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# Numerical calculation of flow acoustic

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# Abstract


Yelling and vibration are large problems discovered by natural gas transport in the North Sea. It is believed these problems occur in flexible pipes that are used to transport natural gas. The flexible risers often called by the phenomenon singing risers. Pressure oscillations generated in the pipe and can be heard as acoustic tones. There is still working with research around this. There are solutions to reduce unwanted vibration and yelling, but they are not entirely satisfactory. One of the solutions is to reduce the speed of the gas. This solution will lead to large expenses since speed will be very low. Until now is several researchers investigating singing riser by experiments and simulations.

A pipe with a cavity was studied in this paper. The problem itself was divided into several part tasks where it was taken into use simulations and experiments. The purpose of the thesis was to model a practical setup. The simulations were performed using the software Palabos, which was used in previous investigations in flow context for acoustics. It was studied the effect of changing cavity height in a tube. In the simulation was spent new version of the pipe model, a pipe with dampers. The simulation results led to model has some errors. There was not enough time to explain these errors, so it had to be used an older version of the pipe model. Resonance frequency was found out to each cavity height. Results showed that by changing the cavity height did not change the resonance frequency. Just a length of cavity affected the resonance frequency. The largest cavity height gave the highest whistling sound. Cancelation of a normal mode with the help of the applied frequency was possible. It may have some milliwatts of applied frequency to cancels normal mode. An acoustic hysteresis was found, but a good explanation of why it was formed was not found.

# Sammendrag

Hylinger og vibrasjoner er store problemer som ble oppdaget ved naturgass transport i Nordsjøen. Man tror disse problemer oppstår inne fleksible rør som brukes til å transportere naturgass. Den fleksible stigerør ofte kalles etter fenomenet syngende rør. Trykksvingninger genereres inne et rør og kan høres som akustiske toner. Det er fortsatt pågår undersøkelser rundt dette temaet. Det finnes løsninger for å reduser uønskede vibrasjoner og hylinger, men de er ikke helt tilfredsstillende. En av de løsninger er å redusere hastigheten på gassen. Denne løsningen vil føre til store utgifter siden hastighet vil være veldig lav. Inntil nå flere forskere undersøker syngende rør ved hjelp av eksperimenter og simuleringer.

Et rør med en kavitet ble undersøkt i denne oppgaven. Selve oppgaven ble delt i flere del oppgaver hvor det ble tatt i bruk simuleringer og eksperimenter. Hensikten med oppgaven var å modellere et praktisk oppsett. Simuleringene ble utført ved hjelp av Software Palabos, som ble brukt i tidligere undersøkelser i strømningssammenheng for akustikk. Det ble undersøkt effekten av å endre kavitet høyde i et rør. I simuleringen ble brukt ny versjon av et rør model, et rør med dempere. Simuleringen resultatene førte til at modellen innholdet noen feil. Det var ikke nok tid til å forklare disse feilene, derfor det måtte brukes en eldre versjon av rør model. Resonans frekvensen ble funnet ut til hver enkelt kavitet høyde. Resultat viste at ved å endre kavitet høyde ble ikke endret resonans frekvens, det var kun lengde av kavitet påvirket resonans frekvens. Størst kavitet høyde ga høyest plystrende lyd. Kanselering av normal mode ved hjelp av tilført frekvens var mulig. Det måtte ha noen milliwatt av tilført frekvens for å kansellere normal mode. En akustisk hysteresis ble funnet ut, men en god forklaring på hvorfor den ble dannet ble ikke funnet ut.

# Preface

The master's thesis summarizes my work of a master degree in Electronics and Telecommunications at the Norwegian University of Science and Technology (NTNU) during the spring semester of 2013.

I would like to thank my supervisor Associate Professor Ulf R. Kristiansen for very good guidance throw work with simulation and experiments and constructive discussions with problems. I further want to thank staff engineer Tim Cato Netland and research fellow Bjørn Kolbrek for vital guidance and input to my work with experiment. Last but not least, I would like to thank Daniel Mazzoni to his work with Palabos codes to the use of the simulation software.

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# Abbreviations

Notur - The Norwegian metacenter for computational science

HPC- High Performance Computing

OpenMP- An application programming interface, Api

MPI- Message Passing Interface

AMD- Advanced Micro Devices

Cpp- C++ source file

Si- The International System of Units

RMS- Root mean square

RAM-  Radiation absorbent material

SPL-Sound pressure level

LBM - The Lattice Boltzmann Method

LB- Lattice Boltzmann

BGK- Bhatnagar, Gross og Krook (term comes from three authors)

OS- Operative system

# Chapter 1

# 1 Introduction

## 1.1 Background

More and more people become aware about singing riser phenomenon that occurred in the North Sea. The floating platforms use the flexible pipes to transport gas from sea installations and drill platforms. These pipes are also called risers, their special shape makes them practical in water because they facilitate fluid flow (example nature gas) in water and do not create difficulties with transport between facilities. The flexible pipes itself is consists of several layers where the inner layer consists of the many cavities. It was observed vibration and whistling noise of risers propagated. The postulate says the internal cavities in the riser that creates these problems. This topic has interested many scientists and researchers, much work was reviewed and much is still unclear.

It was made many observations, research about pipes with cavities. Some of research was performed by experimentation **[ 1]**, **[ 2]** and some by simulation **[ 3]**, **[ 4]** and **[ 5]**. All their work is tied one thing, this thing is pipes with cavities. In one of these researches is described whistling sound closely in details. In the work is explained among other vortex sound and whistling of a cross configuration.[ 6]

## 1.2 Previous work

In an earlier project at NTNU was done research with numerical simulation of aeroacoustic in a pipe. This assignment regarded as introduction of the aeroacoustic simulation with Palabos. First and foremost, get to know the program and further use this as a tool. Purpose of experiment was to investigate how the vortex formation was synchronized with the sound of flow in a pipe. The simulation was done using software Palabos where it was used pre-written coded. Two-dimensional acoustic pipe with a simple cavity was simulated, where it was sent air through the pipe. Cavite dimensions were unchanged during the simulation. Large set of working time was spent on studying Palabos and files with codes. The simulation gave visual results on how vortices occurred in a pipe. Also was measured pressure and velocity in a pipe. For more details about the assignment see I.Eriksen. **[ 7]**

## 1.3 Structure of the report

Rapport consists of simulations and experimentations, as well as conducting tests of abel facility. Before this, it will be briefly introduced theory that will be explained some results of job. Also will be provided some chapters where will be described more accurately the experimentation and the simulation. After the completed results, the problems will be discussed. The report will be end with conclusion.

Most part of this thesis will consist of the acoustic part, the effect of sound on the cavities. The other part of the thesis will consist of research. The purpose of the experiment is to model a practical setup where has studied experimentally interaction between sound fields in a flow pipe with an internal cavity and the acoustic field. In addition, it will be made some small tasks. First will be done a simulation, where a pipe will be treated with a simple cavity. To have more realistic boundary conditions will be simulated a pipe with acoustic dampers in the pipe upstream of the cavity pipe. Simulation of a pipe will be conducted with various cavity heights. A program that will be used for the simulation is called Palabos. This software is based on the Lattice Boltzmann method, values uses its own Lattice Boltzmann. An example: sound of the speed in Palabos is $\frac{1}{\sqrt{3}}$. Then will be done some experiments with a simple pipe where various cavity heights will be used. Vacuum clear will be sent air through a pipe. In experiment will be studied whistling sound which occurs when air will be sucked in over a cavity in a pipe. It will be investigated what frequency it is on the tones that occur at different flow rates and noise levels. It will be reviewed how the whistling sound is affected by different cavity height. Also will be performed an experiment with cancellation of the flow generated sound by introducing an added pure tone to the system. Acoustic hysteresis will be studied by experiments.

All the results will be analyzed using theory.

# Chapter 2

## 2 Theory

To understand the motivation behind the thesis this part contains the basic acoustic theory. The work done in the thesis is based on this theory. Some central concepts such as acoustic waves, resonance frequency and their application are presented here.

### 2.1 Boundary Conditions in Fluid Mechanics

In many applications of physics, boundary conditions have a main role. One of these conditions is No slip condition. Velocity of the fluid at solid boundary is equal velocity of that the solid surface. It says that moving fluid in contact with a solid body will have the same velocity as the velocity of the solid body, see equation (2.1(1)). In most situations a solid surface velocity is zero, this causes the fluid velocity is zero. **[ 8]**

$$v_p\big|_{at\ the\ boundary} = V_{solid\ surface} \qquad 2.1\ (1)$$

### 2.2 Resonance or normal modes

In physical system resonances can be mechanical, electrical, acoustic and orbital resonance. Vibrations inside objects can experience resonance. An example of objects can be a pipe. Such objects were also called resonators. The resonance frequencies of the resonators are called normal modes. The resonance states also depend on whether the ends of the pipe are closed or open. Let's look at an example where both ends are open in a pipe, equation (2.2 (1)) shows the mathematical expression. Vibrations inside a pipe travel as waves, they move in the positive x direction and negative x direction at a constant speed. This phenomenon also leads to the formation of standing waves, see next chapter (2.5 Standing waves in a pipe). If the distance between beginning and end of the pipe is L (length of one end) so the distance of both ends is 2L. The condition for resonance in a resonator is the distance of both ends will be equal to whole number wavelengths of the wave.

$$2L = n\lambda_n, \qquad where\ n = 1,2,3\ ... \qquad 2.2\ (1)$$

By using of the basic equation of frequency (f = v / λ) can resonance frequency written as equation (2.2(2)) where v is the velocity of a wave.

$$f_n = \frac{nv}{2L}, \quad where\ n = 1,2,3\ ... \qquad 2.2\ (2)$$

The fundamental frequency is equal to the distance between the overtones of a minimum frequency. This means that the first normal mode of vibration will be equal to the fundamental frequency. Comparison of closed-open pipe with open-open pipe shows that the fundamental frequency in open-open pipe has double frequency of the fundamental frequency in closed-open pipe. The mathematical expression for closed-open pipe shows equation (2.2(3)).

$$4L = (2n - 1) * \lambda_n, \qquad where\ n = 1,2,3\ \ldots \tag{2.2 (3)}$$

To find resonance frequency for closed-open pipe shows equation (2.2(4)).

$$f_n = \frac{(2n - 1)v}{4L}, \qquad where\ n = 1,2,3\ \ldots \tag{2.2 (4)}$$

Each resonance frequency can be presented graphically. Figure below shows the graphical presentation of the normal modes, where 1st harmonic corresponding to the fundamental frequency and 2nd harmonic corresponds to the 1st overtone. The normal modes in open-open pipe will look different compared to normal modes in closed-open pipe.

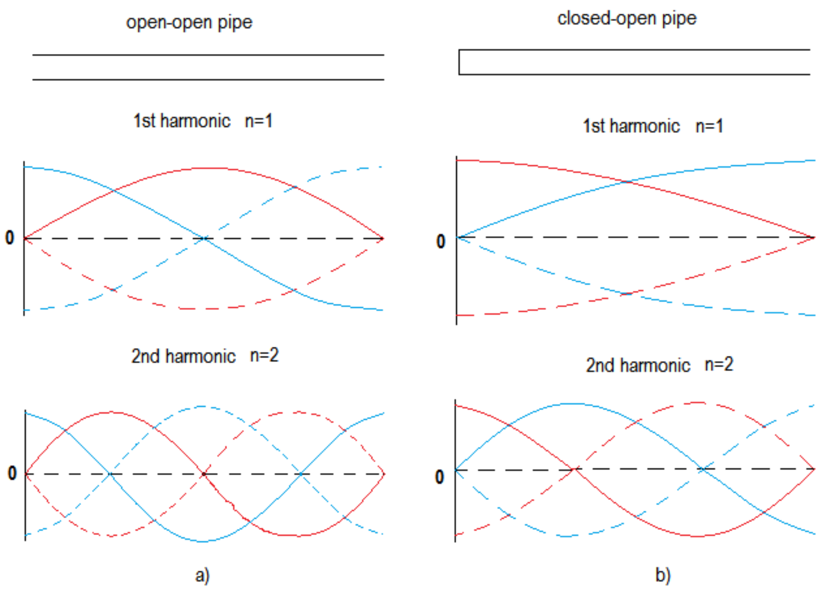



Figure 2-1: Resonance condition in a smooth pipe. a) The resonance condition with two open ends. b) The resonance condition with an open and a closed end.

A Comment to figure 2-1: The red line is the amplitude of the variation in pressure. The blue line is the amplitude of the variation in the air flow. A full blue and red line show snapshot at fixed time. Dotted blue and red lines show the snapshot at later time.

Boundary conditions for pressure and air flow are: variation in pressure is zero at the open end, and a maximum at a closed end. The variation in the air flow will be opposite to the variations in pressure. That is, the variation in the air flow has a maximum at an open end and zero at a closed end.

## 2.3 Introduction to sound and waves

The sound that comes to receiver (microphone) is actually sound waves which move through medium, like air. These sound waves created by sound vibrations from the source (Loudspeaker). The number of waves produced per second is pitch, in physics is defined as the frequency [Hz]. In the frequency scale 0 [Hz] - 2 [MHz] waves divided in three groups. -Infrasound waves (0 -20 [Hz]), -acoustic waves (20 [Hz]-20 [kHz]) and -ultra sound waves (20 [kHz]-2 [MHz]). In this thesis will be used acoustic waves. Low frequencies will have a shorter period than high frequencies. The wavelength is a form of one period, the distance sound travels. The volume is determined by the amplitude usually specified in decibels [dB]. Using the frequency and amplitude may appear how the sound is. The frequency indicates whether the sound is dark or light and amplitude indicates how weak or strong sound is. Example of sound wave in standard x-axis and y-axis shows figure below.

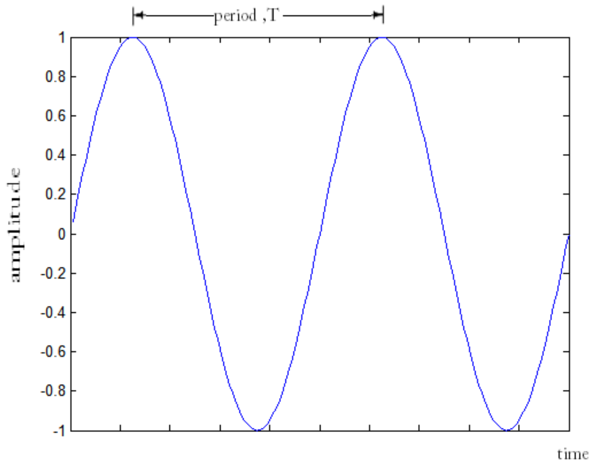



Figure 2-2: Plot of sine wave, where the x-axis is time and y-axis is amplitude of signal.

## 2.4 Pressure, rms and sound pressure level

In fluid dynamics, total pressure expressed of static pressure and dynamic pressure. The static pressure is the pressure at a specific point in a fluid, while the dynamic pressure is the component of fluid pressure that represents motion, total pressure see equation (2.4(1)). In the acoustic information transfer is an important part. Since the static pressure gives no information about the transmission will sound pressure or dynamic pressure defined as total pressure minus the static pressure, see equation (2.4(2)). $p_t$- total pressure, $p_s$- static pressure, $\frac{1}{2}\rho v^2$ *or* $p$-dynamic pressure or sound pressure, unit of pressure is (Pa), $\rho$ – density of the fluid and $v$ - the flow velocity.

$$p_t = \frac{1}{2}\rho v^2 + p_s \qquad 2.4\ (1)$$

$$p = p_t - p_s \qquad 2.4(2)$$

There are several way to measure pressure, one of the most usable way is the root mean square (rms) of the instantaneous sound pressure over a given time interval. Generally sound pressure levels appear in logarithmic scale, equation (2.4(3)) shows a mathematical expression for sound pressure level.**[ 9]**

$$L_p = 10\log_{10}(\frac{P_{rms}^2}{P_{ref}^2}) \qquad 2.4(3)$$

## 2.5 Standing waves in a pipe

As it known for mechanical waves are two types of wave motion. First type of wave motion is transverse waves that occur in stretched strings, where the particle vibration is perpendicular to the direction of wave propagation. It says that when a wave is reflected from an end of the string interferes with the original wave will create standing waves in a vibrating string. Second type of wave motion is longitudinal waves. In longitudinal waves that occur in pipes the particles of the wave vibrate parallel to the direction of wave propagation. This type of wave motion will be discussed in the thesis. Standing waves also occur in a pipe when a sound wave is reflected from the end of a pipe. For a wave component A, waves travelling in positive direction of the pipe and for a wave component B, waves travelling in negative direction of the pipe. The sum of these two components will create the total standing wave, see figure 2-3. For a closed pipe end, the wave will travel to the closed end of the pipe and back in the opposite direction. For an open end, the wave will be transmitted and reflected back. This happens because of the impedance at the open end of the pipe will be different.

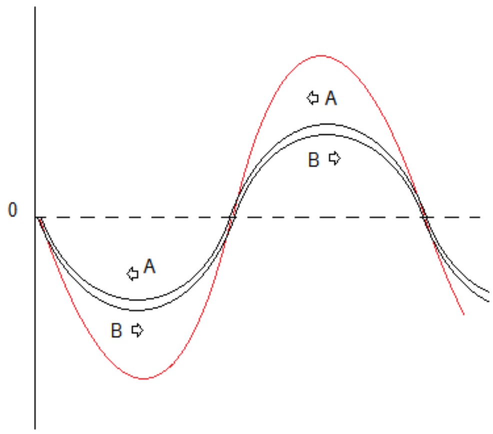



Figure 2-3: Standing waves, where A is incident wave and B is reflected wave. Red wave is resultant wave.

The acoustic pressure maximum is represented by equation (2.5(1)). The acoustic pressure minimum is represented by equation (2.5(2)). $\hat{A}$ *and* $\hat{\hat{B}}$ are the wave components, k is the wave's wave number and x is a point along the x-axis.

$$p_+ = \hat{A}e^{-jkx} \qquad 2.5(1)$$

$$p_{-} = \hat{B}e^{+jkx} \qquad 2.5(2)$$

## 2.6 Sound power and intensity

To find sound or acoustic power we have to know definition of the sound intensity. The sound intensity indicates the time average rate of energy flow transmitted through a unit area in the specified direction. The mathematical expression for the sound intensity is given by equation (2.6 (1)).

$$\vec{I} = \frac{1}{T}\int_{0}^{T} p(t) * \vec{u}(t)\, dt \qquad 2.6(1)$$

Where T is period of the time of a harmonic wave, p (t) is pressure and $\vec{u}(t)$ is particle velocity. The Si unit form for sound intensity is watts per square meter ($\frac{W}{m^2}$). By using theory (2.5 standing waves) can be found equation for particle velocity and equation for acoustic pressure. For a plane harmonic wave traveling in the positive x direction particle velocity is given by equation (2.6(2)) and acoustic pressure given by equation (2.6(3)).

$$\vec{u}(x,t) = Ue^{j(wt-kx)} \qquad 2.6(2)$$

$$p(x,t) = Pe^{j(wt-kx)} \qquad 2.6(3)$$

By setting this two equations, (2.6(2)) and (2.6(3)) into equation (2.6(1)) will give the time-average acoustic intensity in the positive x direction, equation (2.6(4)).

$$I_x = \frac{P^2}{2\,\rho_0 c} \qquad 2.6(4)$$

where P is sound pressure amplitude, c is the speed of sound in the medium and $\rho_0$ is the density. By setting the mean-square sound pressure, $P_{rms}^2 = P_{eff}^2 = \frac{P^2}{2}$ the intensity that passes in the x-direction can also be written as equation (2.6(5)).

$$I_x = \frac{P_{eff}^2}{\rho_0 c} \qquad 2.6(5)$$

For a plane wave harmonic wave traveling in negative x-direction acoustic intensity will be negative.

All kinds of machinery and other equipment which creates mechanical oscillations radiate sound energy. Sound power is a measure of the speed of sound energy radiation. To know how much power passes through a certain surface can be finding by equation (2.6(6)), where

P or W is power, S is a certain surface and I is intensity. In the Si system of units the unit power is (W).

$$P = W = S * I \tag{2.6(6)}$$

To get the downstream power for plane waves traveling in a pipe, set S for the cross section of the pipe and I for the net intensity, see equation (2.6(7)).

$$W_{downstream} = \pi r^2 * I_{net} = \frac{\pi d^2}{4} * I_{net} \tag{2.6(7)}$$

where r is described a radius of a pipe and d described a diameter of a pipe.

To get the upstream power for plane waves traveling in a pipe, have to measure sound pressure at the pipe inlet. In this case intensity will be outside of the pipe and area will equal $4\pi a^2$, where a will be the distance from the measuring point to the pipe inlet, see equation (2.6(8)).

$$W_{upstream} = 4\pi a^2 * I_{out} \tag{2.6(8)}$$

From equation (2.6(8)) a sound field for intensity assumed to be the free field, where there are no reflections. The sound pressure measured only from the pipe.

## 2.7 End correction

A simple representation of the resonance frequency in a pipe shows equation (2.2(2)) for open-open pipe or for closed-open pipe equation (2.2(4)). It is well known that the practical resonant frequency comes out lower than theoretical. This is because flow particle vibrates a short time outside edge of the pipe. By using end correction is shown that a pipe will be longer than its physical length. In the calculation of the resonance frequency length should be the sum of the end correction and physical length. End correction is the distance from the pipe end, usually called the 'e' which is a constant. The effective length ($L_{eff}$) of a pipe can be found by flanged pipe equation (2.7(1)) or pipe unflanged equation (2.7(2)). For a pipe where is unflaged end on one side of a pipe and flanged end on other side of a pipe is ($L_{eff}$) equal equation (2.7(3)).

$$L_{eff} = L + 0.6r \tag{2.7(1)}$$

$$L_{eff} = L + \frac{8r}{3\pi} \quad 2.7(2)$$

$$L_{eff} = L + \frac{8r}{3\pi} + 0.6r \quad 2.7(3)$$

where L is the physical length of a pipe and r is the radius of a pipe. As long as wavelengths much larger than the radius of a pipe, the resonance of unflanged and flanged pipes are valid. This theory provided for a smooth pipe.[ 10]

## 2.8 Reynolds number in a pipe

Reynolds number is a dimensionless number which is used in fluid mechanics. Reynolds number is the quantity which is equal to the ratio between inertial forces and viscous forces, see equation (2.8 (1)). Also, this quantity is used to estimate whether a liquid flow through a pipe is laminar or turbulent. In reality, the flow of real fluids is occurred under three different regimes, a laminar flow, transitional flow and turbulent flow. A laminar flow can be described as liquid particles slide over each other forming a straight line, so that at a moment speed of all points is the same. A typical Reynolds number for a laminar flow is around 2000. A turbulent flow is the opposite of a laminar flow. That is, fluid particles are mixed together creating small vortices. The speed of the fluid particles will change from one point to another causing chaotic vibration. Reynolds number tends to be around 4000 to indicate that there is turbulent flow. Between 2000 and 4000, Reynolds number stands for transition flow. When the flow particles stops slide over each other, they create small vortices. Based on what was noted, conclusions are the more stronger vibrations are the more higher Reynolds number is. **[ 11]**

$$Re = \frac{u * l}{v} \quad 2.8(1)$$

where Re is Reynolds number, u is fluid velocity [m/s], l is the diameter of the pipe [m] and v is the viscosity $[m^2/s]$.. Since the experiment and the simulation performed with flow in a pipe Reynolds number is important in that sense.

In the experiment, [11] was found out that in order to show some turbulent Reynolds number should be above approx. 2000. Turbulent for the project is very important since the study will involve vortices.

## 2.9 The Lattice Boltzmann method

When data machine became popular in science, using computers was created methods to an alternative framework for the mathematical description of physical systems. Such methods are often called cellular automata. An example of a cellular automaton is the Lattice Boltzmann Method. Physical systems can be simulated at three different scales, as microscopic, mesoscopic and macroscopic. In mesoscopic scale tracked movement of distributions of particles, this particular scale is used in the LBM. On the lattice the particle distributions makes up the total fluid. To perform the LBM must be performed a variety of mathematical rules, see in [ 12]. In the LBM can particles colliding with each other and not colliding. For a collusion using an operator called BGK operator [ 13]. This operator used in this thesis, in the simulation.

The system of method or algorithm consists of four steps, where each step realis on previously step, taken from page 26 of [ 12]:

1) From the current distribution of particles, calculate the macroscopic quantities for all node.

2) Calculate the equilibrium distribution for all node from the node's macroscopic variables.

3) Calculate the post collision distribution of particles for all fluid nodes.

4) Move particles one step in the direction of their velocity.

Figure 2-4: Lattice Boltzmann algorithm.

## 2.10 Hysteresis

Hysteresis it is a kind of property systems, where the effects of the intake system has experience with a certain delay. A typical hysteresis loop will be the distance between two lines where there is a common starting point and end point, see Figure 2-5. This type of loop is used extensively in physics when it is talking about magnetic hysteresis, thermical hysteresis and elastic hysteresis. A good example of magnetic hysteresis when the magnetic field is applied to iron and some atoms will pull the magnetic field. On the way is iron exposed to magnetic fields. Thermical hysteresis caused by temperature change, such as a thermostat that controls a heater and set temperature. Elastic hysteresis the most famous hysteresis occurs when the material is elastic, to understand it you can stretch the rubber.

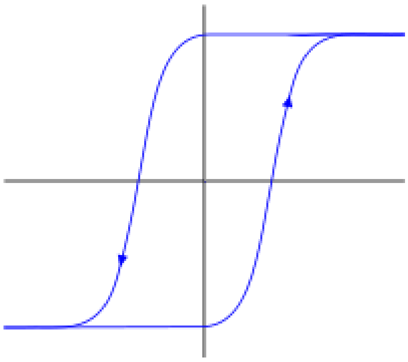


Figure 2-5: Hysteresis loop.

The hysteresis phenomenon is also used in other contexts, such as biology, economics where hysteresis describes the lagging effect. Hysteresis can be found in electrical equipment too. **[ 14]**

# Chapter 3

## 3 High Performance Computing, Simulation and Experement

This section presents what is Notur, what opportunities it can provide to every user of Notur. Also it is given a small introduction about hardware and a little about shell-script. All this is provided to get an insight on how and where simulation of the task is completed.

### 3.1 High Performance Computing

In Norway, there is metacenter for computational science called Notur. This project was prepared for a Norwegian infrastructure for HPC. The aim of the project is to create a new national HPC infrastructure and affect computational science. The project will Notur contribute to the development of a nationwide network. Role metacenter is that it coordinates of objects HPC, which can be found in various universities in Norway, and the University of Iceland. NTNU, University of Bergen, University of Oslo and the University of Tromsø with RCN, they are all financial partners to Notur project.

### 3.2 Hardware

Today there are several facilities where people can get access to. Each facility has got its own name as abel, gardar, hexagon, stallo and vilje. The facilities are different, their specification makes them unique. Each individual facility has some positive and some negative. Some of them are faster than others and some have a greater capacity to store files than others, see table (3-1).

| | Parallel jobs | Serial jobs | Large I/O jobs | Memory per node | MPI applications | OpenMP applications |
|---|---|---|---|---|---|---|
| abel | yes | yes | yes | 64 GB | > 256 | 16 |
| gardar | yes | yes | yes | 24 GB | > 256 | 12 |
| hexagon | yes | no | yes | 32 GB | > 256 | 32 |
| stallo | yes | yes | yes | 32 GB | > 256 | 16 |
| vilje | yes | no | yes | 32 GB | > 256 | 16 |

Table 3-1: Specifications to different facilities. *Retrieved from NOTUR.*[ 15]

The table shows the available systems with respect to the type of applications they are suited for. All of five facilities can parallel jobs and large input / output jobs, but not all can do serial jobs. The numbers that can be seen in Table, OpenMP applications shows the maximum number of cores that can be used per node. For example hexagon system designed for large parallel applications where speed of job takes the main roll. Hexagon has two 16-core AMD processors per node, this makes for hexagon to perform various applications quickly. One of the applications can be computational physics. For example abel has the largest memory per node compared to other this makes abel to work with large tasks. [15]

## 3.3 Abel

Installation Abel is one of the most powerful systems in the world which was named after Niels Henrik Abel (1802-1829), a Norwegian mathematician. This HPC facility can be finding in the University of Olso (UiO). This computing cluster has over 600 computers and over 10, 000 cores (CPU). It is not everyone who can access the HPC facility. Access to Abel determined by several partners who own Abel. Searching is done through e-mail in addition must be applied computational time to a project. Each user gets his storage space on facility where he can use for his own use.

Abel uses operative system Linux (64 bit CentOS 6). To connect from OS Windows to Linux on abel an user need to have a program for remote terminal which supports a network protocol (SSH file transfer protocol). An example would be putty which is freeware and can be downloaded from the internet. Also, might be nice to have X11 server installed, because this application to the program lets an user open the windows. This makes possible to use the windows in some applications, for example if an user want to see a picture.

Table 3-2 presents some useful commands which can help with an job. For a serial or/and parallel job is normally used a shell script which can be made by command vim.

| ***The command*** | ***Description*** |
|---|---|
| Sbatch ‘’your jobscript’’ | To submitt your jobscript. |
| Cost –p ‘’number of project’’ | To see how many CPU hours has been allocated and has used. |
| Squeue –j ‘’users name’’ | List jobs in the queue belonging to the users. |
| Ls | To find out what is in your home directory |
| Cd | To change to the directory you have made |
| make | To get its set of compile rules from a text file called Makefile |
| Scancel ‘’jobid’’ | To cancel running or pending job |
| vi | To show a screen-oriented display editor |

Table 3-2: Some useful commands in abel.

Figure 3-1 presents a simple shell script where a parallel job is written. *module load openmpi.gnu* call parallel job where GNU stands for compiler. The compiler is used to compile the program. To run a task is used the command *mpirun ./(task)* where task is a name of the file which will be done. Also, a shell script should has the command, *#SBATCH –ntasks=(number of cores)* where number of cores describes the number of cores to be used in an job.**[ 16]**

```
#!/bin/bash
#job name:
#SBATCH--job-name=corrugjob1
#project name:
#SBATCH --account=nn2332k
#
#wall clock limit:
#SBATCH --time=08:00:00
#
#Max memory usage:
#SBATCH --mem-per-cpu=1G
#
#Number of tasks(cores):
#SBATCH --ntasks=16
## Set up job environment
source /cluster/bin/jobsetup
module load openmpi.gnu
module load imagemagick
## Copy input files to the work directory
cp corrug2 $SCRATCH
##Do some work
cd $SCRATCH
mkdir tmp
mkdir tmp/gif
##file to be copied to $SUBMITDIR
chkfile $SCRATCH/tmp/.*
##./corrug
mpirun ./corrug2
```

Figure 3-1: A simple shell script.

# Chapter 4

## 4 Simulation

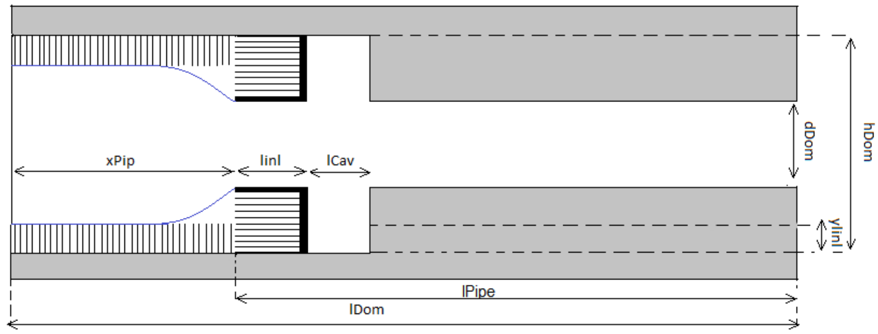
This section presents the simulation, a small introduction about the program, pipe models and a little about the program codes. Since the simulations are done with different cavity height, it had to make some codes. Therefore, chapter 4 has the section about codes and program.

### 4.1 Software , Palabos

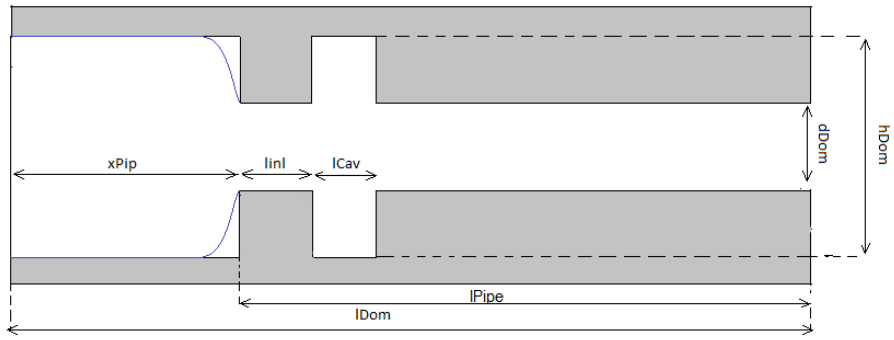
Palabos is software that was used during the simulation which is based on LBM. The software is open source code which is made for Computational Fluid Dynamics to solve different problems. There are several versions of Palabos on web page. The latest version is version 1.2 realise 0 . Instead of using the latest version of Palabos will be used version 1.1 realise 1, that is next to the last version of Palabos. For this thesis will be simulated a simple two dimensional pipe with a different cavity height. Flow will be sent through a pipe. Results will be given numerical and as pictures of situation. All simulations will be performed on Linux OS. To find information about Palabos see home page to Palabos. **[ 17]**

### 4.2 The pipes in simulering

The simulation will be done with two models, the model 1 which is a closed-open pipe with dampers and the model 2 which is a closed-open pipe without dampers. Both codes, for model 1 and model 2 are written by Daniel Mazzoni. Model 1 is not an entirely new model, but the upgraded version of the model 2. Both models presents of themselves as two dimensional models with specific dimensions. Each model consist of a short pipe and a long pipe which are connected, see figure 4-1 where short pipe –xPip and long pipe –lPipe. lPip is the flow entry section which has a small cavity that is located close to the end of a pipe. Since is it difficult to implement acoustic conditions in Palabos, boundary conditions relate to the basic flow. Left of the inlet (linl) is defined an initial turbulent flow where blue lines defines the initial flow confining region. Right of the cavity (lCav) is given an outflow condition, for details see **[ 18]**. The other boundaries like the complete black lines in the system are set as bounce back boundaries. To have more realistic boundary conditions the new model includes acoustic dampers in the pipe upstream of the cavity pipe. Data of velocity and density which the simulation will be carried out will be exported from 50 equally spaced locations along the centerline of the pipe. Also will be exported images of flow simulations, the images will be shown how the flow in the pipe changes with time. Colors on images which can be seen is indicating how great velocity, the darker red color is the higher the velocity of the flow is. The blue color is opposite of the red color. Palabos works with dimensionless units, conversation of the units will be done in cpp, see manual for details **[ 17]**. The simulations will be run by HPC in Oslo. Connection to the HPC will be done throw the university computer at NTNU. In new version of cpp, model 1 Re and N will be changed, it will be taken half of the originally value. Re and N in model 2 will not be changed, see next section (4.3 The dimensions). Through various simulations situations only the height of cavity will be changed, diameter and total length will be stayed the same.




a)




b)

Figure 4-1: View of simulation model. a) Model 1-pipe with dampers. b) Model 2 - pipe without dampers. The blue line in both models defines the initial flow confining region.

Figure above presented are only sketch of the models. What makes the difference between model 1 and model 2 are dampers which sitting in the pipe and the dimensions of the pipe.

## 4.3 The dimensions

Parameters of the physical system, the model 1:

- Size of the multi-block, mesh grid: 2400×600 cells, (Length x Width).
- Size of domain: 0.12 [m] × 0.03 [m], (lDom x hDom).
- Pipe length: lPipe=0.08[m].
- Pipe inside diameter: dDom=0.01[m].
- Inlet silencer: xPip=0.04 [m] × yInl=0.05 [m], linl=0.01[m].
- Cavity length: 0.01[m].
- Cavity height: 1/4[cm], 1/2 [cm], 2/3 [cm] and 1 [cm].
- Sound speed: $c_0$=340[m/s].

- Kinematic or dynamic viscosity of the fluid (air): $v$=0.0000151 [m$^2$/s].
- Fluid velocity on the center of the pipe: $v_0$=10 [m/s].
- Reynolds number in the simulation: Re=6500.

Parameters of the physical system, the model 2:

- Size of the multi-block, mesh grid: 2000×500 cells ,(Length x Width)
- Size of domain: 0.08 [m] × 0.02 [m], (lDom x hDom)
- Pipe length: lPipe=0.06[m].
- Pipe inside diameter: dDom=0.01[m].
- Inlet : xPip=0.02 [m], linl=0.01[m].
- Cavity length: 0.005[m].
- Cavity height: 1/8 [cm], 1/6 [cm], 1/4 [cm], 1/3 [cm], 3/8 [cm] and 1/2 [cm].
- Sound speed: $c_0$=340[m/s].
- Kinematic viscosity of the fluid: $v$=0.0000151 [m$^2$/s].
- Fluid velocity on the center of the pipe: $v_0$=10 [m/s].
- Reynolds number in the simulation: Re=5800

Parameters in Palabos units:

- Sound speed in the dimensionless lattice Boltzmann system: $c_{LB}=1/\sqrt{3}$
- Fluid velocity is given by the invariance of the Mach number: $u_{LB}=\frac{vc_{LB}}{c_0}\approx 0.017$

For both models kinematic viscosity is same. Kinematic viscosity was chosen to $15.1* 10^{-6}$ [m$^2$/s], this corresponds to 20° C temperature in a pipe. Since all things considered it recommended the indoor temperature 19-23° C. Therefore it will be used $15.1* 10^{-6}$ [m$^2$/s] kinematic viscosity in a simulation. The value was calculated using the online calculator **[ 19]**. To get stability of the numerical simulation Reynolds number will be exceptionally lower than the Reynolds number should be the basis of calculation for both situations. From equation (2.8(1)) Reynolds number equal to 6623. As indicated by the simulation parameters for model1 it will be simulated four different height of cavity, and for model 2 it will be simulated six different height of cavity.

The simulation data will be interpreted LB dimensions. For both models a sampling frequency will be equal 100 frequency number. A sampling frequency calculated from equation of sampling time interval in LB unit, $T_S = \frac{1}{F_S}$, where $F_S$ is sampling frequency and $T_S$ sampling time interval. In appendix A1 can be found detailed unit calculation.

## 4.4 Simulations with different cavity height

In first set of simulation will obtained a LB dynamic pressure spectrum. The simulation will be given the result of LB velocity and LB density. By equation (2.4(1)) LB density will be converted to LB dynamic pressure. First will made simulation with model 1 with different cavity height and try to find the difference between them. This will be needed fft transform and spectrum of LB dynamic pressure. Also, will done analyses around results. Next simulation will be performed for model 2.

As has been noticed the model1 will be simulated with four different heights of cavity. Heights of cavity will be chosen by implementing some codes in cpp file. The code itself describes four blocks in the file where one of block describes cavity. Height of cavity is defined in the figure 4-2. Line 6, next last one line is defined height of cavity which is 1/4 [cm].

```
// Create a block distribution with the three added blocks.
plint envelopeWidth = 1;
SparseBlockStructure2D sparseBlock(nx, ny);
sparseBlock.addBlock(Box2D(xb0, xb1-1, y0, y5), sparseBlock.nextIncrementalId());
sparseBlock.addBlock(Box2D(xb1, xb2-1, y0, y5), sparseBlock.nextIncrementalId());
sparseBlock.addBlock(Box2D(xb2, xb3-1, (y2)*3/4, (y5-(y2*3/4))), sparseBlock.nextIncrementalId());
sparseBlock.addBlock(Box2D(xb3, xb4,   y2, y3), sparseBlock.nextIncrementalId());
```

Figure 4-2: Creation of height of the cavity for Model 1.

In the case of model 2, height of cavity will be defined a little bit differently. A new dynamic will be defined for cavity in the model, see figure 4-3. y4 and y5 from the figure describes height of cavity, one at the bottom and one at the top, see figure 4-1.

```
 //Define the hight of the cavity
defineDynamics(lattice, lattice.getBoundingBox(),
               new RectangleShapeDomain2D<T>(xcav,xcav+lcav,y0,y4),
               new plb::BounceBack<T,DESCRIPTOR>);

defineDynamics(lattice, lattice.getBoundingBox(),
               new RectangleShapeDomain2D<T>(xcav,xcav+lcav,y5,y3),
               new plb::BounceBack<T,DESCRIPTOR>);
```

Figure 4-3: Creation of height of the cavity for Model 2.

# Chapter 5

# 5 Experiments

The start of this chapter presents the physical experiments. Experiment setup, instruments and place where the experiments were done. This chapter contains some detailed descriptions how every single experiment is done and what is needed to perform experimenter.

## 5.1 About the physical experiment

The experimental laboratory will not be done in anechoic room. Physical experiment will be done in audio lab in NTNU, c-block basement. The setup was used in previous tasks as Anders Krogvig **[ 20]**. In addition to previous model here will be done some modifications. This setup consists of a simple metallic pipe with some holes, as called the pipe 1. Holes can be used to take the necessary measurements inside the pipe. In this experiment, two openings will be unused and the third opening will be used to measuring device, - velocimeter 2, see figure 5-1. Measuring device task is to measure the flow velocity [m/s] inside a pipe. The flow velocity will be measured between around 10 and 30 [m/s]. Later in the thesis also will be used a pipe that will be assembled of several metallic parts, on the task will be called the pipe 2. Pictures of experiment setup see in Appendix B2.

It is also will be used different cavity devices in experiments that will be connected to the end of the pipe. One of these devices has cavity height 5 [mm], others two have cavity height 1 [mm] and 8[mm]. Also device with 5 [mm] is possible to adjust cavity length which makes it more practical than other devices. The other two units had fixed cavity length and cavity depth. Both of them have cavity length 10 [mm]. A wood box which will be used in experiments presented himself as an intermediary between metallic pipe and vacuum cleaner. A loudspeaker transducer will be mounted on the side of the box, so that the front side of loudspeaker will be turned inward of the box. A metallic pipe will be connected to a wood box by help of a metallic device which will be screwed in to a wood box. This will be done to avoid any gaps between elements. Connection between vacuum and a wood box will be done differently. It will be used plasticine to cover openings between connections. Figure 5-1 shows the view of experiment setup.

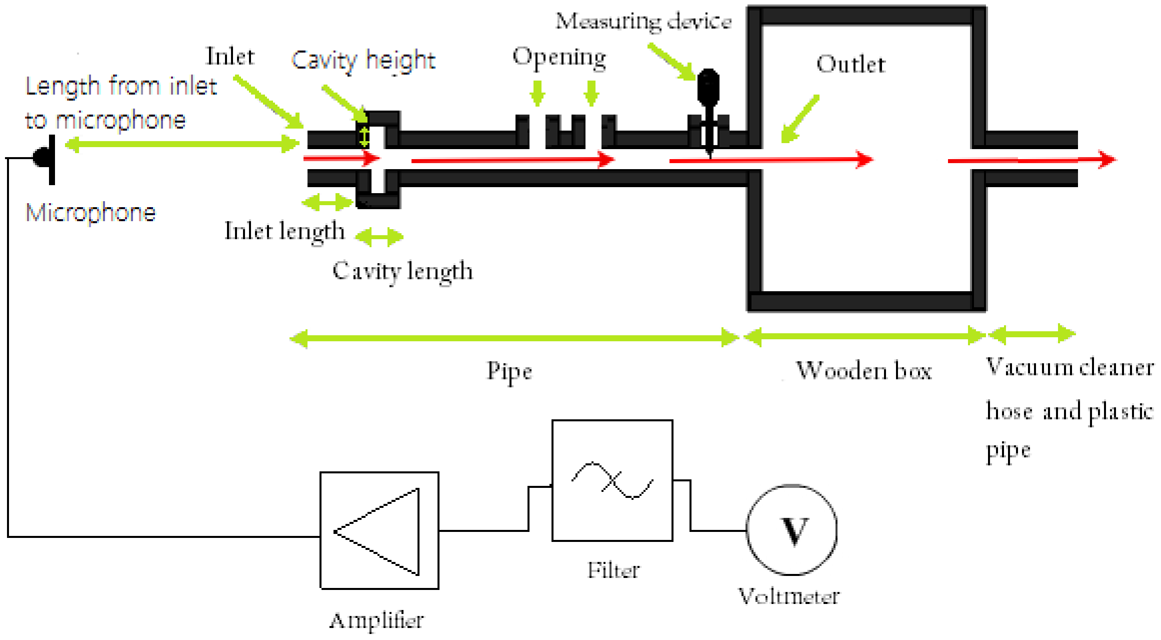



Figure 5-1: Schematic of the experimental setup and microphone setup, the red arrows shows direction of the air flow.

Measurements will be getting by microphone, which will be placed as it can measure data along the centerline of the pipe. Microphone will be stand still on a stand. The stand will be placed all the time on the table, see pictures in Appendix B2. By default distance of the microphone will be 0.5 [m], in some experiments this value will be changed. Microphone connection can be found in figure 5-1. A bandpass filter will be used in experiments. This will be help to take measurements for each mode. A bandpass filter passes frequencies within a certain range. Range comprises of a high pass filter and low pass filter, so that high-pass filter blocks frequencies that are too low and low pass filter blocks frequencies that are too high. Idea behind the measurements is that measurements will be done only from a source, namely the inlet of a pipe. To help realize it will be used acoustic mineral wool. This will be placed around on the table and some on a wooden box. Also will be used a piece of a pyramidal RAM, see in the picture, Appendix B2. This will be help a little bit to reduce unwanted sound reflections, especially from the table. In experiment with cancellation of the sound will be used a probe which will be attached to a microphone. Length of the probe is 80.5[cm] and diameter inside of probe is 0.4 [cm]. This probe will be used in one of experiments where will be measured sound pressure level inside a pipe.

An analog voltmeter will be used in some experiments where the sound pressure levels will be read, voltmeter setting will be set to slow RMS [dB]. To have accurate measurements correct will be the calibration granted in experiments that in future will be they used with standards. Calibration will be done with a simple calibrator with 94 [dB] output at 1000 [Hz] with a special opening for the use of microphones. Calibration will be happen in the same room where will be conducted experiments. Setting for bandpass filter will be set to 990-1010[Hz]. Calibration of microphone with probe will be performed by comparing the microphone without probe for two frequencies. The measurements will be made outside the pipe at certain distance from the inlet of a pipe to the microphone. Also, it will be provided distance. The distance will be similar as for microphone well as for probe with microphone. Velocimeter will be calibrated by use the default option in instrument. In some experiments will be used a mobile phone with an acoustic program to read frequency and measure sound pressure level. The experimental equipment can be finding in Appendix B1.

## 5.2 The dimensions.

Pipe number 1:

- Diameter of the pipe: 4.3 [cm].
- Length of the pipe: 85 [cm].
- Length of the cavity: 1 [cm]- 2 [cm].
- Height of the cavity: 0.1 [cm], 0.5 [cm], 0.8 [cm].
- Kinematic or dynamic viscosity of the fluid (air): $v$=0.0000151 [$m^2$/s].
- Fluid (air) velocity: around 10 [m/s] – 30 [m/s].
- Reynolds number: 28477-85431.

Pipe number 2:

- Diameter of the pipe: 4.3 [cm].
- Length of the pipe: 55 [cm].
- Length of the cavity: 1 [cm].
- Height of the cavity: 0.1 [cm], 0.5 [cm], 0.8 [cm].
- Kinematic or dynamic viscosity of the fluid (air): $v$=0.0000151 [$m^2$/s].
- Fluid (air) velocity: around 10 [m/s] – 30 [m/s].
- Reynolds number: 28477-85431.

For both pipes was temperature measured inside pipes by velocimeter 2. The measured temperature led to the viscosity was equal 0.0000151 [$m^2$/s]. Reynolds number was calculated by using the equation (2.8(1)). According to theory this Reynolds number was very high which resulted to turbulence.

## 5.3 Acoustic modes

Acoustic modes will be found by calculation with equation from theory (2.2 Resonance or normal modes). Not least, mobile phones with acoustic programs (''deciBel'' and ''Spectrum analysator'') will be help during exercise. Pipe 1with a cavity length 1[cm] and cavity height 0.5 [cm] will be reviewed. It will be set away from the accuracy of velocity and sound pressure level since it does not reflect badly on frequencies. Distance from inlet of the pipe to microphone will be 16.5 [cm]. Idea behind the study is that theoretical method will match with experimental method.

## 5.4 Sound pressure level with various heights

The experiment will be used two types of pipe. First experiment will be done with acoustic filter 1 and pipe 1 for normal mode 1, 2 and 3. The filter will be tuned to each simple mode. For example of normal mode 2 frequency range will be set to 340-380 [Hz]. Next experiment will be done with acoustic filter 2 and pipe 2 for normal mode 2, 3 and 4. This time settings of bandpass filter will not be similar. It will be selected center frequency for each mode instead of manually setting of frequency range. For example of normal mode 2 will center frequency be selected to 500 [Hz], this corresponds to 447 -562 [Hz] frequency range.

## 5.5 Cancellation of mode.

From previous experiment **[ 20]** it was observed some cancellation of mode 2 and 3 with added sound. In this thesis will be looked a little closer to what happen with signal. First will be used simple methods to look at frequencies, find some frequencies that can cancel originally normal modes, normal mode 2 and 3 for pipe 1. It will be set a cavity length to 1 [cm] and cavity height to 0.5 [cm]. Since first experiment was determined to perform this part as a test of experiments, calibration and accuracy to sound pressure level will not be taken into account. As receiver it will be taken mobile phone with acoustic programs. In ‘’deciBel’’ sound pressure level will be given in [dBA]. It means that the measurements will be taken into consideration A-weighted filter.  This filter is used in program to implement high precision weighting filters to achieve the best possible sound pressure level readings out. Calibration of program will be set to standard value. Frequencies which will be studied at are 1000-5000[Hz]. A loudspeaker will be generated a sinusoid tone. Normal modes will be read from mobile phone program. Frequencies that are able to cancel normal modes will be analyzed. This experiment will be done with cavity height 5 [mm] and cavity length 10 [mm]. Measurements were done on axis, where distance from inlet of the pipe to receiver will be set to 16.5 [cm].

Next experiment will be done with microphone and analog voltmeter instead of the mobile phone and its programs. Settings for cavity length will be changed from 1 [cm] to 2 [cm], the cavity height will be same. Frequency range of sinusoid tone as before will be remained same. Frequencies that are able to cancel normal modes will be analyzed. Further, will be studied the intensity and power for generated frequency and added frequency. Probe will be attached to microphone to get intensity inside the pipe. Pressure maximum and pressure minimum levels will be measured. Also, it will be made some measurements of intensity outside of the pipe with microphone and probe.

In both cases will not be taken into account flow velocity.

## 5.6 Power

The downstream propagating power can be found by intensity in a pipe with plane wave, see theory section (2.5 Standing waves in a pipe and 2.6 Sound power and intensity). From the theory given that the waves travel in a pipe, in positive direction, component A and negative direction, component B. Figure 2-3 from theory shows how standing wave looks. Standing waves in this experiment will not be look like from theory, figure 5-2 shows how standing waves will be look. Top of the waves presents acoustic pressure maximum, pmax that equal the sum of absolute component A plus absolute component B. The bottom of the waves presents acoustic pressure minimum, pmin that equal the sum of absolute component A minus absolute component B. It means that all measured sound pressure will be positive, the negative values will appear positive. In this experiment, first will be discovered pmax and pmin of a pipe by probe. Total will be taken seven measurements. Then, by calculation will be found out intensity in positive direction and intensity in the negative direction. Finally will be used equation (2.6 (7)) to find the downstream power at added frequency. Calculation can be found in Appendix B3.

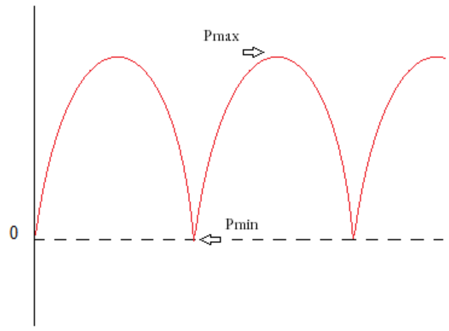



Figure 5-2: The measured standing wave with P minimum and P maximum.

To find the upstream power at generated frequency will be tried an equation from experiment that was made at NTNU **[ 21]**. In the experiment was studied upstream radiation by numerical simulations and measurements which were done in an anechoic chamber. It was used a box with mounted pipe, the acoustic pressure was measured at a distance of 1[m] in front of the opening and on the pipe axis. It was verified that a linear relationship exists by equation (5.6(1)). It was studied the third mode of the pipe at 540 [Hz], length of the cavity region was variable 10-20 [mm].

$$W_{upstream,1(m)} = k * p_{1\,(m)}{}^{2} \qquad 5.6(1)$$

- $W_{upstream,1[m]}$ - the sound power out of opening, 1 [m].
- k - the constant is 0.0205.
- $p_{1\,[m]}$ – the sound pressure at the outside position, 1 [m].

In relation to early experiment, in this experiment will be measured by microphone with attached probe the acoustic pressure at a distance of 0.5 [m] in front of the opening and on the pipe axis. In this time normal mode is almost equal to the previous experiment where difference equal 5 [Hz]. It means instead of 540 [Hz] is used535 [Hz], but it is still same normal mode. The bandpass filter range will be set to 520-550 [Hz]. Height of the cavity will be used 5 [mm] and length of the cavity 10 [mm]. Therefore equation for this experiment will be changed little bit, see equation below (5.6(2)).

$$W_{upstream,0.5(m)} = k * p^2 \, {p_{0.5(m)}}^2 \qquad 5.6(2)$$

- $W_{upstream,0.5(m)}$ - the sound power out of opening, 0.5 [m].
- k - the constant is 0.0205.
- $p_{0.5\ (m)}$ – the sound pressure (rms) at the outside position, 0.5 [m].

For upstream power at added frequency will be used normal method, equations from theory section (2.6 Sound power and intensity). Prms will be measured at distance 0.5 [m] from inlet of the pipe. For a more detailed calculation see Appendix B3.

# Chapter 6

## 6 Results

This chapter presents the results of simulation and experiment. The results are obtained by simulation on supercomputing machine through Notur with Palabos and also experiment tests in the lab. The result of a little test with abel facility is also presented here.

### 6.1 Notur

#### 6.1.1 Test of CPU

Even though Notur offers several facilities in Norway was a selected Abel machine to run Palabos. Main reason of why it actually was chose abel facility was that this facility was recommended by Notur. Before the simulation started, it was made a little test of CPU on abel machines. This was done to see how the velocity changes with certain number of CPU. It was taken a simple example,  cavity2d which was found in Palabos its folder, ... \ palabos \ examples \ showcases \ cavity2d. First observation was done with 1 CPU after that 2 CPU, next was 4CPU and finally with 8CPU, the result is shown in Tab 6-1.

| Physical time | LB time | Number of CPU |
|---|---|---|
| 2.41 | 10 | 1 |
| 1.57 | 10 | 2 |
| 1.31 | 10 | 4 |
| 1.24 | 10 | 8 |

Table 6-1: A test of CPU with cavity2d file.

Table 6-1 shows clearly that by increasing the CPU decreases physical time. With 8 physical CPU, time was reduced by 1.17 minutes. This corresponds to more than half of the originally time.

#### 6.1.2 CPU in model 1 and model 2

Table 6-2 shows result of simulation of model 1 and table 6-3 shows result of simulation of model 2 . Results were obtained after the simulation was done on abel computers. From previous simulation **Feil! Fant ikke referansekilden.**, it was found that by simulating cavityMain.cpp file required approximately 27 hours. To avoid same situation for cavityMain.cpp file it was decided to increase the number of cores to 16. For corrug.cpp file was decided to use 15 cores.

The simulation of model 1 was performed to account for physical time, 7 hours. After several tests with 15 cores, it was found out to get stable system are required about 7 hours. For each single cavity height LBtime ranges from 38 to 39.81, as samples of the signal from 3630 to 3980.

The simulation of model 2 was performed to account for LB time, 30.1. 30.1 LB time corresponds to 3011 samples of the signal. To get stable system needed about 2 hours 50 minutes, for model 2 with 16 cores. Comparison of previous simulation **Feil! Fant ikke referansekilden.** physical time was reduced very much.

| Physical time (hour) | LB time | Number of CPU | Cavity hight [cm] |
|---|---|---|---|
| 7:00 | 39.81 | 15 | 1/4 |
| 7:00 | 38.00 | 15 | 1/2 |
| 7:00 | 38.24 | 15 | 2/3 |
| 7:00 | 38.90 | 15 | 1 |

Table 6-2: A simulation of model 1.

| Physical time (hour) | LB time | Number of CPU | Cavity hight [cm] |
|---|---|---|---|
| 2:58 | 30.1 | 16 | 1/8 |
| 2:51 | 30.1 | 16 | 1/6 |
| 2:50 | 30.1 | 16 | 1/4 |
| 2:58 | 30.1 | 16 | 1/3 |
| 2:53 | 30.1 | 16 | 3/8 |
| 2:57 | 30.1 | 16 | 1/2 |

Table 6-3: A simulation of model 2.

## 6.2 Simulation

### 6.2.1 Normal modes for the simulations

As has already been noticed earlier in the theory to find normal modes of the pipe can be used two different equations. One of them is equation (2.2(2)) which is for the open-open pipe and other one is equation (2.2(4)) which is for the closed-open pipe. Model 2 in the simulation is based on two pipes, an open-open pipe and a closed-open pipe. Boundary conditions are the same as in theory. Since the simulation was done with LB values, frequency is converted to LB frequency by same equations as in theory, provided that the sound speed (v) is changed to LB velocity. According to the theory was founded results of first 12 normal modes of model 2, see table 6-4. Length of open-open pipe is 8 [cm] and length of closed-open pipe is 6 [cm].

| Normal modes | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Open-open pipe (LB frequency ) | 4.8 | 9.6 | 14.4 | 19.2 | 24.0 | 28.8 | 33.6 | 38.4 | 43.3 | 48.1 | 52.9 | 57.7 |
| Closed-open pipe (LB frequency) | 1.8 | 5.4 | 9.0 | 12.6 | 16.2 | 19.8 | 23.4 | 27.0 | 30.6 | 34.2 | 37.8 | 41.4 |

Table 6-4: Theoretical normal modes for smooth pipes.

In the theory it talks about pipes without cavity, smooth pipes, but in simulation it uses pipes with cavity.

### 6.2.2 Simulation with different cavity heights

The first four figures show results for Model 1, the figure 6-1, 6-2, 6-3 and 6-4. Each figure presents specific cavity height. Spectrums of the system oscillation are the relative velocity values versus LB frequency. The velocity curves are the magnitude LB velocity versus measuring points. The result presents the sum of all the 51 points along the centerline of the pipe. The point 1 is equal 0 [cm] in x-axis which is beginning of the pipe and the point 51 corresponds to 12 [cm] in the x-axis which is end of the pipe. The distance between each point equal 0.24 [cm]. The red vertical line marks inlet of the pipe with diameter 1 [cm].

The LB velocity curve indicates the frequency component in the system is for each cavity height.

First simulation was done with cavity height 1 [cm] where it was found out that plot of LB dynamic pressure versus samples was strange. Instead of a regular wavy shape LB dynamic pressure was observed a line which increased exponential, for more details see Appendix B. Therefore, it was considered to look on LB velocity instead. Figure 6-1:b), 6-2:b), 6-3:b) and 6-4:b) show the result of LB velocity. Next simulation was performed for model 2 where it was analyzed LB dynamic pressure.

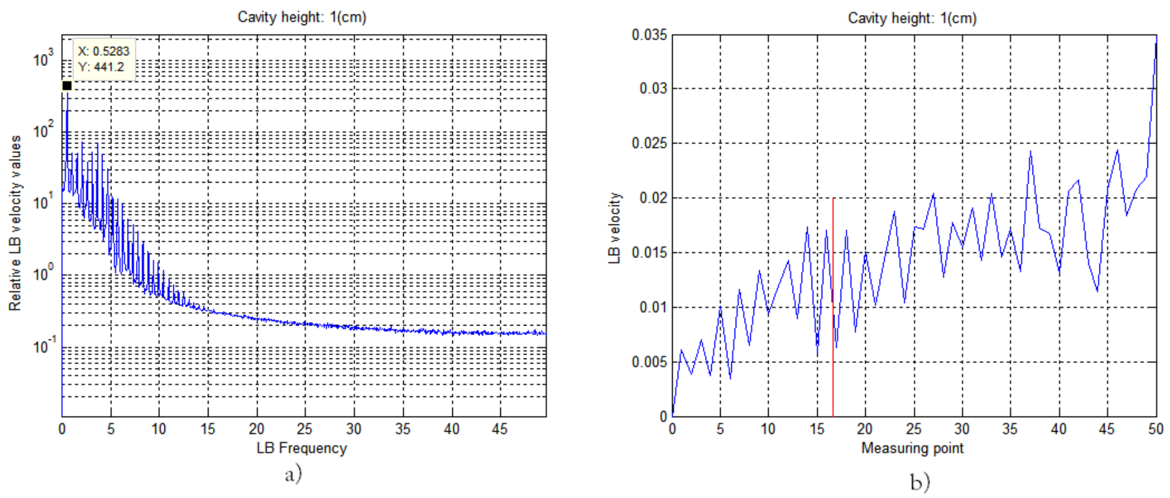



Figure 6-1: Measurement results for cavity height 1[cm]. a) Spectrum of the system oscillation. b) LB velocity distribution.

Figure 6-1 :a) shows fft of the LB velocity where peak of LB velocity is located at 0.5283 LB frequency. For this frequency follows several other frequencies which decrease gradually. From figure 6-1:b) the result is similar to the normal mode 1. Also, in this result is present weird effect, explanation for this may be noise.

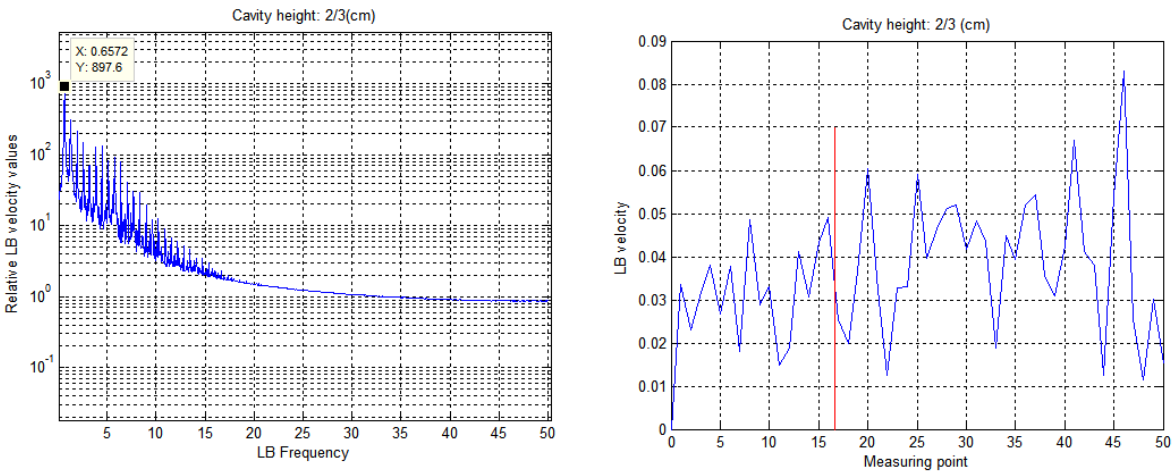



Figure 6-2: Measurement results for cavity height 2/3 [cm]. a) Spectrum of the system oscillation. b) LB velocity distribution.

Figure 6-2:a) very similar to the previous result. This time peak of LB velocity is located at 0.6572 LB frequency. This time, figure 6-2:b) does not look like normal mode 1and there is still same weird effect.

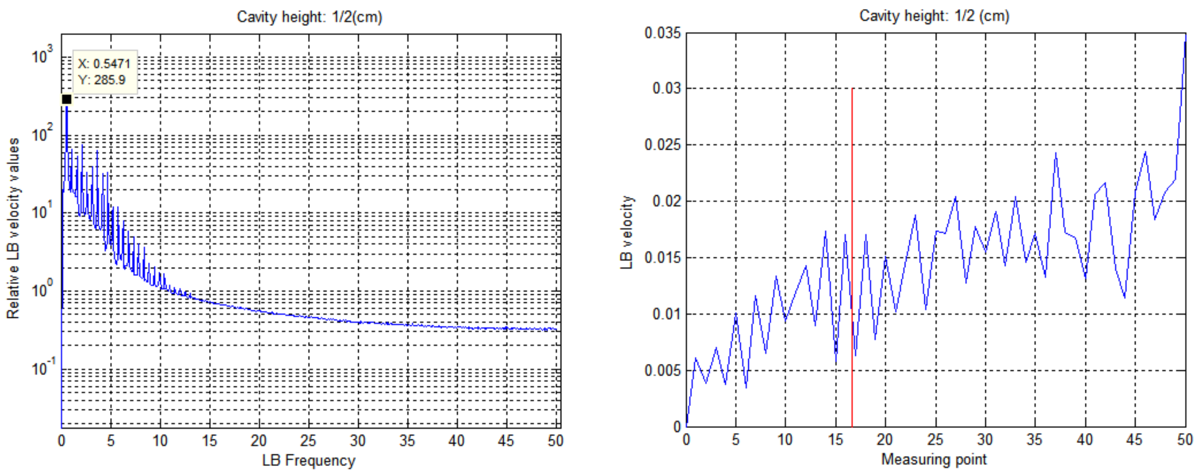
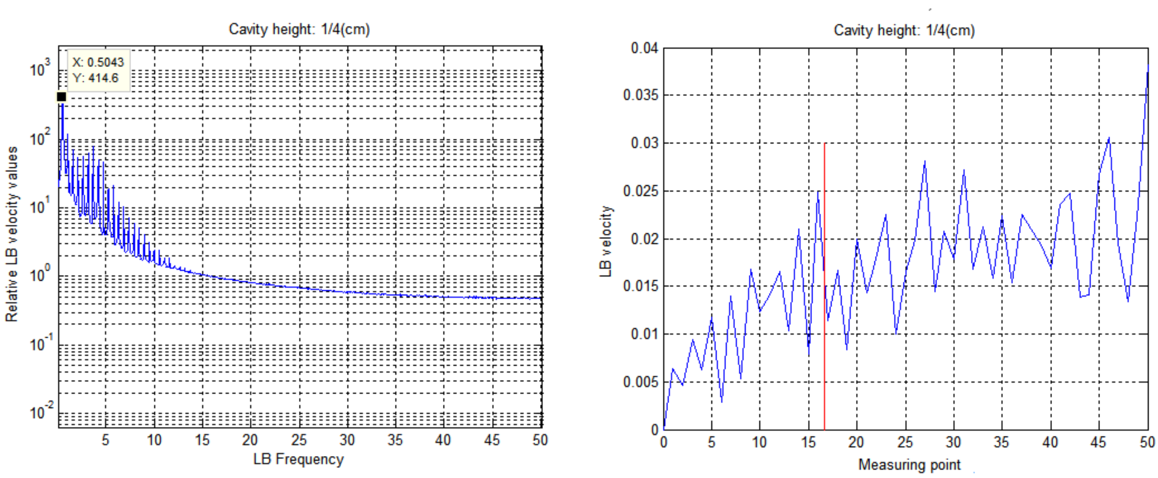



Figure 6-3: Measurement results for cavity height 1/2[cm]. a) Spectrum of the system oscillation. b) LB velocity distribution.

Figure 6-2:a) very similar to the previous result. This time peak of LB velocity is located at 0.5471 LB frequency. Figure 6-2:b) looks like the normal mode 1, but there is still same weird effect.




a) b)

Figure 6-4: Measurement results for cavity height 1/4[cm]. a) Spectrum of the system oscillation. b) LB velocity distribution.

Figure 6-2:a) very similar to the previous result. This time peak of LB velocity is located at 0.5043 LB frequency. Figure 6-2:b) looks like normal mode 1and there is still same weird effect.

Result for model 2 show figure 6-5 – 6-10. Each figure presents specific cavity height. Spectrum of the system oscillation is the relative dynamic pressures values versus LB frequency. The pressure curves are the magnitude LB dynamic pressure versus measuring points. The result presents the sum of all the 51 points along the centerline of the pipe. That is, point 1 placed at the beginning of the end tube 0cm in the x-axis and the last point 51 placed in dropping out of the end tube, 8 [cm] in the x-axis. The distance between each point equals 0.16 [cm]. The red vertical line marks inlet of the pipe with diameter 1 [cm].

From six simulations were detected five main points (peaks) in fft curve. Further these peaks will be discussed. The LB dynamic pressure curve indicates the frequency component for each cavity height in the system.

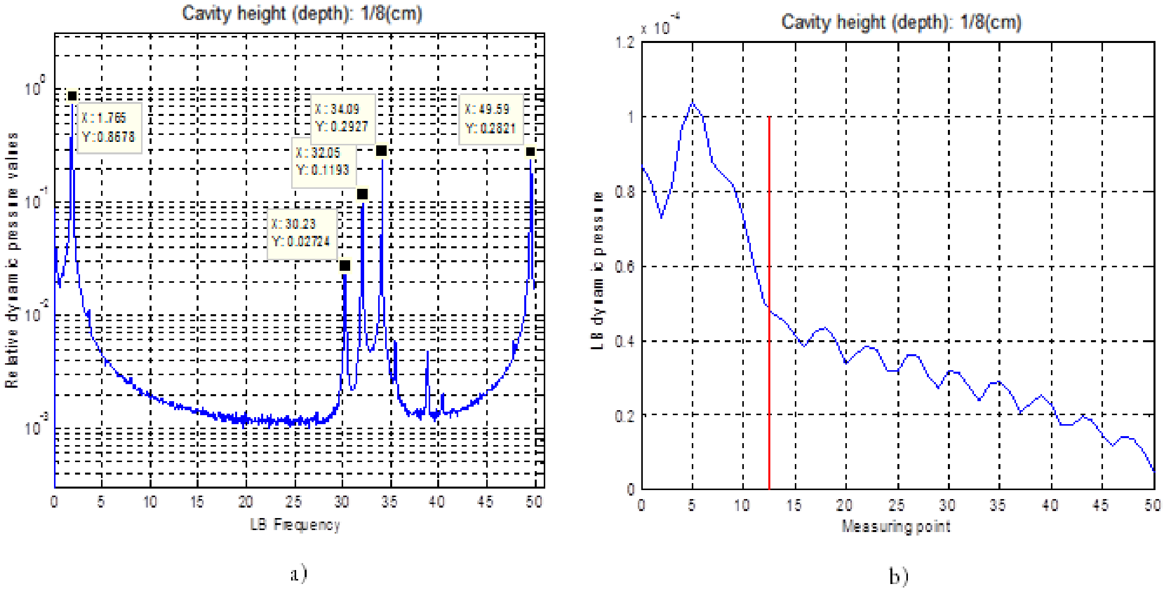



Figure 6-5: Measurement results for cavity height 1/8[cm]. a) Spectrum of the system oscillation. b) LB dynamic pressure distribution.

Figure 6-5: The 1st main peak at 1.765 LB frequency, this peak is dominant in spectrum. This LB frequency corresponds to wavelength equals 0.3271. The 2nd main peak at 34.09 LB frequency, this corresponds to wavelength equals 0.0169. The 3rd main peak at 49.59 LB frequency, this corresponds to the wavelength equals 0.0116. The 4th main peak at 32.05 LB frequency, this corresponds to the wavelength equals 0.0180. The 5th main peak at 30.23 LB frequency, this corresponds to the wavelength equals 0.0190. The Result of figure 6-5: b) is the LB dynamic pressure distribution shows fundamental frequency, where LB dynamic pressure approaches zero. Also it can be noted that the disturbance created along the way.

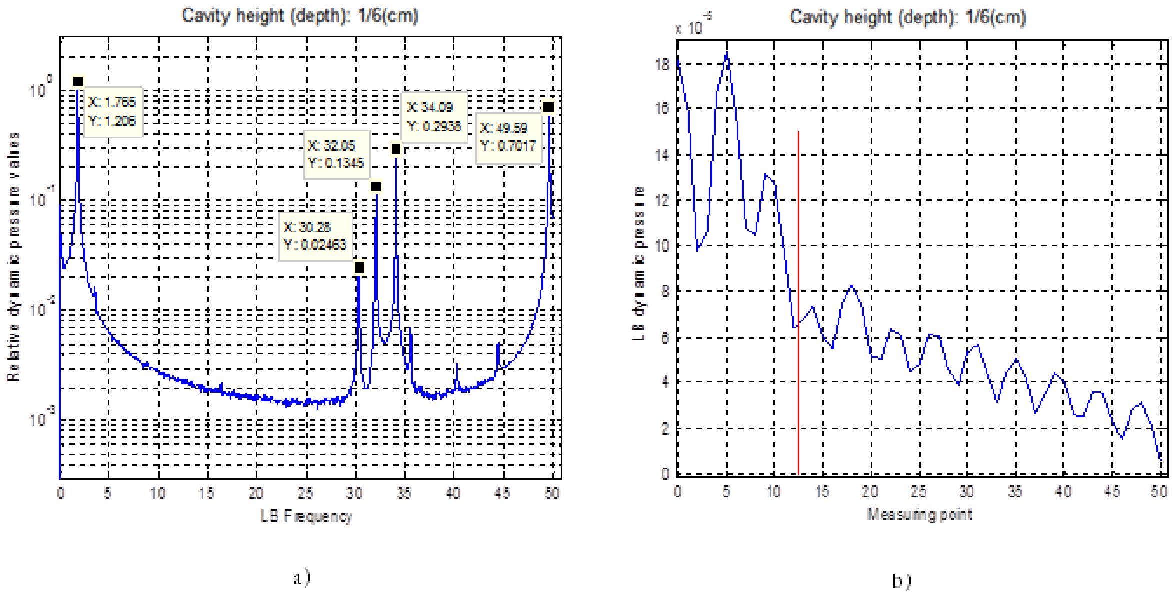



Figure 6-6: Measurement results for cavity height 1/6[cm]. a) Spectrum of the system oscillation. b) LB dynamic pressure distribution.

Figure 6-6: In this situation the 1st main peak at 1.765 LB frequency, like in previous situation the peak is dominant in spectrum. The position of the 2nd and 3rd main peak has changed. Amplitude for the 2nd main peak decreased at 34.09 LB frequency. Amplitude for the 3rd main peak increased at 49.59 LB frequency. The Result of figure 6-6: b) is the LB dynamic pressure distribution shows fundamental frequency, where LB dynamic pressure approaches zero. Status of disturbed or also changed, the curve was wavier.

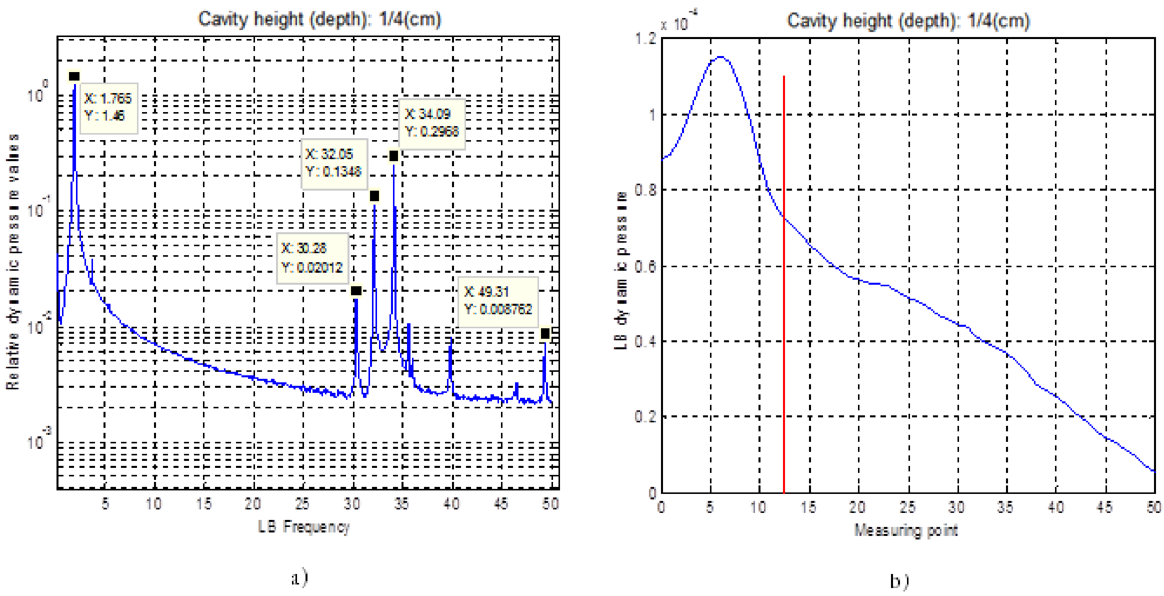



Figure 6-7: Measurement results for cavity height 1/4[cm]. a) Spectrum of the system oscillation. b) LB dynamic pressure distribution.

Figure 6-7: As in previously situation the 1st main peak is unchanged, the peak at 1.765 LB frequency is dominant in spectrum. The 3rd peak, decreased to 49.31 LB frequency, this correspond to wavelength increased to 0.0117. The Result of figure 6-7: b) is same as in previously result of The LB dynamic pressure. Status of distribution changed very much, the curve is more evenly.

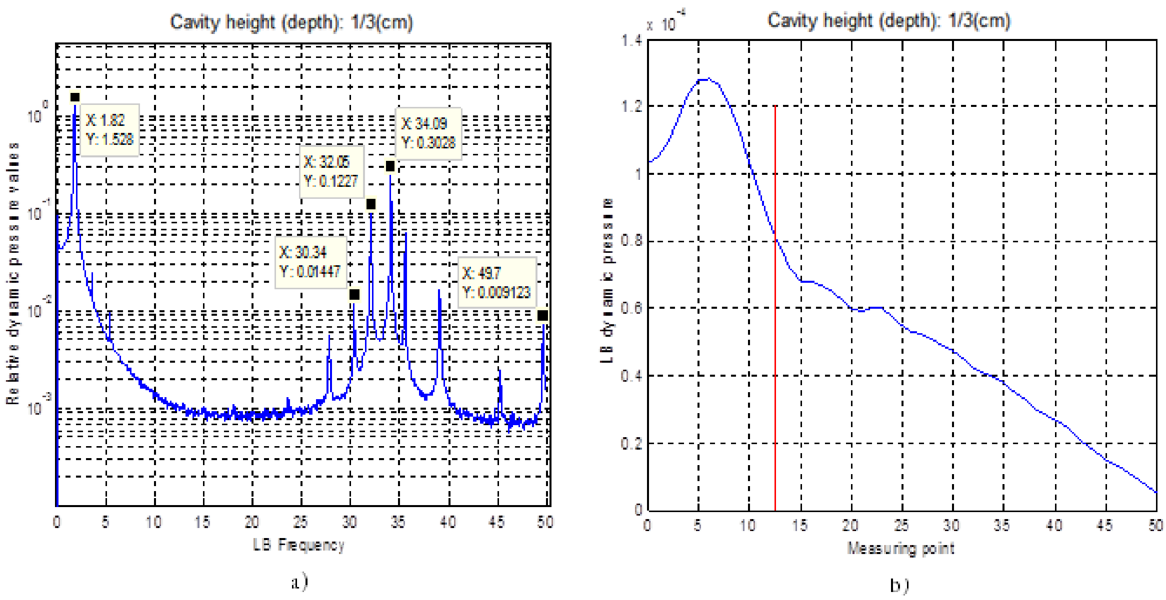



Figure 6-8: Measurement results for cavity height 1/3[cm]. a) Spectrum of the system oscillation. b) LB dynamic pressure distribution.

Figure 6-8: In this situation, the 1st main peak increased to 1.82 LB frequency, this corresponds to the wavelength equals 0.3172. It is still 1st main peak is dominant in spectrum.

The 3rd peak, increased to 49.7, this corresponds to the wavelength is 0,0116. Also, it was found more peaks than in previously case. The Result of figure 6-8: b) is same as in previously result of the LB dynamic pressure.

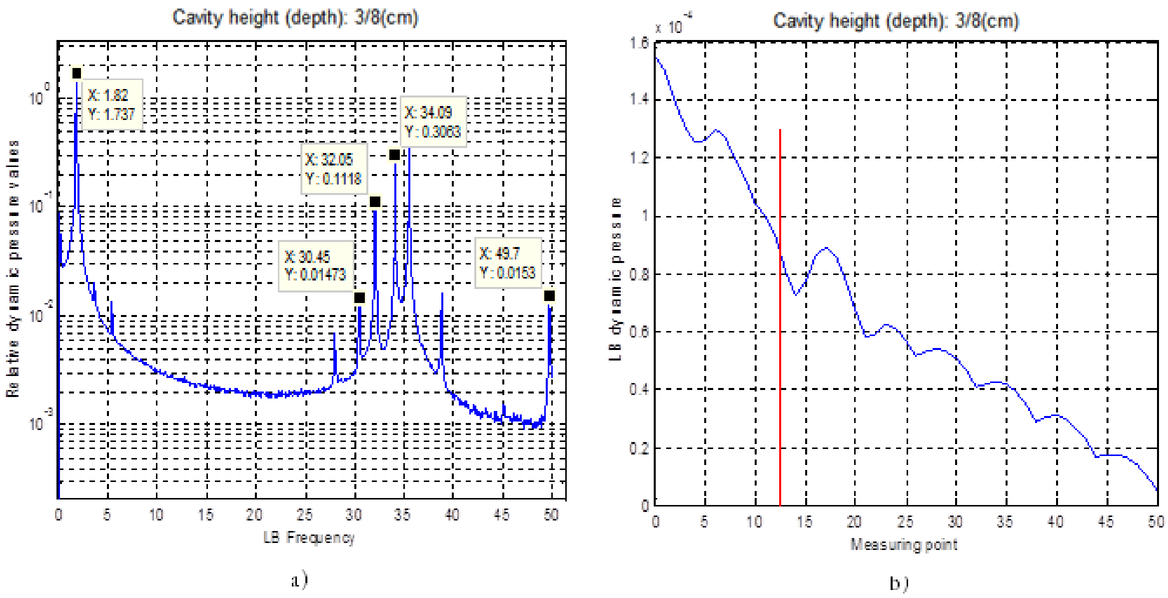



Figure 6-9: Measurement results for cavity height 3/8[cm]. a) Spectrum of the system oscillation. b) LB dynamic pressure distribution.

Figure 6-9: As in the previous situation the 1st main peak is unchanged. The peak at 1.82 LB frequency is dominant in spectrum. The 5th peak increased to 30.45 LB frequency, this corresponds to the wavelength is 0.0189. The Result of figure 6-9: b) is the LB dynamic pressure distribution shows fundamental frequency, where LB dynamic pressure approaches zero. Disturbance was detected, curve has wavy shape.

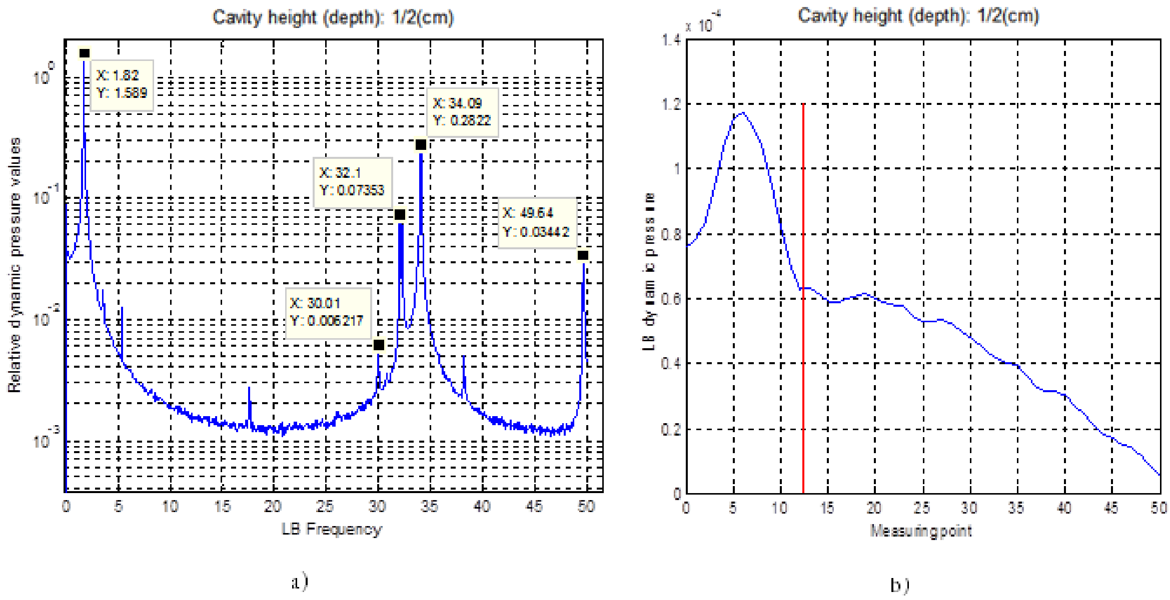



Figure 6-10: Measurement results for cavity height 1/2 [cm]. a) Spectrum of the system oscillation. b) LB dynamic pressure distribution

Figure 6-9: The 1st main peak is still dominant in spectrum. The 3rd peak, now decreased to 49.64 LB frequency, this corresponds to the wavelength is 0.0116. The 4th peak, increased to 32.1LB frequency, this corresponds to the wavelength is 0.0179. The 5th peak, decreased to 30.01, this corresponds to the wavelength is 0.0192. The Result of figure 6-9: b) The LB dynamic pressure distribution still shows fundamental frequency, where LB dynamic pressure approaches zero.

Figure 6-11 shows visual results for model 2. It shows flow simulations for six different situations. The snapshots gated at same time. It clearly can be seen from figure that cavity vortices are formed for each simple situation. A higher cavity equals a larger cavity flow. Pictures are in ascending order of cavity height, where picture 1) is lowest cavity height and picture 6) is highest cavity height.

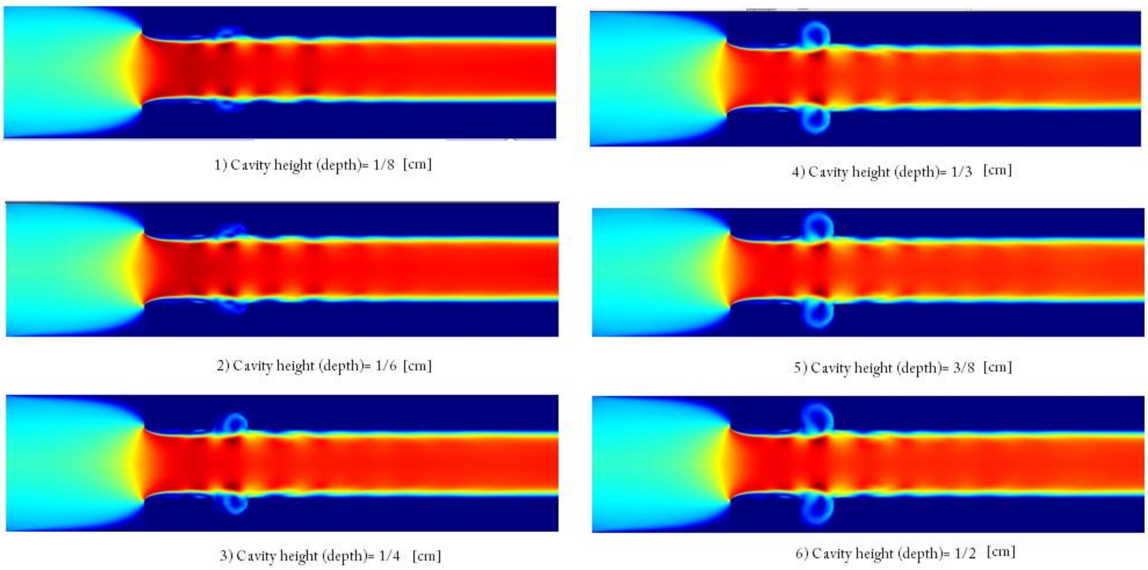



Figure 6-11: The flow simulation of six different cavity heights.

### 6.2.3 Magnitude of the main peaks

The result of five main peaks:

- 1$^{st}$ main peak : 1.765 LB frequency – 1.82 LB frequency
- 2$^{nd}$ main peak : 34.09 LB frequency
- 3$^{rd}$ main peak : 49.31LB frequency – 49.7 LB frequency
- 4$^{th}$ main peak : 32.05 LB frequency – 32.1 LB frequency
- 5$^{th}$ main peak : 30.01 LB frequency – 30.45 LB frequency

Magnitude of the five main peaks are plotted versus cavity height, see figure 6-12. Magnitude found by spectrum of the system oscillation from previously chapter.

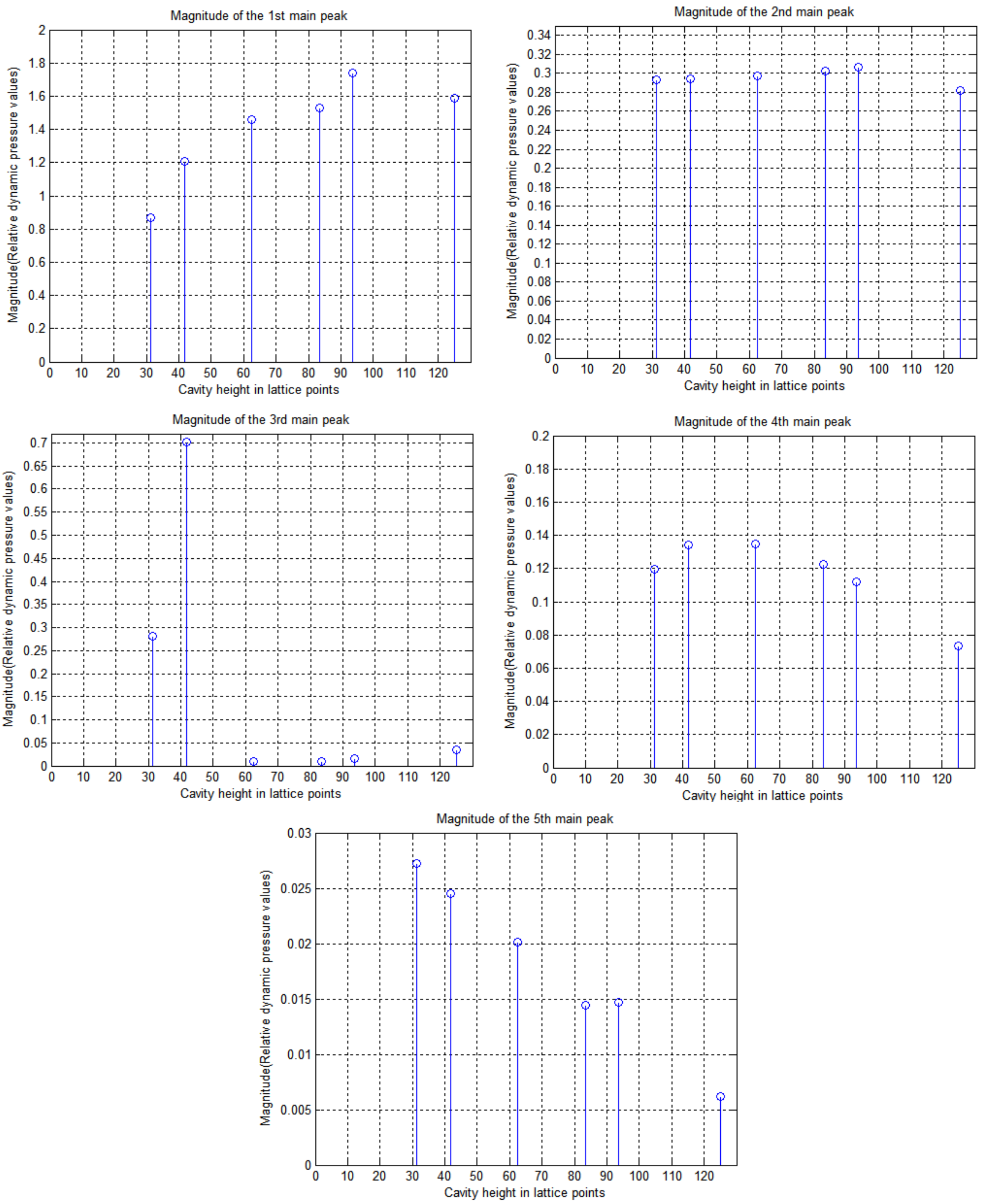



Figure 6-12: The magnitude of five different peaks.

The magnitude of the 1st and 2nd peak increase with the cavity height until cavity height equal 93.75 lattice points or 3/8 [cm]. At cavity height equal 125 lattice point the magnitude decreases. The magnitude of the 3rd main peak increase only until 41.66 lattice point. In next lattice point, 62.5 the magnitude very much decreases. The magnitude of the 4th main peak increase until 62.5 lattice point and from 62.5 lattice point until 125 lattice point the magnitude decreases. The magnitude of the last main peak 5th decreases with the cavity height, until cavity height equal 125 lattice point.

## 6.3 Experiment

### 6.3.1 Normal modes for the experiments

As has been said before, each of the normal modes of the system is characterized by its frequency. Using the equation for open-open pipe from theory (2.2 Resonance or normal modes) was found normal modes for pipe 1 and pipe 2, see table 6-5. The results show the resonance frequency of each normal mode. Calculation was done with end correction, see calculation in Appendix B4.

| Pipe length [cm] | 85 | 85 | 85 | 85 |
|---|---|---|---|---|
| Cavity height [cm] | 0.1 | 0.5 | 0.5 | 0.8 |
| Cavity length [cm] | 1 | 1 | 2 | 1 |
| Cavity device [cm] | 5 | 7 | 8 | 5 |
| Normal modes and resonant frequency [Hz] | Mode1: 184 | Mode1: 180 | Mode1: 178 | Mode1: 184 |
| | Mode2: 368 | Mode2: 360 | Mode2: 356 | Mode2: 368 |
| | Mode3: 552 | Mode3: 540 | Mode3: 534 | Mode3: 552 |
| | Mode4: 732 | Mode4: 720 | Mode4: 712 | Mode4: 732 |
| | Mode5: 912 | Mode5: 900 | Mode5: 890 | Mode5: 912 |
| | Mode6: 1096 | Mode6: 1080 | Mode6: 1068 | Mode6: 1096 |
| | Mode7: 1276 | Mode7: 1260 | Mode7: 1246 | Mode7: 1276 |

a)

| Pipe length [cm] | 55 | 55 | 55 | 55 |
|---|---|---|---|---|
| Cavity height [cm] | 0.1 | 0.5 | 0.5 | 0.8 |
| Cavity length [cm] | 1 | 1 | 2 | 1 |
| Cavity device [cm] | 5 | 7 | 8 | 5 |
| Normal modes and resonant frequency [Hz] | Mode1: 271 | Mode1: 263 | Mode1: 259 | Mode1: 271 |
| | Mode2: 542 | Mode2: 526 | Mode2: 518 | Mode2: 542 |
| | Mode3: 813 | Mode3: 789 | Mode3: 777 | Mode3: 813 |

b)

Table 6-5: Normal modes by calculation with end correction. a) Pipe 1 with length 85 [cm]. b) Pipe 2 with length 55 [cm].

Table 6-5: a) shows three different cavity heights for the same pipe length. The fundamental frequency difference equals 4 [Hz] between cavity device 0.5 [cm] and cavity device 0.7 [cm]. In table 6-5:b) pipe 2 presents also three different cavity heights. Cavity height 0.5 [cm] has two different cavity length, 1 [cm] and 2 [cm] as in a previously table 6-5:b). This time fundamental frequency difference equals 8 [Hz] between cavity device 0.5 [cm] and 0.7 [cm].

Result of the normal modes by experiment sees in figure 6-13. The Plot presents sound pressure level [dB] versus flow velocity in the pipe [m/s]. As receiver of frequencies was used mobile phone program Spectrum analyzer. The flow velocity was measured by velocimeter 1.

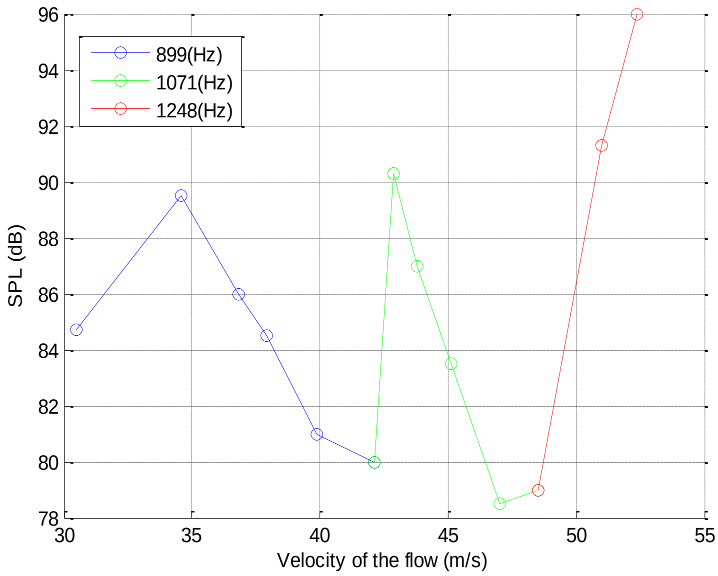



Figure 6-13: Normal modes by experiment.

The peaks of frequency increase by velocity. Each normal mode presented with color. The blue color equals to 899 [Hz], where the peak of frequency is around 89 [dB] and velocity is around 34 [m/s]. The green color equals to 1071 [Hz], where the peak of frequency little higher than frequency of 899 [Hz], velocity is around 43 [m/s]. The red color equals to 1248 [Hz] where the peak of frequency reaches 96 [dB] and most likely it is not the limit, to find out it did not happen because it was the speed limit of the vacuum cleaner. Velocity at that peak is around 53 [m/s].

Results from experiments are very similar to the results from the theory. If don't take as to accuracy normal mode 5 is equal to around 899 [Hz], the normal mode 6 is equal to 1071 [Hz] and also normal mode 7 is equal to 1248 [Hz]. Therefore, further in experiments like in figures are used normal modes instead of frequencies.

### 6.3.2 Sound pressure level.

Figure 6-14 demonstrates the result of the sound pressure level versus velocity of the flow where it was used acoustic filter 1 and pipe 2. Figure 6-14 a), b) and c) shows a normal mode for three different cavity heights. The blue line demonstrates the lowest cavity height 1 [mm]. The red line demonstrates the highest cavity height, 8 [mm]. The table 6-6 shows the sound pressure level peak at specific velocity for three normal mode from figure 6-14:a), b) and c).

Results show that the cavity height 8[mm] dominates over all three modes, except by a few points. For normal mode 1 at 24.4 [m/s] sound pressure level for the red line is lower than sound pressure level for the green line, the difference equals 6-7 [dB]. For normal mode 2 results lead to the same conclusion as for the normal mode 1, but this time the difference of sound pressure level corresponds to 8 [dB]. For normal mode 3 in some points sound pressure level for the red line are lower than sound pressure level for the green line. The first point is at 10 [m/s] where the difference equals 7 [dB], the second point is at 18.4 [m/s] where the difference equals 19 [dB] and the third point is at 24.4 [m/s] where the difference is at 16 [dB].

Figure 6-14: d), e) and f) show the normal modes behavior for each cavity height. For cavity height 1 [mm] dominates normal mode 2, from 10.3[m/s] to 22.7 [m/s] and again from 27[m/s] to 30[m/s]. From 22.7 [m/s] to 27 [m/s] management is taken normal mode 1. The sound pressure level peak for normal mode 2 is 67 [dB] for normal mode 1 is 66 [dB]. For cavity height 5[mm] dominates normal mode 2, from 10 to 16 [m/s]. The sound pressure level peak is 83 [dB]. Further from 16 to 29.9 [m/s] dominates mode 3, where the sound pressure level is 99 [dB]. For cavity height 8 [mm] it clearly can be seen that mode 2 dominates from 10 to 20 [m/s] where sound pressure level peak for normal mode 2 is 91.4 [dB]. From 20 to 29.3 [m/s] dominates normal mode 3 where sound pressure level peak is 104 [dB].

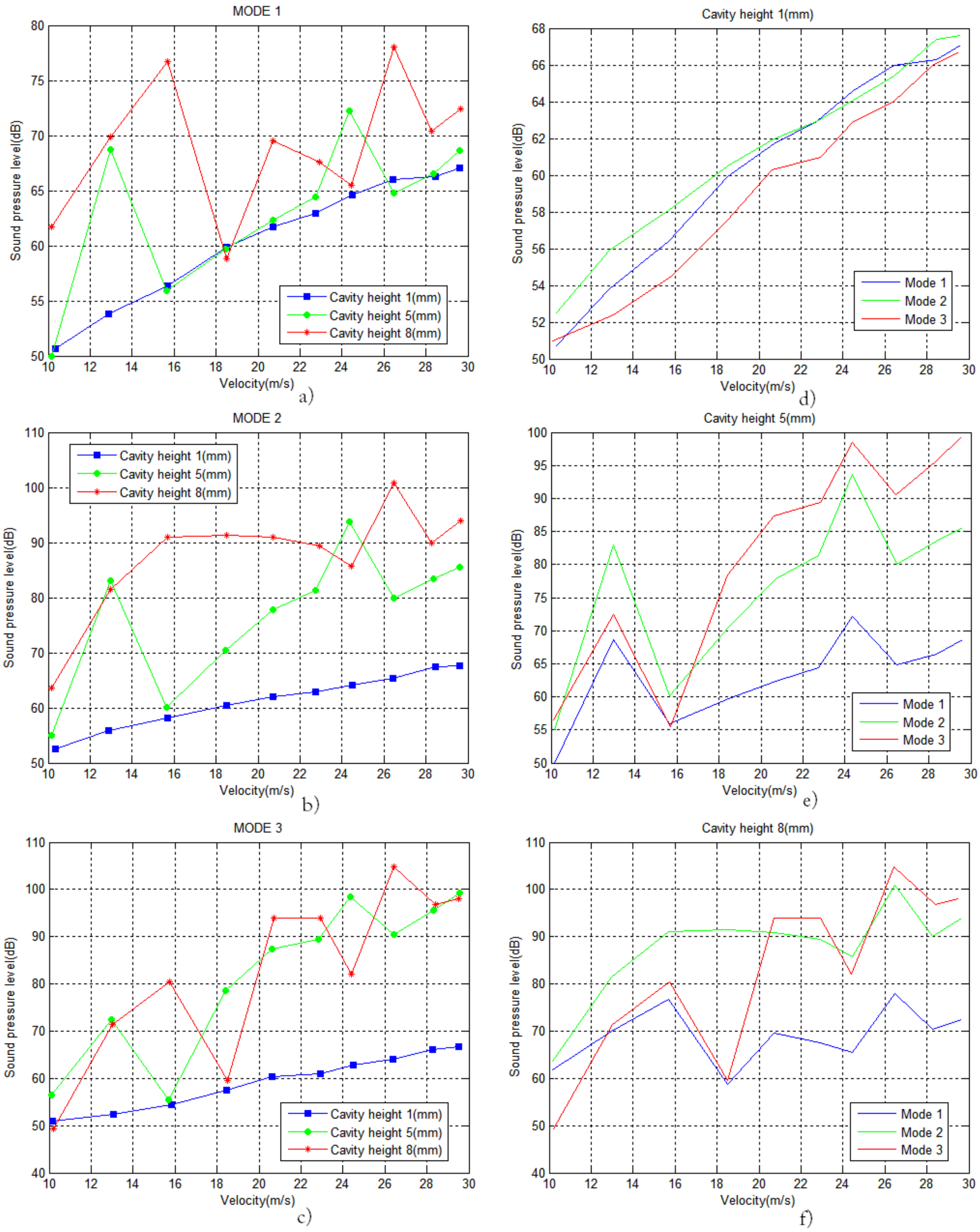



Figure 6-14: Measured sound pressure level versus velocity, with bandpass filter. a),b) and c) Three different normal modes. d),e) and f) Three different cavity height.

| | Mode 1 | | | Mode 2 | | | Mode 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | C.h. 1[mm] | C.h. 5[mm] | C.h. 8[mm] | C.h. 1[mm] | C.h. 5[mm] | C.h. 8[mm] | C.h. 1[mm] | C.h. 5[mm] | C.h. 8[mm] |
| SPL[dB] peak | 67 | 72 | 78 | 68 | 94 | 100 | 67 | 99 | 105 |
| Velocity [m/s] | 29.6 | 24.4 | 26.4 | 29.6 | 24.4 | 26.4 | 29.5 | 24.4 | 26.4 |

Table 6-6: Sound pressure level peak using acoustic filter 1.

Figure 6-15 demonstrates the result of the sound pressure level versus velocity of the flow. This time was used acoustic filter 2 and pipe 1. Table 6-7 shows the sound pressure level peak at specific velocity for three normal mode from figure 6-15:a), b) and c). As in previous experiment with acoustic filter 1, cavity height 8 [mm] has the highest sound pressure level. It can be clearly seen from spectrum, normal mode 2. The cavity height 8 [mm] dominates from 10[m/s] to 16 [m/s]. From spectrum, normal mode 3, the cavity height 8[mm] dominates from 11 [m/s] to 27 [m/s]. From spectrum, normal mode 4, the cavity height 8 [mm] dominates almost the entire range of velocity disregard of area 17 [m/s] - 19 [m/s] and 27 [m/s] – 30 [m/s] where normal mode 2 dominates.

Figure 6-15: d), e) and f) show the normal modes behavior for each cavity height. For cavity height 1 [mm] dominates normal mode 2, from 10 to 30 [m/s]. The sound pressure level peak for normal mode 2 is 67 [dB]. For cavity height 5[mm] dominates normal mode 2, from 10 to 11.7 [m/s]. The sound pressure level peak for normal mode 2 is 76 [dB]. Further from 11.7 to 16 [m/s] dominates normal mode 3, where the sound pressure level peak for normal mode 3 is 60 [dB]. From 16 to 30[m/s] dominates normal mode 4 where the sound pressure level peak for normal mode 4 is 94 [dB]. For cavity height 8 [mm] it clearly can be seen that mode 2 dominates from 10 to 13.3 [m/s] where sound pressure level peak for normal mode 2 is 85 [dB]. From 13.3 to 17.1 [m/s] dominates normal mode 3 where sound pressure level peak for normal mode 3 is 79 [dB]. Further, from 17.1 to 30[m/s] dominates normal mode 4 where sound pressure level peak for normal mode 4 is 100 [dB].

The result of this experiment leads to conclusion. The greater will be the cavity height than more whistling sound will come out of the pipe and the less will be cavity height than the less will be whistling sound will come out of the pipe.

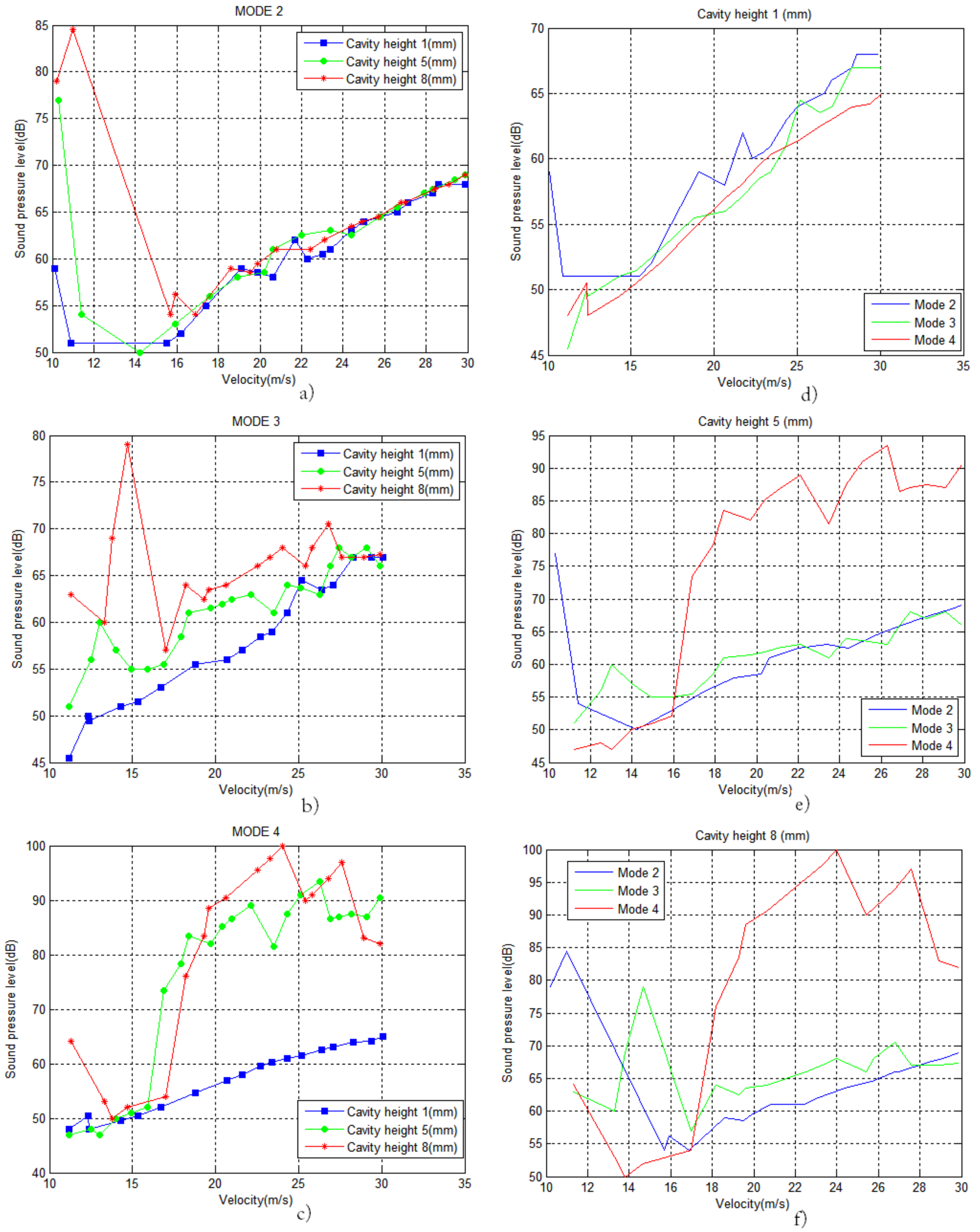



Figure 6-15: Measured sound pressure level versus velocity, with acoustic filter 2. a),b) and c) Three different normal modes. d),e) and f) Three different cavity heights.

| | Mode 2 | | | Mode 3 | | | Mode 4 | | |
|---|---|---|---|---|---|---|---|---|---|
| | C.h. 1[mm] | C.h. 5[mm] | C.h. 8[mm] | C.h. 1[mm] | C.h. 5[mm] | C.h. 8[mm] | C.h. 1[mm] | C.h. 5[mm] | C.h. 8[mm] |
| SPL[dB] peak | 68 | 77 | 84.5 | 67 | 68 | 79 | 65 | 93.4 | 100 |
| Velocity [m/s] | 29.9 | 10.3 | 11 | 30<br>29.4<br>28.3 | 27.4<br>29.1 | 14.7 | 30.1 | 26.3 | 24 |

Table 6-7: Sound pressure level peak, using acoustic filter 2.

### 6.3.3 Cancelation of the mode

Tables 6-8 and 6-9 show the obtained experiment results for normal mode 2 and normal mode 3 with increasing added frequency. From tables 6-8 and 6-9, Gf is the flow generated frequency and Gs is the sound pressure level to Gf. Af is the added frequency and As is the sound pressure level to Af. The observations of experiment are in Appendix B5, the result given graphically. Blue line present sound pressure level (dBA) of the normal mode and the pink line presents sound pressure level (dBA) for added frequency.

| Gf(Hz) | Af (Hz) | As(dBA) | Gs (dBA) | Comment |
|---|---|---|---|---|
| 360 | 1400 | 91.1 | 87.3 | Gf cancelled |
| 360 | 1500 | 79.2 | 85.4 | Gf cancelled |
| 360 | 1600 | 75.5 | 76.5 | Gf cancelled |
| 360 | 1700 | 76.7 | 79.6 | Gf cancelled |
| 360 | 1800 | 79.4 | 80.5 | Gf cancelled |
| 360 | 2000 | 86.5 | 89.2 | Gf cancelled |
| 360 | 2500 | 73.1 | 71.4 | Gf cancelled |
| 360 | 3000 | 72.3 | 68.9 | Gf cancelled |
| 360 | 3500 | 74.7 | 78.1 | Gf cancelled |

Table 6-8: Cancellation of mode 2.

| Gf(Hz) | Af (Hz) | Aas(dBA) | Ags (dBA) | Comment |
|---|---|---|---|---|
| 540 | 1650 | 86.2 | 88.4 | Gf cancelled |
| 540 | 2300 | 69.8 | 74.7 | Gf cancelled |
| 540 | 2500 | 79.4 | 70.5 | Gf cancelled |
| 540 | 3000 | 80.3 | 83.2 | Gf cancelled |
| 540 | 3500 | 75.5 | 73.3 | Gf cancelled |
| 540 | 4000 | 74.3 | 70.6 | Gf cancelled |
| 540 | 4200 | 68.1 | 73.7 | Gf cancelled |

Table 6-9: Cancellation of mode 3.

Cancellation of normal mode 2 was found nine different frequencies opposite to cancellation of mode 3 where it was found just seven different frequencies. In some situations were observed that signal of mode was not completely cancelled. It means tone of Gf were heard occasionally while Af-dominated. This applies to the cancellation mode 2 where Af equal 1500 and 3500 [Hz] and for cancellation mode 3 where Af equal 2300 and 4200 [Hz].

### 6.3.4 More about Cancelation of the mode

Opposite to chapter (6.3.3 cancellation of mode) this chapter was adopted voltmeter to find the rms value to signal. Total length of pipe 1 was changed to 93 [cm], by that length of the cavity was changed to 2 [cm]. Even though frequency of modes 2 and 3 were changed it was tried to find frequency that will cancel generated frequency for modes, 2 and 3. Expectation was to find similar frequency as in Table 6-8 and 6-9.

The observation led to added frequency 1580[Hz]. It is just this one frequency that can cancel generated frequency, namely mode 3. Figure 6-16 is demonstrating graphic result of cancellation mode 3 with added frequency 1580 [Hz], where y-axis introduce mode 3 and x-axis introduce 1580 [Hz]. At the start of cancellation of mode 3, sound pressure level at mode 3 shows 95 [dB], and the sound pressure level at added frequency 0 [dB]. When mode 3 was cancelled, whistling sound was not long audible, sound pressure level at mode 3 showed 43 [dB] and sound pressure level at 1580 [Hz] was 96 [dB]. Result causes that to cancel the flow generated frequency of 95 [dB] needed inflict 96[dB] of the added frequency.

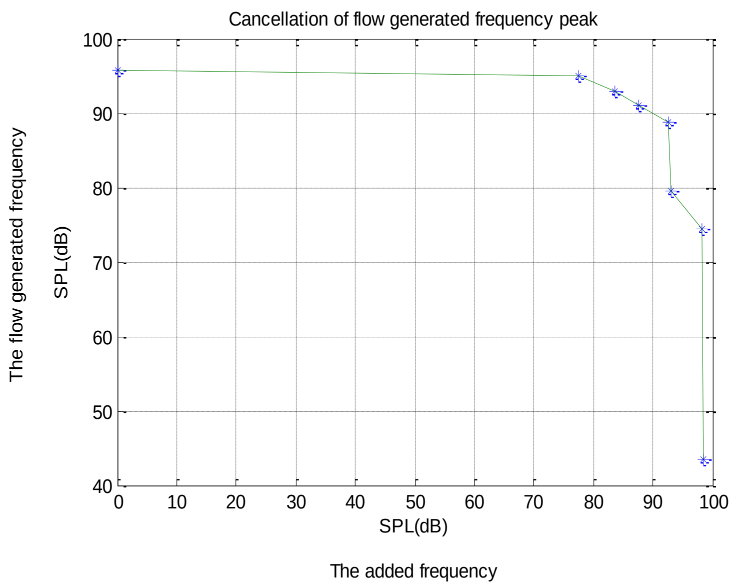



Figure 6-16: Cancellation of mode 3 with added frequency 1580 [Hz].

### 6.3.5 Power

The source will generate power in both directions the downstream and the upstream. Figure 6-17: a), b), c) and figure 6-18 a), b) shows the obtained experiment results for an acoustic power, the upstream and the downstream. By comparing upstream power at 1580 [Hz] with the downstream power at 1580 [Hz] it clearly can be seen that upstream power at 1580 [Hz] increase from 0 to 21.6 [mW], while downstream power at 1580 [Hz] increase just from 0 to 1.8 [mW]. Difference between upstream and downstream power equals to 19.8 [mW] which is high. Figure 6-17: c) shows that the upstream power at 535 [Hz] decreases from 16 to 0 [mW]. In figure 6-17: a) it can be seen that increasing of upstream power is slow, from first measurement to sixth is around 6 [mW]. From measurement sixth to measurement eighth upstream power increase very fast. Power is increased from 6 to 21 [mW]. In figure 6-17:b) downstream power at 1580[Hz] does not look like upstream power at 1580[Hz]. It looks like downstream power increase almost linear with 0.2 [mW] per measurement. In figure 6-17: c) upstream power at 535 [Hz] decreases almost linear, from first measurement to sixth measurement. After sixth measurement power decreases very slow.

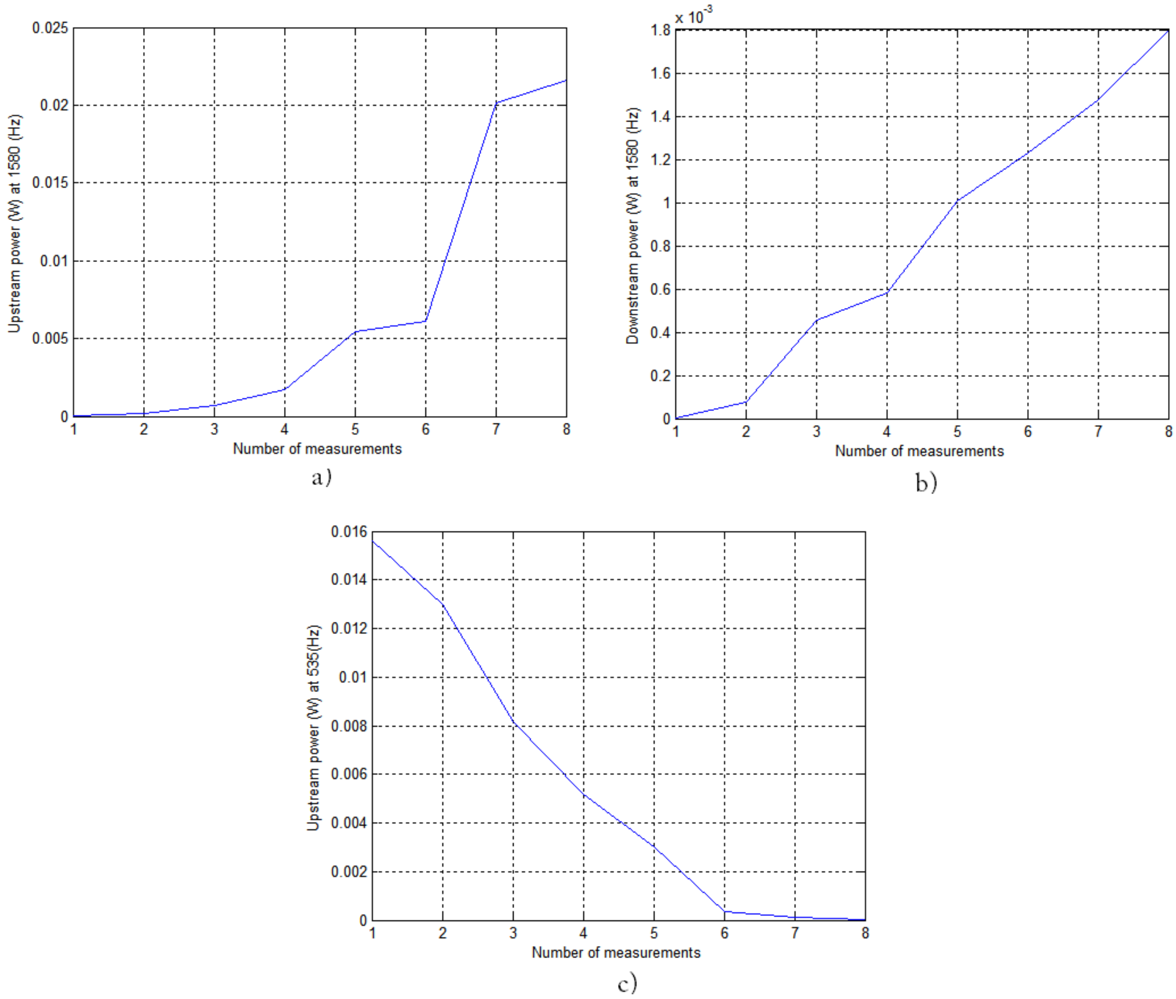



Figure 6-17: Power spectra 1. a) Upstream power at 1580 [Hz] versus number of measurements. b) Downstream power at 535 [Hz] versus number of measurements. c) Upstream power at 535 [Hz] versus number of measurements.

Both figures 6-17 a) and b) show how fast decreases generated sound. Figure 6-17: a) shows the upstream propagating power at 535 [Hz] versus the downstream propagating power at 1580 [Hz]. To cancel generated sound it required 22 [mW] of added sound. Over 1 [mW] reduction reduces the 7 [mW] . Figure 6-18: b) shows the upstream propagating power versus the downstream propagating power. This time the result shows that 1.8 [mW] needed to cancel generated sound. Over 1 [mW] reduction reduces the 13[mW].

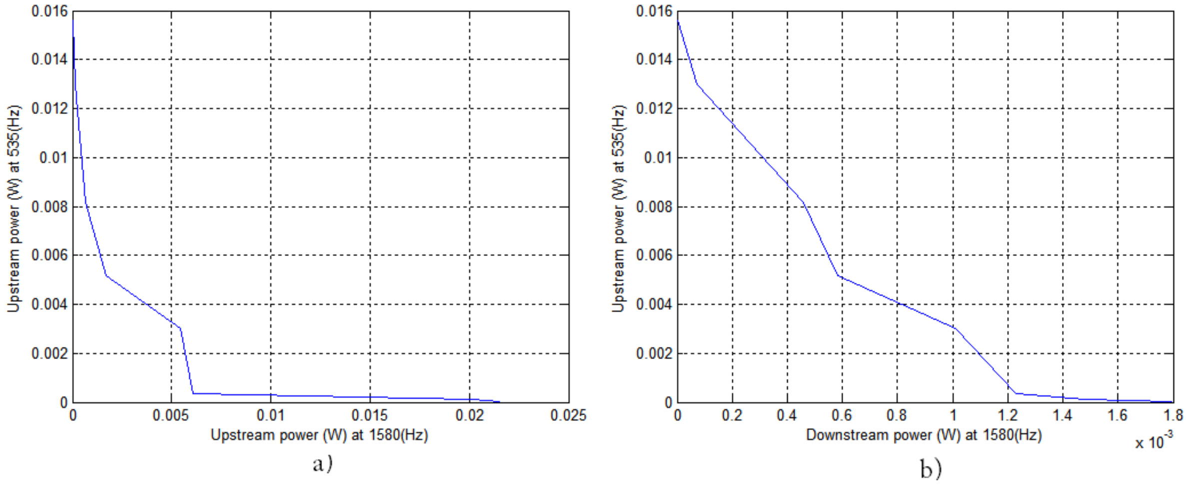



Figure 6-18: Power spectra 2 . a)Upstream power at 535 [Hz] versus upstream power at 1580 [Hz]. b) Upstream power at 535 [Hz] versus downstream power at 1580 [Hz].

### 6.3.6 Hysteresis

Figure 6-19, 6-20 and 6-21 show different situations of acoustic hysteresis which was discovered in pipes. The results demonstrated graphically where y-axis is the profile of the measured sound pressure level and x-axis is the profile of the flow in a pipe. The green line is presented as velocity decreasing and the blue line is presented as velocity increasing. To measure the desired frequencies was used acoustic filter 1. For mode 4, filter range was 710-730 [Hz] and for mode 5 it was 890 -910 [Hz]. Acoustic hysteresis in figure 6-19: a) can be observed clearly for the velocity of the flow lying between 21 and 24 [m/s]. In figure 6-19: b) can be observed for the velocity of the flow lying between 26.4 and 28.7 [m/s]. The hysteresis loop was found to be as soon as the velocity of the flow decreased. In figure 6-19:a) and b) 2-3 [m/s] separates the onset of the hysteresis loop appearance from the end of his disappearance. It can be seen as a green and a blue line almost have the same data until hysteresis loop. The reason for this may be is inaccurate data, sound pressure level for velocity increasing was not read at the same velocity, as for velocity decreasing.

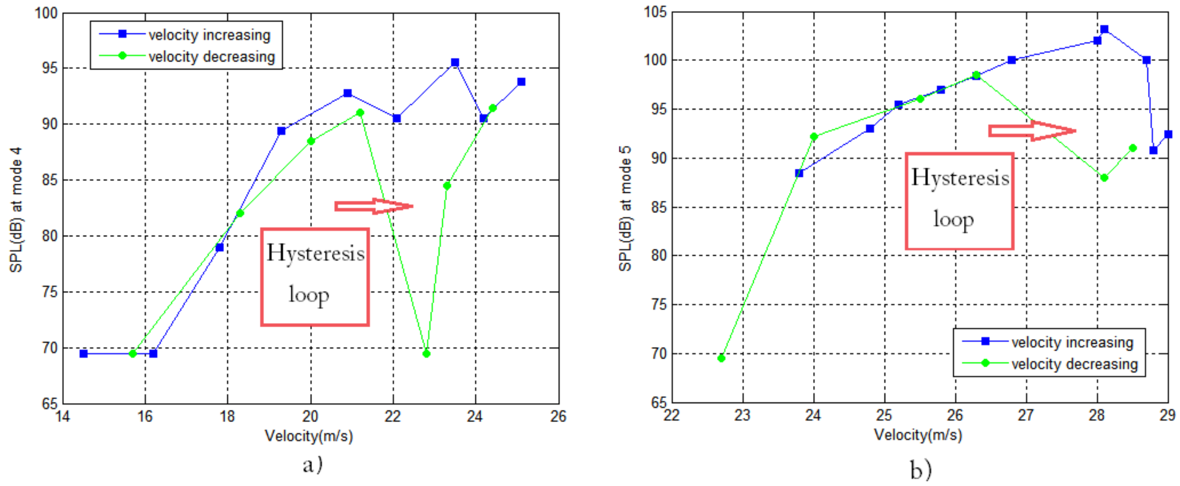



Figure 6-19: Hysteresis loop with acoustic filter 1. a) Sound pressure level at mode 4. b) Sound pressure level at mode 5.

Also, figure 6-20 demonstrated hysteresis loops which was formed immediately after the velocity of the flow in a pipe started to decrease. In this situation was used graphical software WinMLS to measure sound pressure level. Before using WinMLS was used sound level calibrator Type 4230 (94[dB]-1000[Hz]), calibration was given directly. To read sound pressure level was not used bandpass filter, sound pressure level for normal mode 4 and 5 was read directly from the result of the software. After, the result was summed up which can be seen in figure 6-20. In this time acoustic hysteresis lying between 20.2 and 23.7 [m/s] in figure 6-20: a) and in figure 6-20: b) acoustic hysteresis lying between 27.1 and 28.8 [m/s]. In this figure unknown effect is present which is lying between 23.2 and 25 [m/s]. Reason for this effect can be different numbers of measurements between the green line and the blue line, or any imprudence by measuring sound pressure level. Points on lines indicate how many measurements were made.

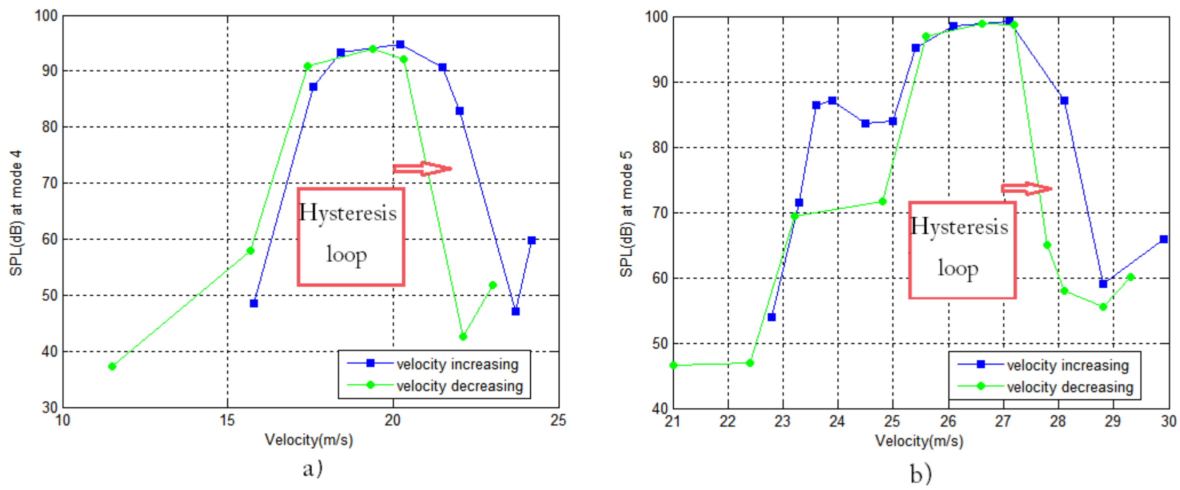



Figure 6-20: Hysteresis loop with software, WinMLS, a) Sound pressure level at mode 4 and b) Sound pressure level at mode 5.

Measurements in the last figure 6-21 were done in the same way as in the two previous experiments, but this time was used acoustic filter 2. It can be seen clearly in figure 6-21:a) that acoustic hysteresis is  lying between 22.4 and 24 [m/s].  Acoustic hysteresis in figure 6-21: b) is lying between 27.9 and 29 [m/s]. The green and the blue lines almost have the same values of sound pressure level. Compared with the two earlier hysteresis loops this hysteresis loop has more similar to hysteresis loop of theory.

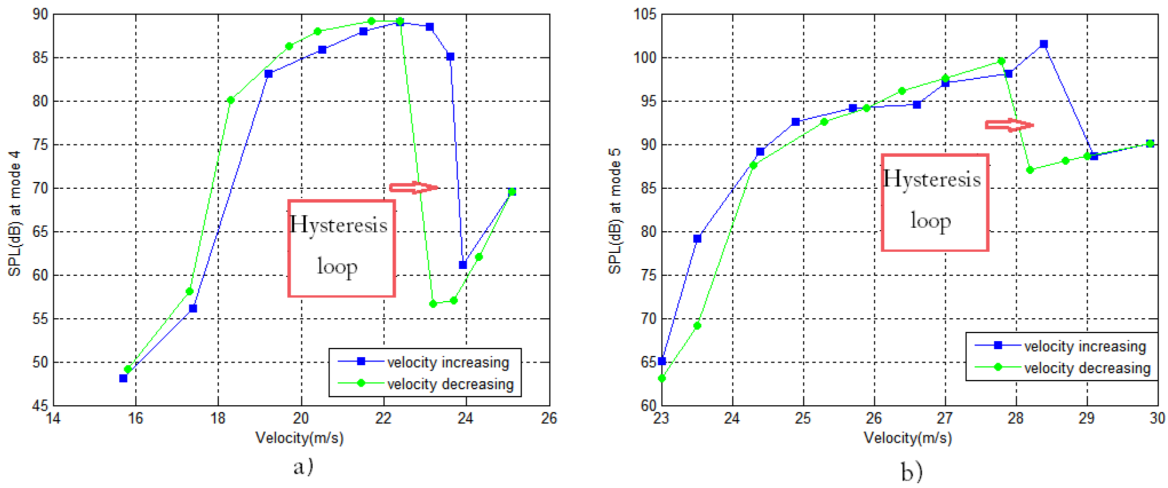



Figure 6-21: Hysteresis loop with acoustic filter 2. a) Sound pressure level at mode 4 and b) Sound pressure level at mode 5.

# Chapter 7

## 7 Discussion

This section discusses some important points which are seen in the simulation and experiment. It also is indicated weaknesses that can be examined in further work.

### 7.1 Notur

Abel was determined to use in experiments since this was advised by NOTUR. This facility is very powerful and work fast with different tasks. During this thesis it was done several tests. One of the tests was try to run multiple tasks at the same time where it was used many nodes. Simulation of mode 1 and mode 2 was used only one node. Through the tests was observed that each node can have maximum 16 cores. This leads to the distribution per node is 16 cores. To perform the tests used shell-script as called job-script. By using shell script gave the opportunity to see an overview of the job. An user can decide for himself what commands he wants to use in an job he performs. Add more number of cores or putt clock limit for the job, it is up to him. In this thesis, work with job-script was necessary. Generally focus was on the MPI job, it was not taken much time to study alternative commands. For example, the user can decide for himself how many tasks he will run on each node. It could be interesting to run some more tests with advanced commandos. In this task was used CPU test with cavity2d file. The test led to the expected result, by increasing the number of CPU reduces physical time. Simulations on abel facility has run without problems. Alternative to abel facility could be hexagon facility which is located in Bergen. It is also a good system, with many cores and memory. Some negative sides with this is hexagon can't run serial job and memory per node is reduced to 32 [MB]. Hexagon has also some positive sides, namely each node has 32 CPU , it is twice more than abel has. Execution of simulation on abel computers proves that abel computers provide a good performance and speed of the simulation process.

### 7.2 Some problems with simulation

Model 1 is not entirely new model of the pipe, but improves the older model by setting dampers in a pipe. In the file corrug.cpp code is written in a more orderly way. There has been easier to understand codes, commandos and their use. As in the previous simulation **Feil! Fant ikke referansekilden.** contains this simulation model 2. Results in chapter (6.2.2 Simulation with different cavity heights) show why a simulation has done with model 2. Observation over LB pressure has made for the four different cavity heights, all they has almost similar results. In appendix A2 is demonstrated one of these results. LB dynamic pressure is increased exponentially, explanation for this effect has not found. Usually, LB dynamic pressure over sample looks like waveform with a certain amplitude and period. Other problem with model 1 has found in LB velocity spectrum. FFT transform of LB velocity for the different cavity height has showed many peak frequencies, where they occurred consecutively

LB velocity behavior is appeared to be a bit weird. Peaks of LB velocity are arranged descending, where the highest peak is occurred at the lowest frequency. First peak of LB velocity start at 0.5-0.6 LB frequency and last peak of LB velocity ends at 12-15 LB frequency. En graphical representation of LB velocity over all measuring points shows that LB velocity contains a kind of noise. This shows at all four cavity height. If not pay attention to this noise it can be concluded that the cavity height 1 [cm], 1/2 [cm] and 1/4 [cm] has fundamental mode. Cavity height 2/3 [cm] led to a non-acoustic mode. By comparing theoretical results with these observations proves that the normal modes of observations do not match the theoretical normal modes. According to the equation of closed-open pipe model 1 fundamental mode equal 1.20 LB frequency. In the simulation the highest peak has found at 0.5-0.6 LB frequency, 1.20 LB frequency has not found. This is a big difference has led to conclusion, use the previous model of a pipe, model 2 instead of model 1. These are main reasons that led to take this decision.

## 7.3 Experiments

Normal modes for experiment were examined for both pipes length. Measured frequencies in experiments almost matched the theoretical frequencies. Difference between reading frequency and theoretical frequency has observed to varying values, from + / -1 [Hz] to + / -5 [Hz]. Disregard this accuracy, normal modes from experiments is matched normal modes from theory.

A rough experiment for pipe 1 also has showed 3 different levels which has matched with theoretical normal modes. Instead of taking velocimeter 2 it has decide to take velocimeter 1. Reason for this choice has been that velocimeter 2 measures only in velocity range 0 -30 [m/s] and no more. In experiment has been analyzed announce three normal modes at high velocity, from 30-53 [m/s]. Software that has been installed on the mobile phone has been used in acoustics context. The use of program to find the resonance frequency is very useful and convenient and easy to use. Other way of find resonance frequency is possible using frequency meter.

## 7.4 Sound pressure level and whistling sound

In experiment normal mode 1, 2 and 3 has been analyzed. As a result suggests cavity height 8 [mm] has the highest sound pressure level, cavity height 1 [mm] has the lowest sound pressure level. The measurements that have been read from the voltmeter have accuracy 0-3 [dB]. In some cases it has been observed various sound pressure level, therefore it has been taken the average value. This is especially true cavity height 8 [mm] where it has been observed sound pressure level variation of +/- 2[dB] and sometime at low flow velocity +/-3 [dB]. Whistling sound has behaved very fierce in this the condition, it has been possible to hear how sound changed with time (milliseconds). However cavity height 1 [mm] whistling sound has been more quiet and there has been almost no variation in sound pressure level. Whistling sound has been much lower than with other cavity height. From the figure 6-14 it is possible to see an interesting situation at about 24 [m/s] when sound pressure level for cavity height 5 [mm] is higher than the cavity height 8 [mm], it is not possible to see same effect in figure 6-15. 24 [m/s] will be the velocity where the cavity height 5 [mm] have the highest sound pressure level, as compared to other cavity height. The graphic representations of modes also show expected results. Situation for cavity height 1 [mm]: It has been difficult to discern whistling sound of normal mode2 with whistling sound of normal mode 3 or whistling sound of normal mode 3 with whistling sound of normal mode 1, sound pressure level is increased almost linearly with velocity.. This is consistent with the theory, as it says 1-2 [dB] difference will not be heard as the volume-related difference for people. For the normal people it is almost impossible to hear the difference which is low. For cavity high 5 [mm] has been observed two normal modes, 2 and 3. For cavity height 5 [mm] and cavity height 8 [mm] whistling sound has been observed in some situation before it has been heard next normal mode.

In other experiment has been analyzed normal mode 2, 3 and 4. As in the previous experiment cavity height 8 [mm] has the highest sound pressure level. Since in the experiment has not been used the same parameters and the same filter the result is different. Accuracy of measurements is 0-3 [dB]. For cavity height 8 [mm], normal mode 4 has been discovered beats at about 26 [m/s]. Whistling sound has been deformed to" whow-whow" sound. This is a phenomenon that occurs when two sound waves with different or same frequencies encounter each, sound produced will be both low and high. It is common to hear beats in tuning musical instruments such as guitar. This leads to two different or equal frequencies hitting each other at 26 [m/s]. The normal mode 2 has been almost equal velocity of 16 - 30 [m/s] for all three different cavity heights. Sound pressure level increased linearly with velocity. Whistling sound has been also very low for cavity height 1 [mm]. In relation to the other cavity height cavity height 1 [mm] has the lowest sound pressure level of 10 - 30 [m/s]. It has been showed the expected results for all three modes of the cavity height 5 [mm] and cavity height 8 [mm].

## 7.5 Cancellation of normal mode

This experiment has made earlier results led to it was cancelled the normal mode 2 and normal mode 3 with some added frequency. This time expectations have been to do this experiment again and see if they will match the previous result. First observation has led to the possible cancel both normal modes, 2 and 3 Frequencies that have found do not the same as in earlier experiment. Reason for this can be several. One of the reasons can be the length of a pipe. Length of the pipe in this experiment is longer than in an earlier. This causes means that the resonance frequency is different. Another reason may be the inlet to a pipe, this time the inlet has been constant, 1 [cm] for normal mode 2 and normal mode 3. Other reason can be the sound pressure level that has read from the mobile phone. Software on mobile phone could be wrong since it has not used any calibrator and it was not compared with other measurements.

After it has changed cavity length from 1 to 2 [cm] has added frequency been unusable. These added frequencies do not cancel normal mode 2 and 3. One luckily added frequency, 1580 [Hz] has found out. This added frequency has canceled normal mode 3. The measurements have made several times and they led to almost the same result. Final result has taken in the report. In experiment it has taken 8 measurements total. Last measurement which has read from the voltmeter of generated frequency has taken right after that whistling sound of generated frequency has not long heard. The last measurement has not read accurately from the voltmeter, it has been decided to take approximately value. It is said that the sound pressure level at around 40 [dB] corresponding to whisper, so this area has used for the measurement.

## 7.6 Measurments in a pipe

Further in experiment it has decided to study more closely cancellation of normal mode. Velocity to normal mode 3 has not taken into account, the velocity has been around 17-20 [m/s]. The main point of the measurements has been to take equal numbers of measurements inside of the pipe as outside of the pipe. The measurements in the pipe does not start from 1 to 8, they start from 2 to 8. Because the first measurement was not measured it has assumed to be 0 [dB]. Total has measured 7 measurements inside of the pipe. The first measurement in the pipe has taken when the sound pressure level of the flow generated frequency equal around 95 [dB]. The last measurement has taken when the sound pressure level of the flow generated frequency equal around 43 [dB]. Thereby it has been shown appropriate number of measurements, see figure 6-17.

It has not done, but it could be done an experiment, to find results of theoretical equation upstream power at normal mode 3 and compare with result of upstream power at normal mode 3 which has found in cancellation of normal mode experiment. Try to find out if the will give similar results.

## 7.7 Hysteresis

Acoustic hysteresis was conducted in three different situations, and in three different situations was brought almost the same result. Hysteresis loop was formed immediately after the velocity began to decrease. Found this hysteresis is not one of the previously listed hysteresis in the theory, although visually hysteresis loop is very similar to hysteresis loop from theory which refers to three types of hysteresis, see chapter (6.3.6 Hysteresis). Analyzing the mechanism from figures 6-19 - 6-21 of three different types of hysteresis has shown that for its realization it is necessary fast changing the velocity to a negative direction. To improve that it is possible to do some experiment, but this time try to take measurement in opposite direction. Start from high velocity, go to low velocity and again back, an experiment has to show almost the same results. If an experiment will show quite different result assertion will not be proved.

This hysteresis can be seen as a flaw in the measurement when the data will be the main part of experimentation.

## 7.8 Reynolds number

Reynolds numbers in the simulation were changed. In theory says that the Reynolds number of 4000 will detect turbulence. Reynolds number was higher than 4000 in models, one and two. This means that in both cases was available turbulence. When speaking about the experiment turbulence becomes much higher than in simulation, Reynolds number reaches up to 85431. Further work needs to simulate a new file, model 1 with different Reynolds numbers and try to find effect of it. This time has not used so much time to find it out. May be it will give answer to why there is a problem with velocity and pressure in new file, model 1. To find it is necessary to do more thoroughly experiments.

# Chapter 8

## 8 Conclusion

In this thesis has examined simulations and experiments with acoustic pipe where it has used different cavity height. Not least, it has studied abel facility by using some tests. Test of the facility have shown that abel is a facility that can work with large tasks quickly and effectively, where each node can use maximum 16 cores per job. Of course it is possible to use more cores, but then it has to use more nodes. Also it has found that use of shell scripts is necessary for performance of any job. Shell script gives user the opportunity to collect all the necessary commands into a single command, thus preserving the time to complete each of them. By simulation Palabos on computers abel has not detected any problems.

The simulation result has revealed clearly that model 1, pipe with dampers has not understandable effect of pressure. With help of represented theory this effect has not been explain. To explain this effect correctly at least necessary to use more time for study cpp file of model 1. It has been shown that the spectrum of the pressure was not like him a primary wave form. In this case the pressure has increased exponentially. At velocity has been seen the effect of strong noise. All this has led to it had to use older version of model, a pipe without dampers. The older model has been performed simulation earlier, in other type research where reviews of file were positive. These results have shown that with each change cavity height has found fundamental frequency. Also, it has found one more frequency that has been similar to the acoustic frequency, 10. Of expectation with a magnitude of pressure has been that the greater the cavity height will be than the higher magnitude of pressure will be. The result of magnitude has shown not exactly expected result. The magnitude of 1/2 [cm] cavity height has detected lower than the magnet of 3/8 [cm] cavity height. This result has not been explained. The visual representation of the simulation has provided a way to understand the behavior of flow in each individual cavity height. The visual result has shown that cavity height effects on velocity inlet of an open-open pipe.

An experimental study has conducted to by changing the cavity height changes sound pressure level. This corresponds to the deeper the cavity the louder the whistling sound is. It has observed that shorter pipe corresponds to shorter wavelength. Changing of cavity height has not changed resonance frequency, but changing of cavity length has given change of resonance frequency. It has also found that the change of velocity of the flow in a pipe affects to resonance frequency. At low velocity dominates the low resonance frequency, at high velocity dominates the high resonance frequency. In experiment, for sound pressure levels measurements have found beats phenomenon, this phenomenon has also met in the cancellation of normal mode experiment. Result of the cancellation of the whistling sound for certain modes shows that it is possible. In this experiment has been reviewed normal mode 2 and 3, the frequency range has used 1000 -5000[Hz]. The most interesting that the change of the cavity length from 1 [cm] to 2 [cm] give a very different results. In this case has found only one added frequency which has able to cancel normal mode 3. It has been reviewed in detail and concluded, it is necessary 22 [mW] upstream power of added frequency to cancel 16[mW] upstream power of generated frequency. This observation has done for own interests, for industry this is not interesting.

In three different situations has demonstrated acoustic hysteresis. There has used same method, first try to increase the velocity of the flow and then decrease. Hysteresis loop has been very similar to the one in theory. To find explanation of this has not found. It could be said that the reason for this is some electrical tools, but it is not proven.

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# 10 Appendix

## 10.1 A. Simulation

### 10.1.1 A.1 Callculation

Model 1 : 1 [cm] equal 200 cells

Modul 2: 1 [cm] equal 250 cells

Ts= 0.01 sample interval.

Fs=1/Ts=100- LB frequency.

### 10.1.2 A.2 Simulation of model 1

LB dynamic pressure versus number of samples:

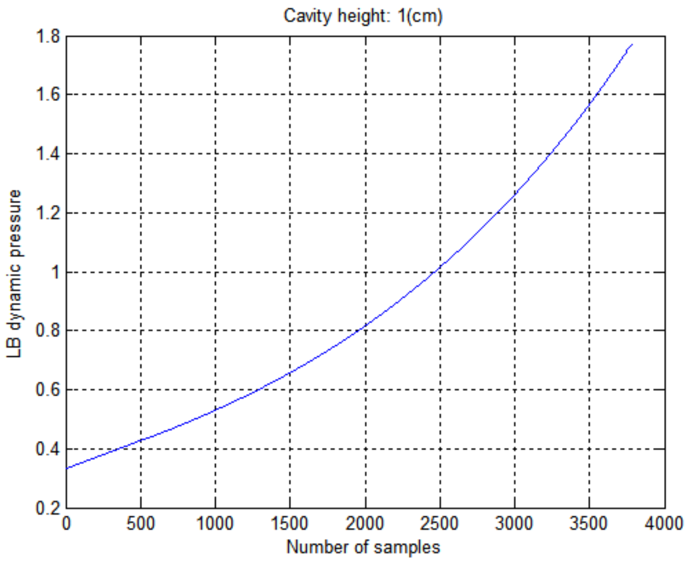


Figure 10-1: LB dynamic pressure versus number of samples.

## 10.2 B. Experiment

### 10.2.1 B.1 List of equipment in experiment.

- ⊗ Wooden box 1: 57[cm] x 29[cm] x 32.5[cm]. (Length x Width x Hight)
- ⊗ Wooden box 2: 59.5[cm] x 32.5[cm] x 32.5[cm]. (Length x Width x Hight)
- ⊗ Acoustic filter 1: Wavetek Dual, mode HI/LO Filter, model 442.
- ⊗ Acoustic filter 2: Bandpass filter ,type 719

- ⊗ Amplifier to microphone: Norsonic, front end type 336.
- ⊗ Microphone: Cortidge, type 4134
- ⊗ Velocimeter 1: ALNOR, AXD 560 .
- ⊗ Velocimeter 2: VelociCalc, air velocity meter 9545.
- ⊗ Voltmeter: Metric Bruel & Kjaer, type 2409.
- ⊗ Frequecy generator: Wavetek, Lin/Log sweep generator, model 135.
- ⊗ Amplifier to loudspeaker: Dynergy, soundcraft SA 1000.
- ⊗ Loudspeaker: JBL, GT 5-10
- ⊗ Vacuum cleaner: Simens Z 5.0.

### 10.2.2 B.2 Pictures of experiment setup.

Picture 1: A pipe with a simple cavity devise mounted to wooden box with an attached loudspeaker transducer.

Picture 2: A vacuum cleaner pipe mounted to wooden box with an attached loudspeaker transducer.

### 10.2.3 B.3 Calculation of power

By using sound pressure level find pressure in Pascal:

$$L_p = 10\log_{10}\left(\frac{P_{rms}^2}{P_{ref}^2}\right)$$

$P_{ref}$- Reference sound pressure ,pref = 20 μPa

$$p_{maxrms} = P_{ref} * 10^{\frac{pmax}{20}}$$

$$p_{minrms} = P_{ref} * 10^{\frac{pmin}{20}}$$

Downstream of a wave component A:

$$A = \frac{pmaxrms + pminrms}{2}$$

Upstream of a wave component B:

$$B = \frac{pmaxrms - pminrms}{2}$$

Intensity in the positive direction:

$$I_{plus} = \frac{|A^2||}{\rho c}$$

Intensity in the negative direction:

$$I_{minus} = \frac{|B^2||}{\rho c}$$

The product of the integration time and the number of measurements given:

$$I_{net} = I_{minus} - I_{plus}$$

The downstream power at 1580[Hz]:

$$P_{downstream} = I_{net} * S$$

Density of air:

$\rho$- 1.2 [ kg/m^3] at 20°C

Speed of sound:

c=343.2 [ m/s] at 20°C

The radius of the pipe:

r=0.0215 [m]

The cross section of the pipe :

S=$\pi * r^2$ [m^2]

The upstream power at 535 [Hz]:

$$W_{\frac{1}{2}m} = I_{\frac{1}{2}m} * \pi r_1^2 = I_{1m} * \pi r_2^2$$

$$I_{1m} = I_{\frac{1}{2}m} * \frac{r_1^2}{r_2^2} = I_{\frac{1}{2}m} * \frac{1}{4}$$

$$P_{1m}^2 = P_{\frac{1}{2}m}^2 * \frac{1}{4}$$

$$P_{1m} = P_{\frac{1}{2}} * \frac{1}{2}$$

It is led to:

$$P_{mode3} = 0.0205 * \frac{P_{rms}^2|0.5m}{2} \text{ [W]}$$

### 10.2.4 B.4 Calculation of resonance frequency with end correction

The resonance frequency calculation:

An ope-open pipe: $F_n = \frac{c_0}{2n*L_{eff}}$ [Hz]

$$c_0 - sound\ speed\ at\ 20^0\ C$$

$$n - number\ of\ resonanc\ frequency$$

$$L_{eff} - the\ effective\ length$$

The effective length: $L_{eff} = L + \frac{8r}{3\pi} + 0.6r$ [m]

$$r - the\ radius\ of\ a\ pipe$$

$$L - the\ physical\ length\ of\ a\ pipe\ and\ cavity\ device$$

Calculation with numbers:

Pipe 1:

$$L_{eff} = (0.92) + 8 \cdot \tfrac{0.0215}{3\pi} + 0.6 * 0.0215 = 0.951[\mathrm{m}]$$

$$L_{eff} = (0.90) + 8 \cdot \frac{0.0215}{3\pi} + 0.6 * 0.0215 = 0.931[\mathrm{m}]$$

Pipe 2:

$$L_{eff} = (0.62) + 8 \cdot \tfrac{0.0215}{3\pi} + 0.6 * 0.0215 = 0.651\ [\mathrm{m}]$$

$$L_{eff} = (0.60) + 8 \cdot \frac{0.0215}{3\pi} + 0.6 * 0.0215 = 0.631[\mathrm{m}]$$

## 10.2.5 B.4 Cancellation of generated frequency

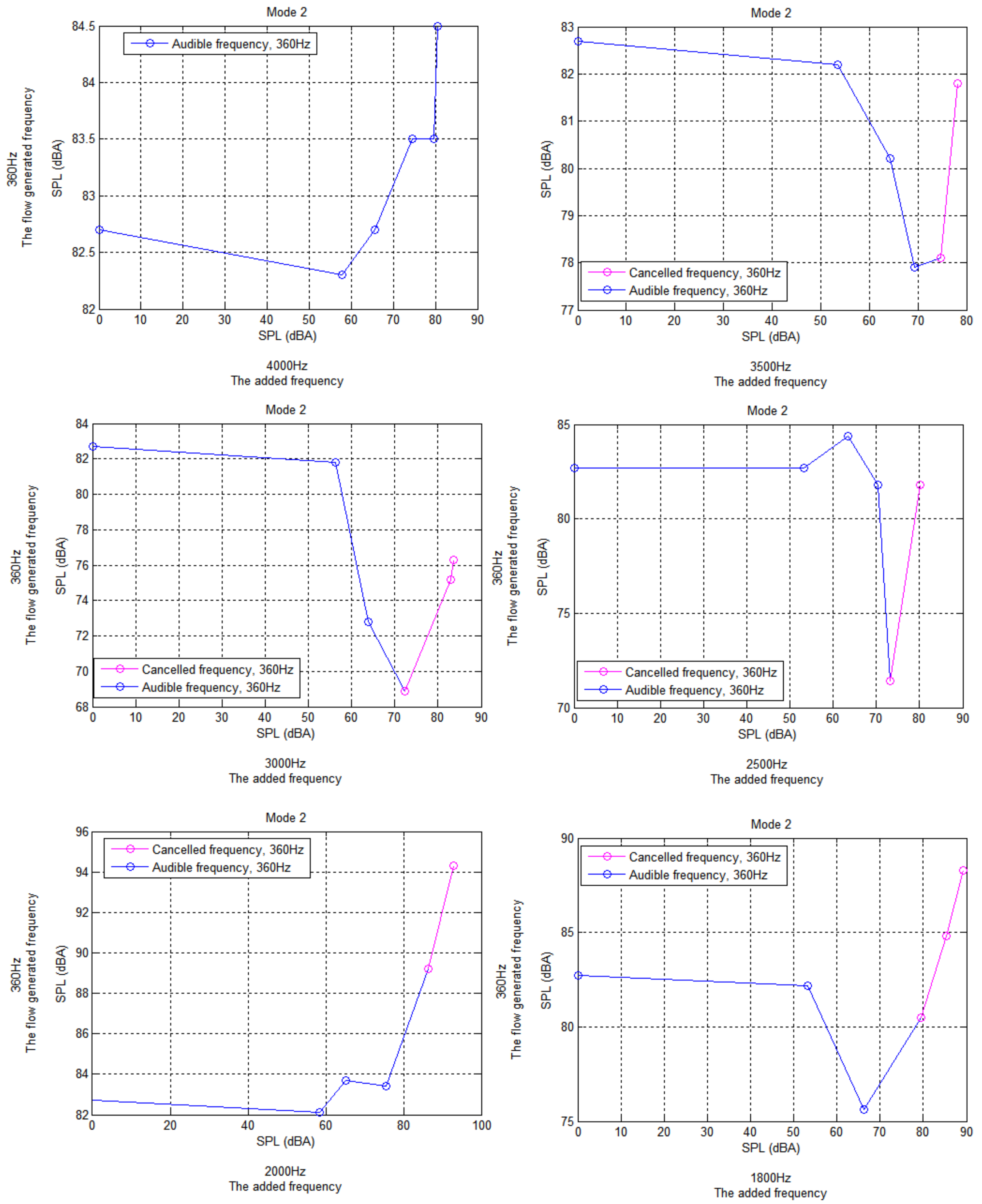


Figure 10-2: Cancellation of mode 2, part 1.

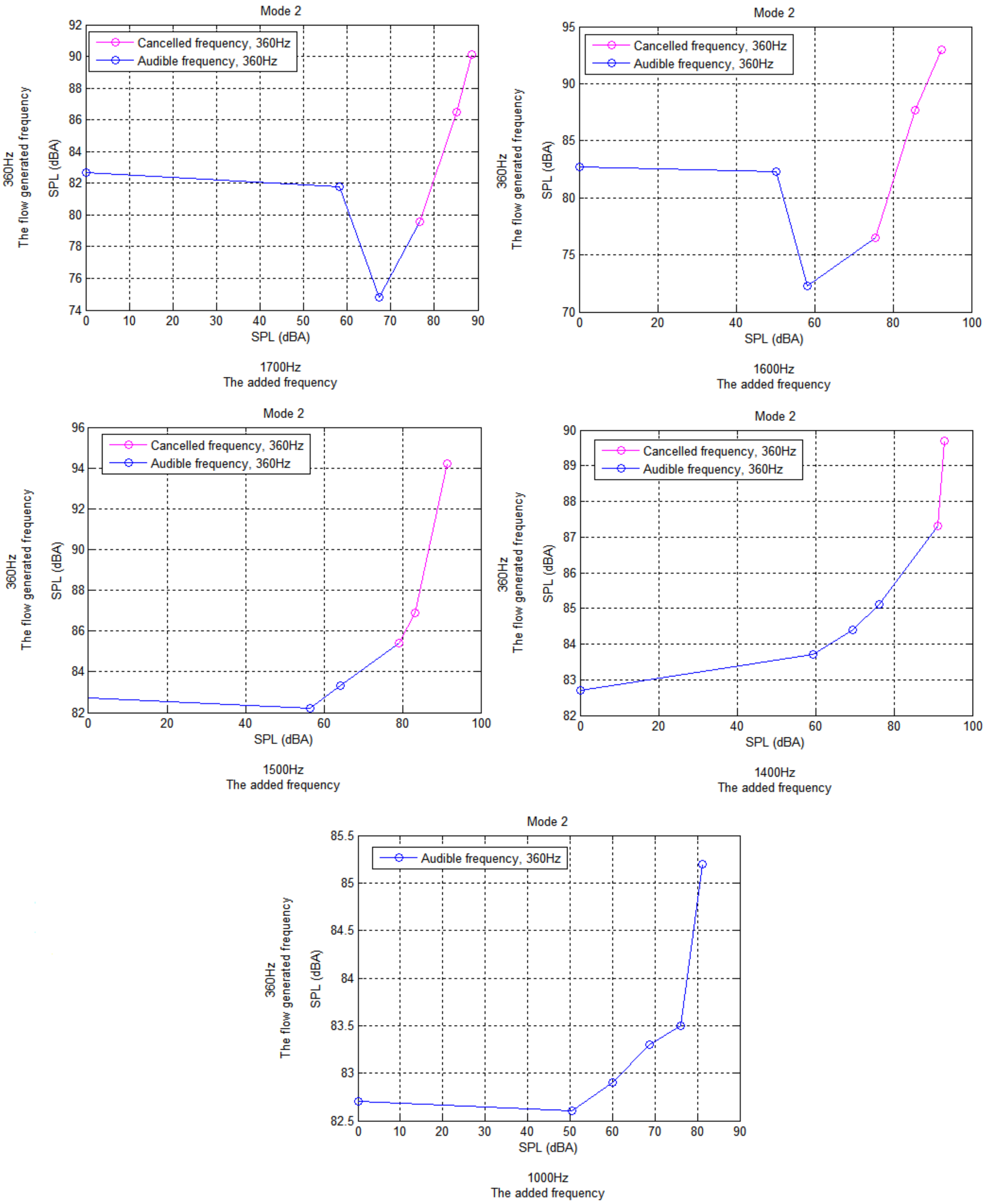


Figure 10-3: Cancellation of mode 2, part 2.

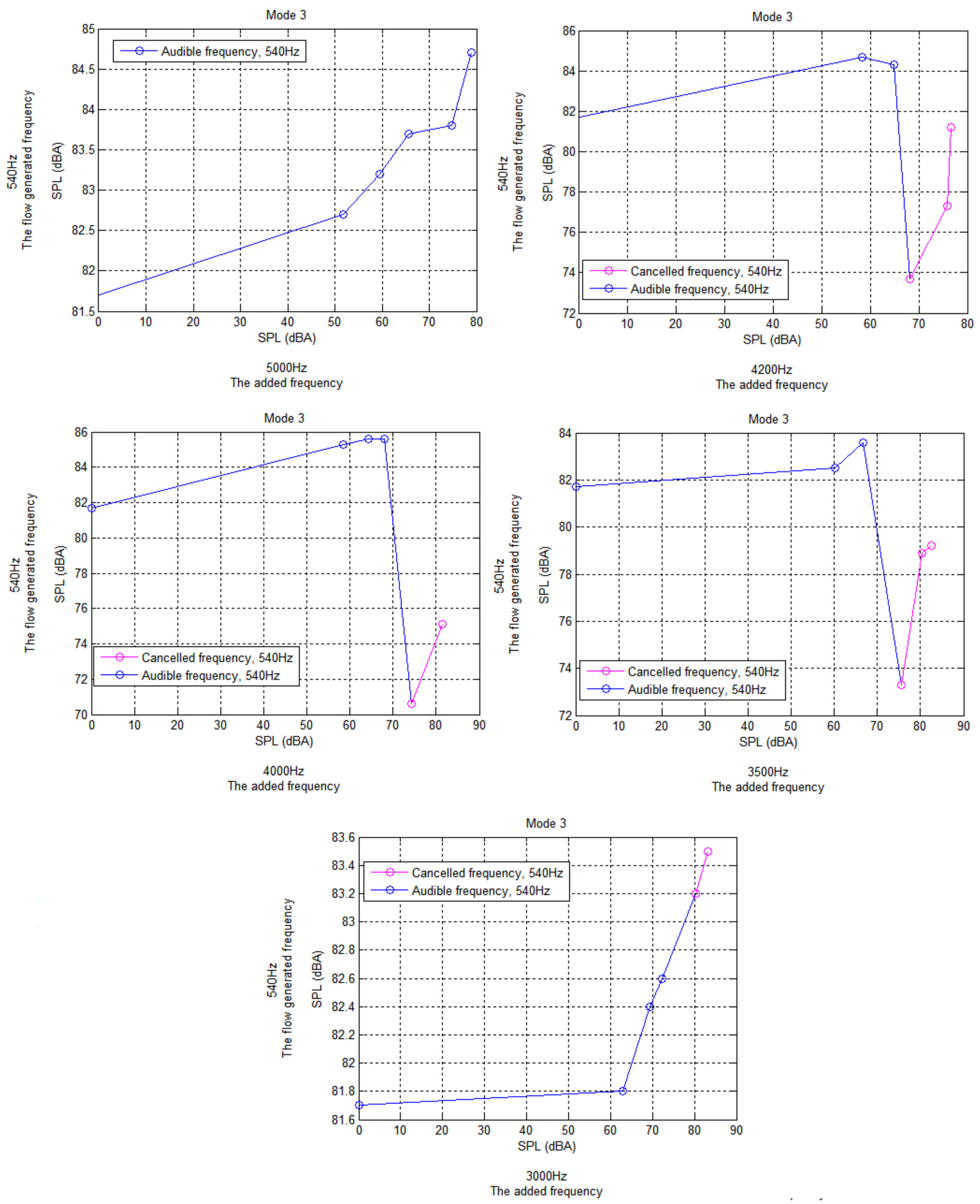


Figure 10-4: Cancellation of mode 3, part 1.

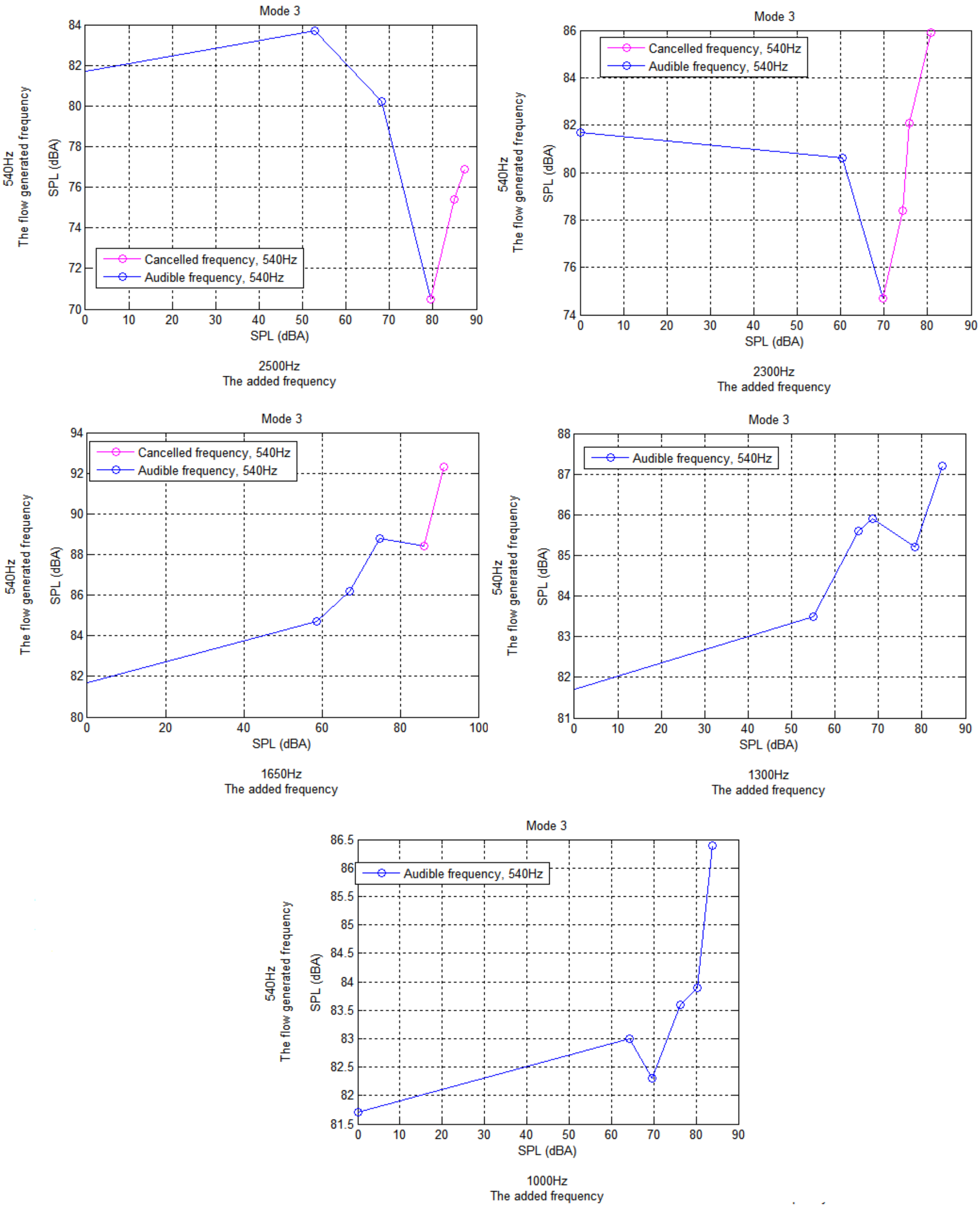


Figure 10-5: Cancellation of mode 2, part 2.