleed down until about half of the pressure in the system. In this way, we had three different pulses that we could apply on the same system. The result for this can be seen in figure 5.8

To begin with, we start by looking at the pulses generated from the regular chamber. As seen, there are not any significant differences between these two. The liquid level response is more or less identical and the amplitude of the echoes

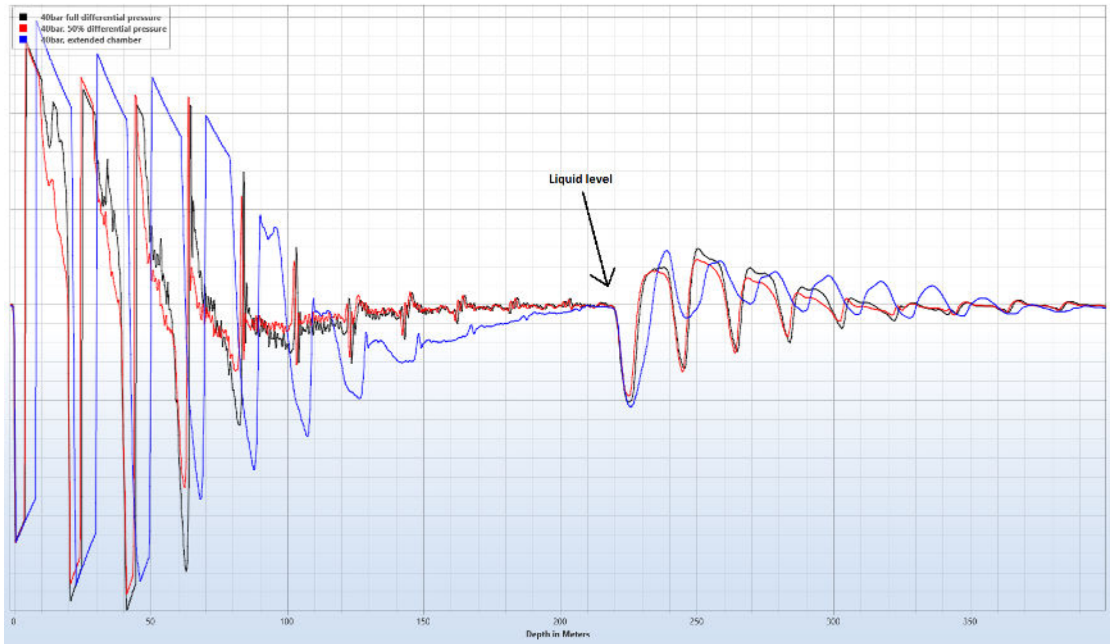


Figure 5.8: Chamber comparison

follow each other very closely. As for the blue signal with the gas bottle used as the chamber, we clearly see that the generated pulse is much wider. This can not only be seen from the echoes in the beginning of the signal, but also by looking at the liquid level response. The reason for this is the fact that the gas bottle contains a lot bigger volume. Hence, when the shooting valve is opened, it takes longer for the pressure to equalize. The latter will therefore decide how wide the introduced pressure pulse will become. In addition, there are no changes in the amplitude of the liquid level response. What this can tell us, is that a bigger chamber not necessarily means a greater pulse. To explain this we recall that the chamber contains atmospheric pressure, which will introduce a negative pressure pulse into the system. In other words, the pressure contained on the downhole side will cause the transmission medium to flow into the chamber, thus creating the pressure pulse. The latter proves that the type of chamber will not have any impact when it comes to the amplitude of the pressure pulse, since it is generated from downhole side and not from the actual chamber. It is also consistent with the fact that the pressure pulse becomes wider, since a bigger volume can contain a lot more transmission medium. The same cross section, will therefore increase the amount of time it takes to equalize the same differential pressure.

To summarize, neither the size of the chamber nor a smaller differential pressure has a significant effect on the resulting pressure pulse. A conclusion

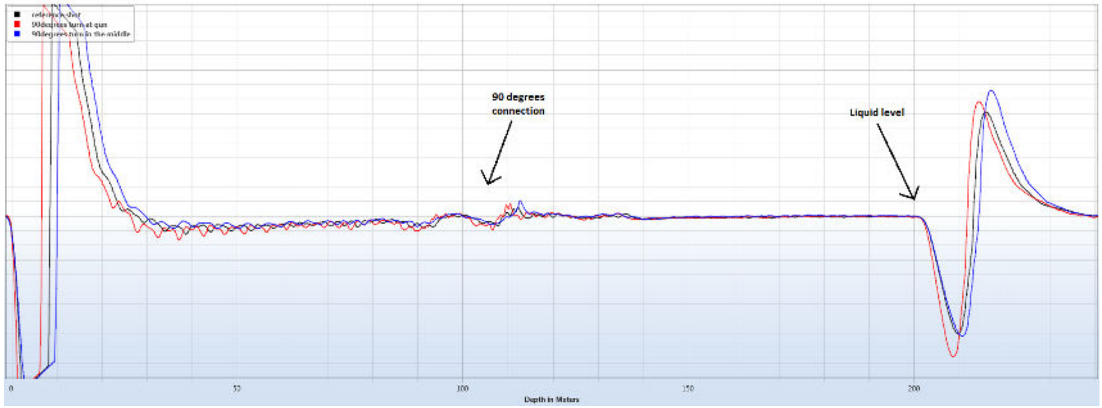


Figure 5.9: A comparison between the reference shot, 90 degrees connection next to gun, and 90 degrees connection between the hoses.

that can be drawn from this is therefore that there is no need to decrease the differential pressure and the type of chamber has little impact on the power of the generated pulse. It is however, the conditions in the transmission medium such as the pressure that ultimately decides how big the pressure pulse will become.

5.7 Perpendicular shot

In order to be able to tell at all whether a 90 degrees turn would affect the pressure pulse, a reference signal was needed. A shot without the 90 degrees connection was therefore performed on the same layout so that it was possible to compare the two signals afterwards. Adding to this idea, another test was carried out with the same components. In this case however, the 90 degrees connection was moved from the gas gun and put in between the two 100 meter hoses as seen in figure 4.11. By doing this, we could see if a sudden bend like this would give any reflected waves when it was placed further down in the setup. Most wells, after all, contain sections with different angles.. Some wells even have horizontal pipes for several kilometers before they start to go vertical again. Hence, if the pressure pulse can go past the 90 degrees turn without any problems we can be absolutely sure that it can handle all kinds of wells, regardless of the mechanical design. In figure 5.9 we can see the three cases plotted together. Overall there are no significant differences between the reference shot and the other two. Some fluctuations around the baseline can be seen in the shot where the acoustic gun was connected perpendicular to the hose, but this is insignificant. The liquid level response in also similar in all of the cases. As for the connection in between the hoses, the response is quite similar either it's a 90 degrees turn or not.

What this can tell us is that the shape of the transmission line has little to no effect on the pressure pulse. Again it's only a change in impedance caused by discontinuities in the cross section that will produce reflected waves. The fact that the pressure pulse is unaffected by twists and turns in the transmission line also shows how robust acoustic logging really is.

5.8 Leak through pinhole

In the attempt of simulating a tubing leak a T-connection was installed between the hoses, as seen in figure 4.13. Furthermore, the needle valve was closed so that it was possible to bleed down the T-branch to about half of the value on the other side. This was done by opening a bleed valve on the T-branch. Right before the shot was carried out, the needle valve was opened up in order to introduce a leak from the T-branch into the hose. However, since the total volume in our system is significantly smaller than for an actual annulus, the resulting leak set the whole medium in motion. On the other hand, a small hole in the tubing would only affect the volume in the immediate neighborhood of that hole. Thus, this way of simulating a hole in the tubing would not be very accurate. It would however represent a shot performed immediately after shutting in a well. At this point, gas would still be flowing in the annulus causing non stationary conditions for the propagating pressure pulse. The acquired data would therefore help to understand how a noisy transport medium would affect the acoustic signal. During the testing for this scenario, we also became aware of that it is impossible to detect a gas leak with acoustics. The reason for this is that a gas flow into or out from the annulus won't affect the cross sectional area in any way. With a liquid leak on the other hand, the liquid would take up space so that the experienced cross section for the pressure would become smaller. Consequently, this would appear as a downkick in the acoustic graph. In figure 5.10 we can the see comparison between a shot in stationary conditions and a shot with a moving transmission medium. Represented in black and red color, respectively.

The signals are scaled so that the amplitude of the liquid level response matches. In this way we can see how it affects the reflection from the T-connection. In the black signal it is easy to spot both the upkick from the increase in area at the T-connection and the downkick from the end of the hose on the T-branch. It is still possible to spot these in the red signal, but they are much less defined. It is immident how noisy conditions in the transmission medium results in less distinct reflections with lower amplitude. This tells us that flow in the transmission medium does nothing else than to worsen the acoustic measurements, so prior to an acoustic survey it would be preferable to have as stationary conditions as possible. Thus, the acquired data will become as good as possible.

Another factor that we wanted to investigate in regards to tubing leak, is how the volume on the other side of the hole affects the reflected wave. Therefore one more test was done where we terminated the T-branch immediately after

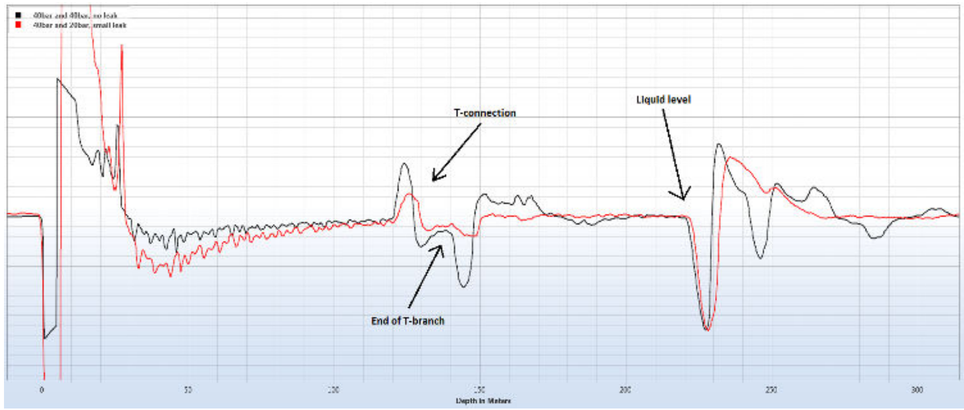


Figure 5.10: Non stationary transmission medium

the connection. This is depicted to the right in figure 4.6. The needle valve was in this case fully open, so that our only variable would be the length of the T-branch. The first two tests had 20 meters and 40 meters of hose on the T-branch and in the last test the T-branch was terminated immediately. The results can be seen below.

As expected, the two tests with 20 meters and 40 meters of hose is quite similar. Both of them have the upkick from the T-connection and the downkick from the end of the hose. Obviously, the downkicks has 20 meter in between them since this is the difference in length on the T-branch. Anyhow, when looking at the blue signal with the terminated T-branch, we can see that there are almost no response at all in this part of the signal. As it turns out, this is not due to a small volume but rather due to destructive interference. Put differently, the area increase in the T-connection will still cause an upkick but since the stub is so short, there will be an upkick immediately after causing the pressure waves to cancel each other out. The outcome is depicted in the middle illustration in figure 2.7. Hence, there must be a significant length so that interference of the pressure waves is avoided. What this tells us is that it can be very difficult to spot a tubing leak close to a restriction. An example on the latter could be a leak immediately after the ASV. In this case the upkick from the leak would interfere with the downkick from the ASV and the result would be destructive interference.

Since it was very difficult to simulate a tubing leak in the small scale version, we will have a look at a real tubing leak in a gas lifted well in The North Sea. The leak was caused by a pinhole similar to that in figure 4.14. Fortunately, acoustic shots were performed both in the tubing and the annulus, enabling us to get the full picture of the situation. Suspicion of a possible tubing leak, always arises when comparing the reflections in the acoustic signal with the well barrier schematic. Thus, if there are any reflections at a depth with no elements, this suggests a possible tubing leak. It can then be a good idea to carry out

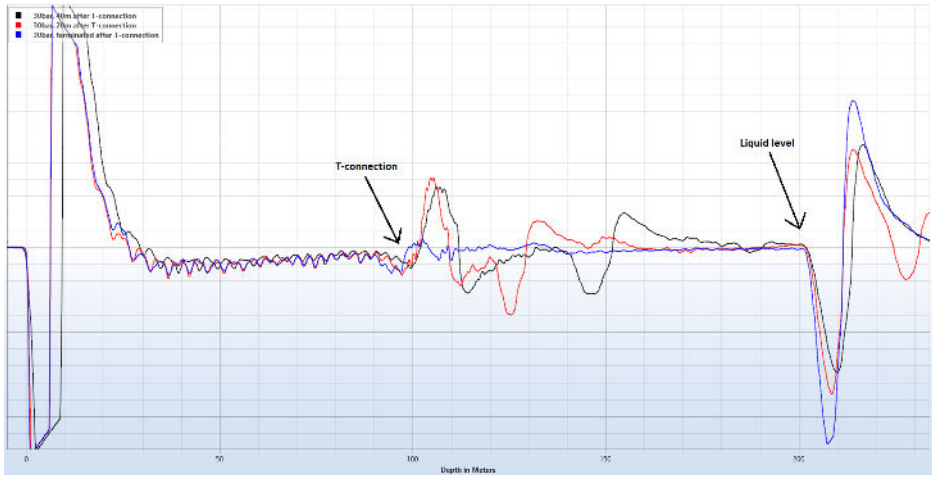


Figure 5.11: Different layout for the T-branch

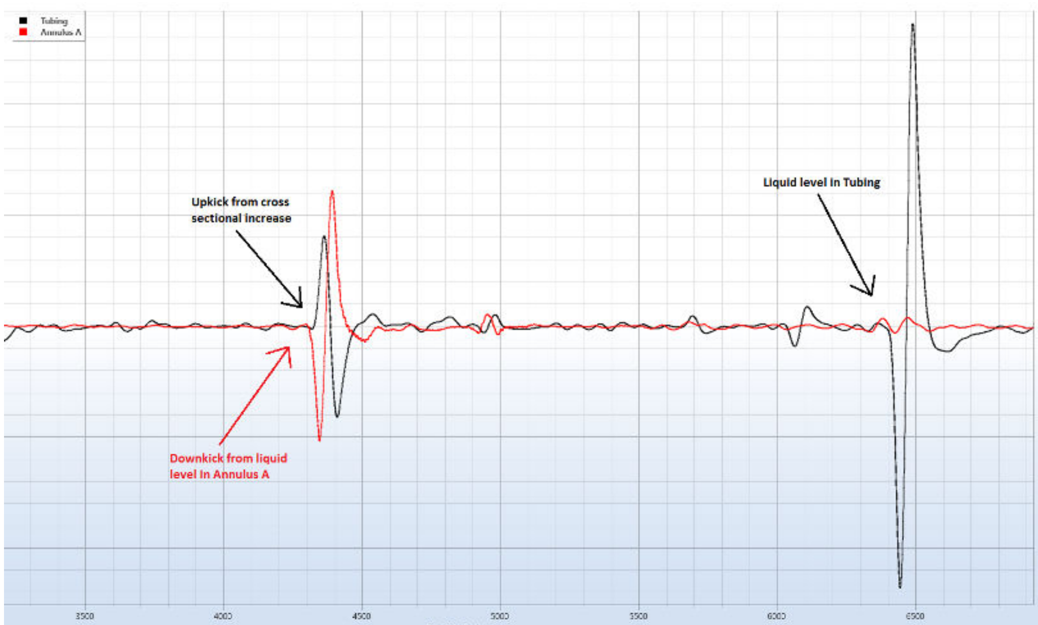


Figure 5.12: Example of a real tubing leak

a shot in the tubing as well. Hence, if there is a reflection at the same depth this indicates that there is a tubing leak in the well. Such a scenario is shown in figure 5.12. Obviously the teabing leak is located at 4300 feet where we have reflections from both the tubing and annulus. In order to understand what happens we need to understand the situation in the well. From the tubing point of view, the pressure pulse will propagate down until it reaches the pinhole. At this point, it will experience an area increase due to the pinhole and the result is a reflected wave viewed as an upkick in the acoustic signal. Furthermore, the big reflection located at 6400 feet corresponds to the liquid level in the tubing.

If we now have a look at the situation from the annulus point of view, we see that we have one downkick at 4300 feet. The downkick is a consequence of the communication through the pinhole. Since the gas has been flowing through the pinhole, the liquid level has naturally stabilized under the injection point. With this in mind, it is always a good practice to perfrom acoustic measurements in both the tubing and annulus whenever there is a suspicion of leak.

Chapter 6

Conclusion and Further Work

To conclude, this thesis has presented many different scenarios in acoustic wave propagation and theory regarding this subject has been provided in order to explain the results obtained in the small scale experiments. First of all, we have seen how it is possible to model the pressure wave propagation by the use of the wave equation. A reflection coefficient has been derived in order to describe the relationship between the incident wave and the reflected wave. It has been shown how both the sign and the magnitude of this reflection coefficient is determined by change in impedance, which again is directly caused by discontinuities in cross sectional area and density in the transmission media. Furthermore, it has been shown how a higher pressure in the system causes a greater amplitude for the propagating pressure waves in form of a greater acoustic impedance.

Secondly, it is shown how it's possible to utilize the Short Time Fourier Transformation in order to combine both the frequency and time domain in the representation of a signal. This type of representation allows us to see how the frequency content in the signal changes with time and also which frequencies that contribute the most in the time varying signal. The frequency analysis revealed that when a lowpass filter is applied to a signal with strong reflections, the frequency transformation decomposes the signal into a fundamental frequency and several harmonic multiples. The harmonic frequencies can become very strong compared to the transmitted signal if the ASV is located close to the surface. Two different cases are therefore compared in order to show how strong harmonic frequencies make lowpass filters unsuitable. It is therefore suggested to install a one-way valve on the acoustic gun so that the strong reflections can be attenuated.

Thirdly, a small scale setup is designed and a detailed description on how this can be related to a real sized gas lift well is provided. The scenarios are designed so that we can investigate how different factors influences the acoustic signal. The experimental testing showed several things. It was seen that the bigger the area reduction in a restriction, the less the amplitude would decrease for each echo since a bigger part of the signal gets reflected every time. As for the pressure, it was found that not only did a higher pressure yield in greater amplitude for the reflected waves, but it was also the pressure that had the biggest influence on the amplitude of the introduced pressure pulse. It was also carried out a test where the gun was attached perpendicular to the hose. In this test, it was seen that the design of the transmission line did not play any role on the quality of the acoustic measurements.

Lastly, a real tubing leak was analyzed in order to get a better understanding on what to look for if there is a tubing leak suspicion. It was seen how measurements in both tubing and annulus can help to detect tubing leaks since the liquid level in the annulus tends to stabilise below the gas injection point. A good indication that the well contains a tubing leak is therefore an upkick in the tubing at the depth of the pinhole, together with a downkick from the liquid level in the annulus at the same depth. If however the leak is located immediately after an area change, this can disguise the leak in form of interference of the pressure waves.

Throughout this thesis, many aspects within the acoustic field have been covered. This has not only resulted in a better understanding of the acquired data, but it has also provided more knowledge on the problems that still needs to be dealt with. Some of these are:

- How to optimize the signal to noise ratio in wells with a shallow annular safety valve.
- Perform experimental testing with a check valve as part of the gas gun assembly and see if it's possible to attenuate the strong harmonic frequencies.
- Investigate alternative methods to attenuate strong echoes in the signal.
- Simulate a leak which is located very close to a restriction and see what role the distance has when it comes to distinguish between different reflections.
- Implement a mathematical model and simulate an acoustic shot that can be used as a reference shot.

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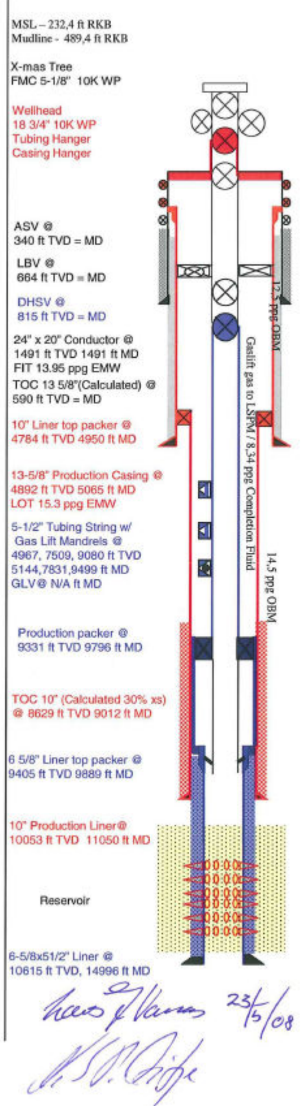
Appendix A

Ekofisk M-25 well barrier schematic

Well Barrier Schematic - 2/4 M-25A Production Well - Final Rev 1



Comments: Horizontal EA producer

Maximum Operating Pressures:
Tubing: 5000 psi
A Annulus (Tbg x 10") : N/A
B Annulus (Tbg x 13-5/8") : 2000 psi
C Annulus: (13-5/8" x 24") : 200 psi

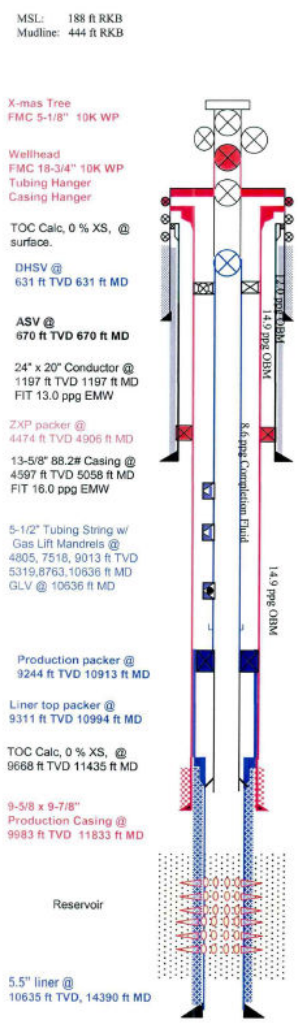
Barrier Elements	**Tests/ Other Verification**
Primary Barrier Envelope	
1.1 6 5/8" Reservoir Liner	5000 psi with seawater – 19/01/07
1.2 6 5/8" Reservoir Liner Cement	100% return during cement job, no rotation on liner
1.3 6 5/8" Reservoir Liner Top Packer	5000 psi with seawater – 19/01/07 Negative test of 1888 psi differential when displaced to seawater
1.4 10" Production Liner	3550 psi with 14,5 ppg OBM – 07/01/07 5000 psi with seawater - 19/01/07
1.5 Production Packer	4500 psi differential from above - 23/01/07
1.6 Production Tubing	5000 psi burst with seawater – 23/01/07 4500 psi collapse with seawater – 23/01/07
1.7 GLV / **dummy** **GLV**	5000 psi differential test – 23/01/07 1000 psi differential test – 22/05/08
1.6 DHSV (No Insert)	2500 psi differential from below – 23/01/07 8000 psi shop test
Secondary Barrier Envelope	
2.1 10" Production Liner	3550 psi with 14,5 ppg OBM – 07/01/07 5000 psi with seawater – 19/01/07 4500 psi with seawater above packer – 23/01/07
2.2 10" Production Liner Cement	1464 psi inflow test differential when 10" shoe drilled 07/01/07
2.4 10" Production Liner Hanger	3550 psi with 14,5 ppg OBM – 07/01/07 5000 psi with seawater – 19/01/07
2.5 13 5/8" Production Casing	4000 psi with 12,5 ppg OBM – 02/01/07 5000 psi with seawater – 19/01/07
2.6 13 5/8" Production Casing Hanger	5000 psi test – 19/01/07 5000 psi test between seals – 01/01/07
2.7 Wellhead, Valves	5000 psi test – 19/01/07
2.8 Tubing Hanger	5000 psi from below – 23/01/07 5000 psi test between seals – 23/01/07
X-mas tree body & valves	8500 psi test against tree test plug
Other Elements	
LBV	2500 psi differential from below – 23/01/07 6000 psi shop test
ASV (2nd of new PTC design)	2500 psi differential from below – 24/01/07 5000 psi shop test on valve
24" x 20" Conductor, Wellhead	1000 psi with seawater – 28/12/06

Figure A.1: Well barrier schematic

Appendix B

Ekofisk X-19 well barrier schematic

Well Barrier Schematic – 2/4-X-19 – Production Well. Rev 0



Comments:

Maximum Operating Pressures:
Tubing: xxx psi
A Annulus (Tbg x 9-5/8") : xxx psi
B Annulus (9-5/8" x 13-3/8") : xxx psi
C Annulus: (13-3/8" x 24") : xxx psi

Barrier Elements	Tests/ Other Verification
Primary Barrier Envelope	
1.1 Reservoir Liner	5000 psi with 8.6 ppg brine (Aug, 03.2001).
1.2 Liner Cement	Returns during cement job.
1.3 Liner Top Packer	5000 psi with 8.6 ppg brine (Aug, 03.2001). Negative test to ± 775 psi differential after displaced to 8.6 ppg brine (Sept, 29.2001).
1.4 Production Casing (Gas tight connection, BTC or not?)	5000 psi with 14.9 ppg OBM (July, 19.2001). 5000 psi with 8.6 ppg brine (Aug, 03.2001).
1.5 Production Packer	5000 psi differential from below (Aug, 06.2001) 4500 psi differential from above (Aug, 06.2001)
1.6 Production Tubing	5000 psi burst with 8.6 ppg brine (Aug, 06.2001). 4500 psi collapse with 8.6 ppg brine (Aug, 06.2001).
1.7 GLV	xxx psi differential test (Date)
1.8 DHSV (TRSV)	2600 psi differential from below (Aug, 06.2001). xxx psi shop test
Secondary Barrier Envelope	
2.1 Production Casing Production casing is common barrier with 1.4 between liner Top and production packer. ZX Packer installed as compensating measure.	5000 psi with 14.9 ppg OBM (July, 19.2001). 5000 psi with 8.6 ppg brine (Aug, 03.2001). 4500 psi with 8.6 ppg brine above packer (Aug, 06.2001). ZX packer tested to xxxx psi from above with xxx ppg mud (date)
2.2 Production casing cement	2544 psi differential inflow test when shoe drilled (July, 20.2001)
2.3 Production Casing Hanger	5000 psi with 8.6 ppg brine from above (Aug, 03.2001). 5000 psi test between seals (July, 19.2001).
2.4 WH & 2-1/16" Valve	5000 psi (Aug, 03.2001).
2.5 Tubing Hanger	4500 psi from below (Aug, 06.2001). Test between seals failed (Aug, 06.2001).
2.6 X-mas tree body & valves	10000 psi against tree test plug (Aug, 07.2001).
Other Elements	
ASV (ASCV innstalled)	xxxx psi differential from below (Date)
13-3/8" Casing, Hanger Wellhead Body, Valves	3500 psi with 12.0 ppg mud (June, 08.2001). 5000 psi between seals (July, 01.2001).
24" x 20" surface csg & WH	1000 psi with 11.1 ppg mud (July, 03.2001).

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Figure B.1: Well barrier schematic

Appendix C

Acoustic velocity for natural gas

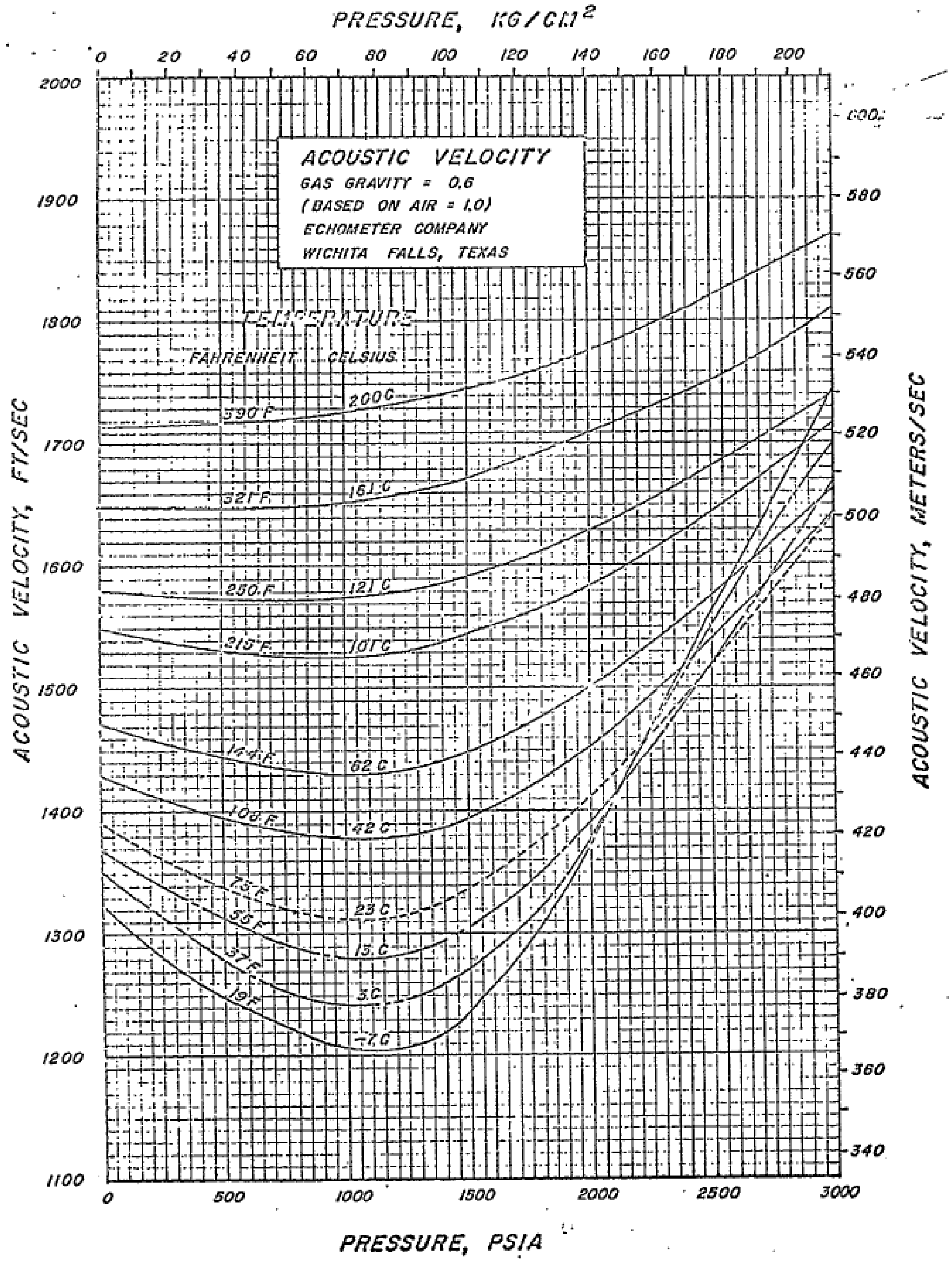

Figure C.1: Acoustic velocity for different temperatures

Appendix D

Matlab implementation code

D.1 Power Spectral Density

```
T = length(signal)/1000;
N = length(signal);
t = [0:N-1]'/N; %% define time
vec_fft = abs(fft(signal))/(N/2); %% absolute value of the fft
vec_fft = vec_fft(1:N/2).^2;
freq = [0:N/2-1]/T;
plot(freq, 10*log10(vec_fft));
axis([0 100 -160 -40])
ylabel('Power [dB]')
xlabel('Frequency [Hz]')
legend('Power spectrum')
```

D.2 Spectrogram

```
[Y,F,T,P] = spectrogram(signal,256,255,512,1E3,'yaxis');
surf(T,F,10*log10(abs(P)),'EdgeColor','none');
axis xy;
axis tight;
colormap(jet);
xlabel('Time');
ylabel('Frequency (Hz)');
```

D.3 Lowpass Filter

```
%% lowpass filter created from FilterBuilder
Fpass = 1;      % Passband Frequency
Fstop = 10;    % Stopband Frequency
Apass = 1;      % Passband Ripple (dB)
```

```
Astop = 60;     % Stopband Attenuation (dB)
Fs    = 1000;  % Sampling Frequency
h = fdesign.lowpass('fp,fst,ap,ast', Fpass, Fstop, Apass, Astop, Fs);
Hd = design(h, 'butter', ...
'MatchExactly', 'stopband', ...
'SOSScaleNorm', 'Linf');

lowpassed = filter(Hd, signal);
plot(lowpassed);
```