Modeling the Voice of Pathological /a/ Utterance Using Organ Pipe Design Model

Brahim Sabir, Fatima Rouda, Ghizlane Mabchour, Bouzekri Touri and Mohamed Moussetad

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Brahim SABIR[1], *Fatima ROUDA*[2], *Ghizlane MABCHOUR*[3], *Bouzekri TOURI*[4]

Mohamed MOUSSETAD[5]

[1,3,5] Physics Department, Faculty of Science Ben M'Sik
[2]Chemsitry Department, Faculty of Science Ben M'Sik
[2]Language and Communication Department, Faculty of Science Ben M'Sik
sabir@amaquen.org,a-rouda@hotmail.fr, g.mabchour@gmail.com,
touribouzekri@gmail.com

Abstract

Precedents and objectives:

The sound wave is propagating in air and is received by the ear of the listener.

Many models of voice production were done based on two-mass model and source-filter.

The resulted wave is impacted by excitation source properties, the properties of the medium which include vocal tract properties, damping forces, and initial and boundary conditions.

A pathological voice is a sound wave that was impacted by one or more factors cited above.

The objective of the present paper is to simulate the behavior of the fundamental frequency of utterance /a/ by using organ pipe model, In order to know the parameters that govern the behavior of /a/ utterance to be classified as pathological or normal voice of /a/, in order to fine-tune these parameters.

Materials and methods:

The modeling was carried out using the variations of sound pressure level function of difference radius, thickness and young's module of the voice production apparatus.

The used software is COMSOL.

Results:

The resonant frequency could be shifted according to the values of inner radius and thickness; thus a pathological voice can be transformed to normal voice upon fine-tuning these parameters or adjusting damping forces.

Conclusion:

A pathological voice as any voice can be described as a disturbance, a transfer of energy, which travels through the air from one location to another location. It is distinguished by its property: density, Young's module, Poisson's ratio. Such physical properties describe the material itself not the wave. An alteration in the properties of the medium will cause a change in the speed.

Index Terms: Pathological voice, organ pipe mode, modeling, COMSOL, /a/ utterance.

1. Introduction

Mechanical and acoustical vibrations are the sources of sound in human body. Miklós et al.[1]

A familiar example that models the human sound production is the vibrations of air in the organ pipe, which is a topic that has already been examined by a number of researchers. The acoustic roles of organ-pipe have been relevantly recognized, such as determination of a pitch Tashiro et al.[2], and acting an organ pipe as resonators in many musical instruments. Rossing et al.[3]

The Sound production in organ pipes is a complex matter involving interactions between flow fields and sound waves

Angster et al.[4]

Thus, the sound of a pipe organ is created by a jet of air blowing across its mouth and the column of air resonating inside it.

Sound production in organ pipe depends upon the collective behavior of several vibrators, which may be weakly or strongly coupled together. This coupling may cause the apparatus as a whole to behave as a complex vibrating system, even though the individual elements are relatively simple vibrators.

Based on studies of organ pipe, the resulted pitch of an organ pipe is impacted by:

Pipe properties which include: its geometry, inner diameter, Young's module, Poisson's ratio, wall thickness and wall drag force.

Fluid properties which cover: its temperature, absolute pressure, background velocity, density…etc.

By analogy, pathological voice is a result of the way in which the mechanical and acoustical oscillators may be coupled together and the way in which they radiate sound.

2. Related works

Many researchers studied geometry of the organ pipe and its impact on its voicing such the influence of the organ pipe upper lip thickness on the sound frequency spectrum Štafura et al.[5] and how modifications of geometrical of the mouth parameters alter characteristics of the sound , thus the pitch of the pipe sound is determined by modifying the flow geometry.

Außerlechner et al.[6] And Crighton [7] have performed theoretical and experimental works to determine the relations between mode frequencies and flow parameters.

Nakayama et al.[8] Studied the effect of the pipe geometry on the fundamental frequency.

Adachi [9], Außerlechner et al.[6] and Coltman [10] have simulated the complete sound generation mechanism in a stopped flue pipe.

A flue organ pipe can be excited in various acoustic modes by changing the air pressure supplied to it, and the timbre of the sound can be adjusted by adjusting the air flow parameters or jet-lip interaction as shown by Angster et al.[11].

Nakayama et al.[8] Proposed a scaling in which the length of the pipe is calculated such that the pipe produces the desired pitch.

Adachi et al.[12] Reported that adjusting the lip resonance frequency, would reproduce different acoustic modes of the resonator.

Adachi et al.[13] Performed experiences related to the perturbation of the length of the tract applied for male–female vocal tract shape conversion.

As it will be demonstrated in this paper, the frequency of the sound produced by a pipe is primarily affected by the pipe's length. Intuitively, increasing pipe length will lower the frequency while decreasing pipe length will raise the frequency. However, there are other ways of manipulating the frequency without changing physical pipe length.

It is the case of harmonic pipes that sound an octave above where they should. That is, their length is double what it should be.

For instance, a harmonic pipe will sound a C3 note instead of a C2 note. This is due to a small hole that is cut into the pipe at the first harmonic (an octave above).

On the other hand, stopped pipes are closed on the top causing them to sound an Octave lower (they are half the length of a normal pipe).

For instance, a stopped pipe will sound at C1 instead of C2.

This is because stopping a pipe causes it to now become an open-closed pipe and thus, as described by [16]; changing pipe width also changes the timbre of the sound the pipe produces.

As a general rule, the thinner the pipe, the "harsher" the timbre Rucz et al.[14]

As shown by Miklos et al. [15] the mouth tone modes can be linearly frequency-shifted to reach a desired sound, and the main example of adjustments is to obtain the natural resonance frequency, thus, the resonators will be damped by inserting sound absorbing material into the open ends.

And related to pipe with adjustable length, it was to be expected in theory that the fundamental frequency became continuously lower, the longer the resonator was, as the wave length of the standing wave changes in the resonator as notified by Christian [16].

3. Modeling

3.1. Assumptions

We have made the following assumptions:

- The principle of conservation of mass is respected.
- The sound of organ pipe can be considered periodic with small perturbations; thus, the steady state sound spectra of organ pipes are dominated by harmonic components.
- The wavelength of acoustic waves in the organ pipe is long relative to the width of the pipe so that the acoustic waves are one-dimensional (they travel only lengthwise in the pipe).
- The flow of the fluid in the pipe is laminar:
- The pressure at the open is equal to the pressure of ambient air outside the pipe by satisfying the continuity of pressure.
- In the frequency domain all sources and variations are assumed to be harmonic. The solved equations assume that the propagating waves are plane.
- It is assumed that the sound propagates through pressure waves only, which means that other fluctuations of the quantities pressure, density and velocity caused by effects such as eddies are not regarded as sound, but perturbations out of the scope of the linear acoustic framework of this paper.

3.2. Proposed model

Consider a length L of pipe closed by rigid walls at one end. This is precisely analogous to the case of the human vocal apparatus, where there is a way to excite vibrations from lungs and a way for the energy to radiate from mouth, as shown in figure.1.

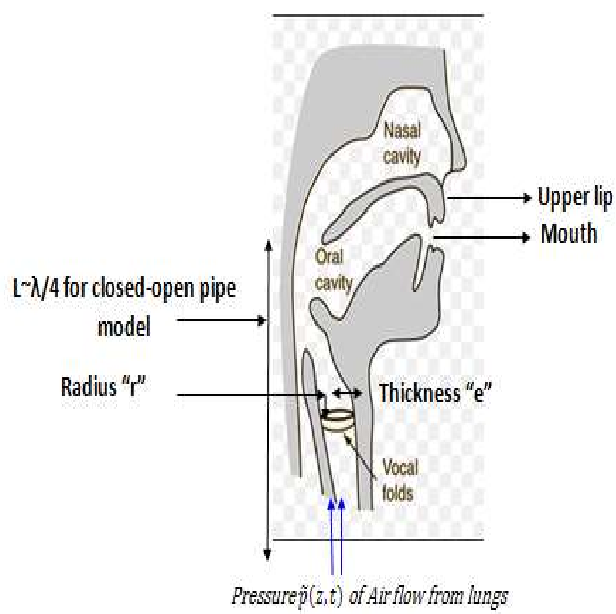


Figure 1 : *Vocal apparatus, Borden et al.[17]*

(λ: Wavelength, r,e,L: Radius ,thickness and length, respictevely of the organ pipe)

The air jet drives the pipe at the pipe mouth. The driving jet produces a pressure fluctuation on the air inside the tube. The frequencies of natural resonance of the pipe are found where the pressure oscillations induce maximal response inside the tube.

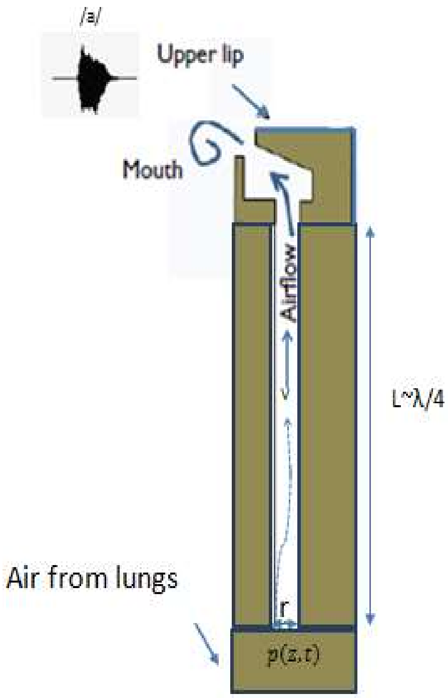


Figure 2 : *Model of vocal apparatus (cylindric duct).*

Governing equation :

It is assumed that the studied domain Ω in the

d-dimensional space is considered Ω⊆ Rd

And that the domain Ω is limited by the boundary Γ.

The problem domain is defined as :

Ω ={r / r<=a; $\theta \in [0,2\pi], z \in R$ }

Whereas the boundary is given as: Γ={r / r=a}

The Euler equation is linearized and simplified as:

$$\rho_0 \frac{\partial \tilde{v}}{\partial t} + \nabla \tilde{p} = 0 \ (1)$$

$$\nabla^2 \tilde{p}(z,t) - \frac{1}{c^2}\frac{\partial^2 \tilde{p}(z,t)}{\partial t^2} \ (2)$$

Where:ρ_0 : the density of air ,
p: pressure perturbaion of air and v: the velocity of the air, inside the organ pipe.

We are interested in steady-state processes, and we assumed a time-harmonic perturbation with an angular frequency ω:

$$p(z,t) = |\, p(z)\,| \ \cos(\omega t + \emptyset(z)) = \Re e\{|\, p(z)\,| \ e^{j(\omega t + \emptyset(z)}$$
(3)

$$\tilde{p}(z) = |\, p(z)\,|\, e^{j\,\emptyset(z)} \quad (4)$$

We introduced complex amplitude $\tilde{p}(z,\omega)$ by using Fourier transformed variables.

$$p(z,t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \tilde{p}(z,\omega) e^{-j\omega t}\, d\omega \quad (5)$$

The Fourier transformed variables can then be attained as:

$$\tilde{p}(z,\omega) = \int_{-\infty}^{+\infty} p(z,t) e^{-j\omega t}\, d\omega \quad (6)$$

And assuming that the corresponding integral exists.

We introduced Acoustic wave number: k = $\frac{\omega}{c}$ (This model is naturally only valid under the cutoff frequency, i.e. ka < 1.8412 as cited by Rucz [18]

The homogeneous Helmoltz equation is obtained as:

$$\nabla^2 \tilde{p}(z,\omega) + k^{\,2} \tilde{p}(z,\omega) = 0 \quad (7)$$

The sound propagated in the vocal tract can be modeled as the wave propagated in a cylindric duct which is assumed with a rigid wall.

The model used is a finite cylindric duct of inner radius a with its axis of symmetry located at the z-axis of the Cartesian coordinate system.

The helmoltz equation is cylindrical coordinates:

$$\frac{\partial^2 \tilde{p}}{\partial r^2} + \frac{1}{r}\frac{\partial \tilde{p}}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \tilde{p}}{\partial \theta^2} + \frac{\partial^2 \tilde{p}}{\partial z^2} + k^{\,2}\tilde{p} = 0 \quad r \in \Omega \quad (8)$$

It is assumed that the normal component of the particle velocity ϑ_n vanished at r=a. making use of the linearized Euler equation :

$$\vartheta_n(a,\theta,z) = -\frac{1}{j\omega\ {}_0}\frac{\partial p}{\partial r}\,|_{r=a} = 0 \text{ if r } \in \Gamma \quad (9)$$

The pipe is of finite length. This means that pressure waves are reflected at the (open or closed) ends of the pipe.

Let us consider a finite cylindrical tube that extends from z = 0 to z = L terminated by the acoustic impedance ZL(ω) at

Z = L.

Since the unidimensional Helmholtz equation is valid inside the pipe under the cutoff frequency, the resulting pressure field of the pipe is the superposition of two counterpropagating planar waves, as obtained by the d'Alembert form solution .

$$\frac{\partial^2 \tilde{p}(z,\omega)}{\partial r^2} + + k^2 \tilde{p}(z,\omega) = 0 \quad r \in \Omega \quad (10)$$

The solution of 1D Helmholtz eq. is given in d'Alembert form as :

$$\tilde{p}(z,\omega) = p^+ e^{-jkz} + p^- e^{-jkz} \quad (11)$$

$$\frac{\tilde{P}\,(L,\omega)}{\tilde{U}\,(L,\omega)} = \text{ZL}(\omega) \quad (12)$$

Making use of the fact that :

$$\frac{p^- e^{-jkz}}{p^+ e^{-jkz}} = \frac{Z_L(\omega) - Z_0}{Z_L(\omega) + Z_0} \quad (13)$$

With Z0 denoting the acoustic plane wave impedance of the tube.consequently,

The input impedance of the pipe Zin is defined as the ratio of the complex amplitude of the pressure and volume velocity at z=0. This can be expressed:

Input impedance :

$$\text{Zin}(\omega) = \frac{\tilde{P}\,(0,\omega)}{\tilde{U}\,(0,\omega)} = Z_0 \frac{Z_L(\omega) + jZ_0 tankL}{Z_0 + jZ_L(\omega)\, tankL} \quad (14)$$

Since the system responds with maximal pressure to unit input volume velocity when Zin(ω)has a local maximum, the natural resonance and anti-resonance frequencies of the system can also be found as the local extrema of the input impedance or input admittance functions.

Two extremal cases regarding the termination impedance ZL are of special interest. The first case is when the pipe is terminated by zero impedance. This corresponds to zero pressure at the pipe end, p(L, ω) = 0. In this case the system can be considered ideally open and from equation, the input impedance is attained as :

$$\text{Zin(open)} = jZ_0 \tan(kL) \quad (15)$$

The second case corresponds to the pipe being terminated by a rigid wall, meaning that ZL-→ ∞

And implying zero volume velocity at z=L. in this case the system is considered ideally closed and its input impedance can beexpressed by taking the limit ZL -→ ∞ of the equation:

$$\text{Zin (closed)} = - jZ_0 cotan(kL) \quad (16)$$

Let us assume a simple model of a labial organ pipe. The jet drives the pipe at the pipe mouth. The driving jet produces a pressure fluctutation on the air inside the tube.

The frequencies of natural resonance of the pipe are found where the pressure oscillations induce maximal response inside the tube i.e: when the acoustic input impedance of the pipe Zin is minimal. Hence the frequencies of natural resonance fn = $\frac{c}{\lambda_n}$ of the system are found by the corresponding wavelength λn as

Therefore, the cylindrical pipe open at both ends acts as a half-wave resonator, whereas the pipe with one end open and the other end closed is a quarter-wave resonator.

$$\lambda n = \begin{cases} \frac{4L}{2n} \text{ if } Z_L = 0 \\ 4\frac{L}{2n-1} \text{ if } Z_L \rightarrow \infty \quad (\text{n} = 1,2, \ldots.) \end{cases} \quad (17)$$

Open-open pipe: $\frac{c}{2L}$ = f; λ= 2L (18)

Closed-open pipe: $\frac{c}{4L}$ = f,c= λ. f --->λ= 4L (19)

-The behavior of the resonator is determined by the input impedance function

Sound pressure level (SPL) Sound pressure level, denoted Lp is defined by IEC [19]

Where prms is the root mean square sound pressure;

The commonly used reference sound pressure in air is Roeser et al.[20]

$$\text{Lp} = 10 \log[(\frac{P_{rms}}{P_{ref}})2] \qquad P_{rms}^2 = \frac{1}{2}\, p\, p^* \quad (20)$$

-The frequency response of the pipe is obtained by plotting the sound pressure level Lp at the open pipe end (at the mouth of the speaker)

Where pref is the reference pressure for air 20 mPa and p* is the complex conjugate.

-The limitations of the one-dimensional model are that (1) it is only capable of handling simple geometries, and (2) it is only applicable under the cutoff frequency of the system.

3.3. Methods

-The modeling was performed by COMSOL Multiphysics software version 5.0. using pipe acoustic model.

- In this model the pipe is driven at 440 Hz which is the A4 note (or a').

-An airflow is pushed in at the bottom of the organ pipe, modeling the flow air from lungs, which is out via the mouth.

-The vibrations will resonate with the organ pipe body to create the note of the pipe.

-The organ pipe geometry as shown in figure.2 is defined in terms of its length L, inner pipe radius a, wall thickness e and cross section shape (here circular).

-The elastic properties of the pipe wall are Young's modulus Ew and Poisson's ratio vw. The model parameters are given in the table.1 below.

Table 1 : *Initial data of the model.*

Parameter	Value	Description
f_n	440 Hz	Frequency of normal /a/ utterance
L_{guess}	$\frac{C}{4\ fn}$	Quarter wavelength for open-closed pipe at f_n
L	0.3715 m	Pipe length giving a resonance at 440Hz
a(r)	3 cm	Pipe inner radius
e	2 mm	Vocal tract thickness
E_w	10^9	*Young's module of the skin*
v_w	0.4	*Poisson's ratio of the skin*
C_0	343.1 m/s	*Speed of sound*

The algorithm of the adjustment is shown in figure 3:

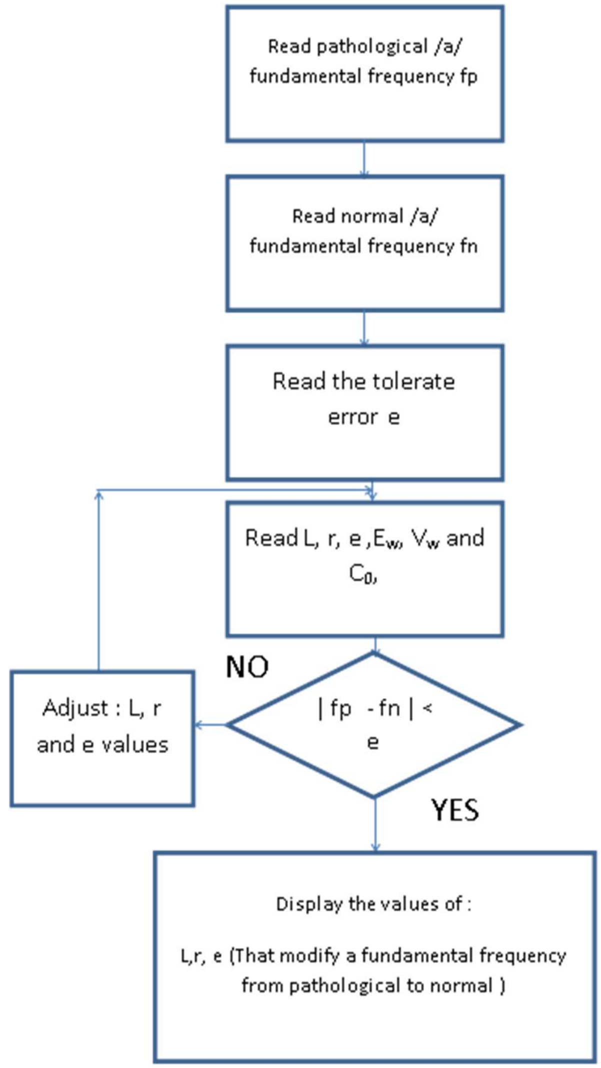


Figure 3 : *Adjustment's algorithm of length L , radius r and thickness e.*

4. Results and Discussion

4.1. Resonance peak of the fundamental frequency for different inner pipe radii

The frequency response around the resonance frequency is plotted in Figure.4 for several values of the pipe radius. Changing the pipe radius clearly shifts the resonance frequency, which occurred when the frequency of the driving force becomes equal to the natural frequency of vibrating particle; the amplitude of oscillation of driven oscillator becomes maximum. The first resonant frequency is the fundamental frequency. Even though, other harmonics (as shown in figures.7 and 8) can be more dominant during transient attacks it is the fundamental frequency which determines the tone of the pipe.

Thus, a pathological voice can be transformed to normal one upon fine tuning of the radius.

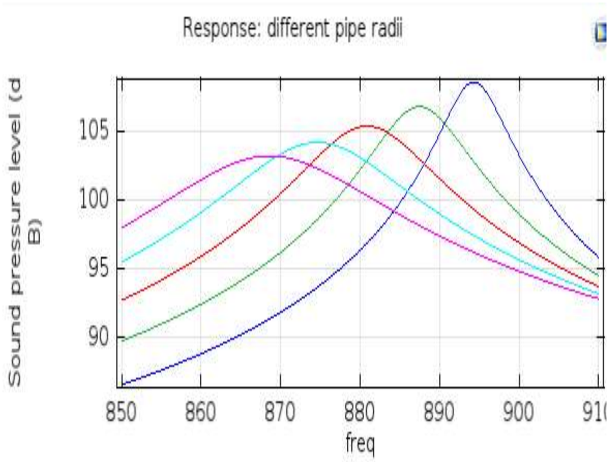


Figure 4 : *Resonance peak of the fundamental frequency at 880Hz for different inner pipe radii for open-closed pipe.*

We noted that the open pipe model gives a resonance peak of fundamental frequency at 440Hz.

4.2. Resonance peak of the fundamental frequency for different pipe wall thickness

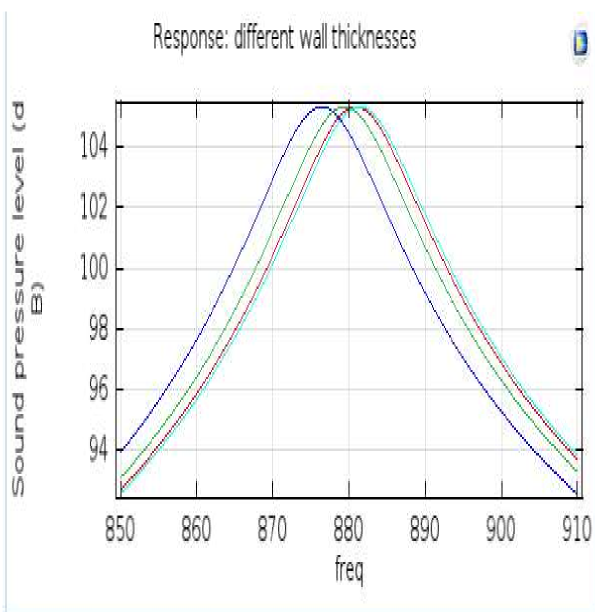


Figure 5 : *Resonance peak of the fundamental frequency at 880 Hz for different pipe wall thickness for open-closed pipe.*

The response for different values of the pipe wall width is plotted in Figure.5. It is here also seen that changing the pipe wall width will change the resonance slightly. This is because the elastic properties of the pipe wall have influence on the effective compressibility of the system in a given cross section. This in turn changes the effective speed of sound in the pipe and thus the resonance.

4.3. Resonance peak of the fundamental frequency and frequencies of the harmonics from 100 to 3000 Hz

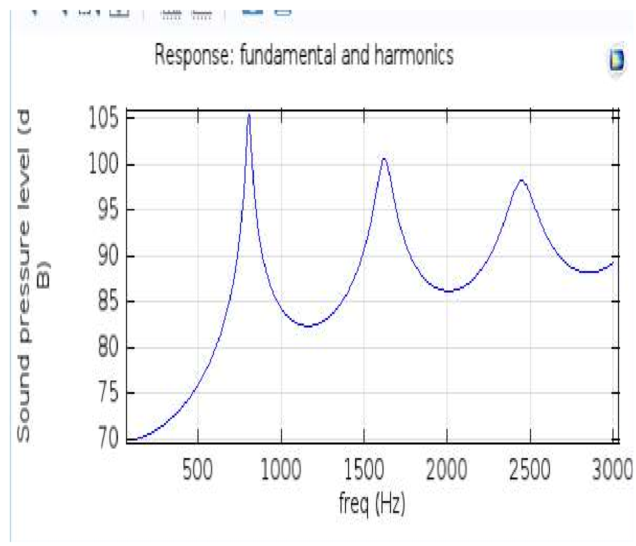


Figure 6 : *Resonance peak of the fundamental frequency and frequencies of the harmonics from 100 to 3000 Hz in opened-closed pipe model*

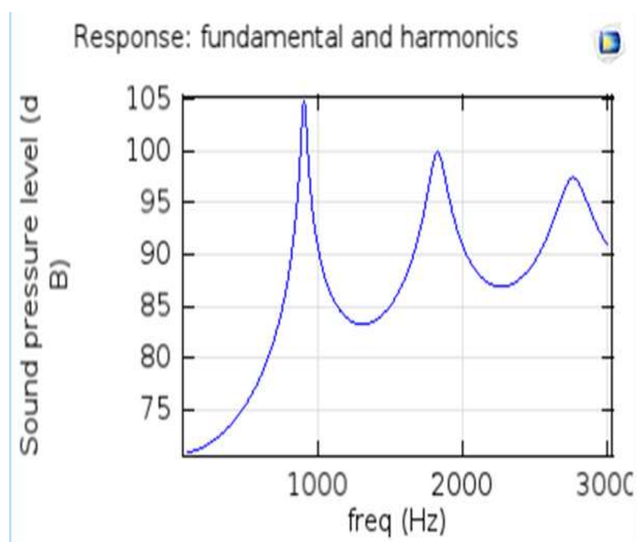


Figure 7 : *Resonance peak of the fundamental frequency and frequencies of the harmonics from 100 to 3000 Hz in open pipe model with L=0.1715[m]: less harmonics.*

In Figure.6 and Figure.7 the parameter values giving a fundamental resonance at 880 Hz are selected, and the response is plotted for frequencies from 100 Hz to 3000 Hz. The plot shows the fundamental resonance at 880 Hz as well as the first harmonics of the organ pipe. The shape of this curve is related to the pitch of the pipe.

The sound is due to the vibratory movement.

The air inside an organ pipe emitted a sound.In the speech, the oscillations occur in viscous media which is air .Hence, a considerable fraction of the energy of the oscillating system is dissipated in the form of heat in overcoming these resistive forces.So the mechanical energy of the body gradually decreases. Consequently, the amplitude of oscillations goes on decreasing gradually with time and ultimately the oscillations die out as shown in figure.6 and figure.7.

The exact pitch of the organ pipe depends on the combination of the fundamental tone and all the harmonics. These depend on the shape of the pipe (the length and diameter) as well as on the elastic properties of the pipe walls and their thickness: Changing any of one of these parameters will result in changes in the damping and the frequency response resonance peaks of the organ pipe. This will in turn yield a different pitch.

The pipe sounds in several different oscillation regimes. As the pressure is increased, the second and the third resonance modes are excited. A pipe can sound with much smaller pressure. In this case, the second and the first resonance modes are excited Delauro et al.[21].

The pitch sound is directly dependent of the frequency of the sound production device and is denoted by the frequency itself. The note produced by narrow organ pipe will be richer in harmonics and is on the other hand, the note emitted by a wider pipe will be poor in harmonics.

According to Rayleigh's end correction , the pitch of sound produced by two open organ pipe of same length but different diameters are different , the wider pipe gives the lower tone that the narrower pipe Prakashan [22]

The fundamental frequency is less than the first resonance frequency. If we increase the length of the pipe, the pressure will decrease and the fundamental frequency also as described by Ruty [23] and Lucero et al.[24].

The expected proportionality the dependence of the fundamental frequency on the length of the resonator is obvious as shown by Rucz [18] and Tilo [25]

4.4. Resonance peak of the fundamental frequency for different young's module values

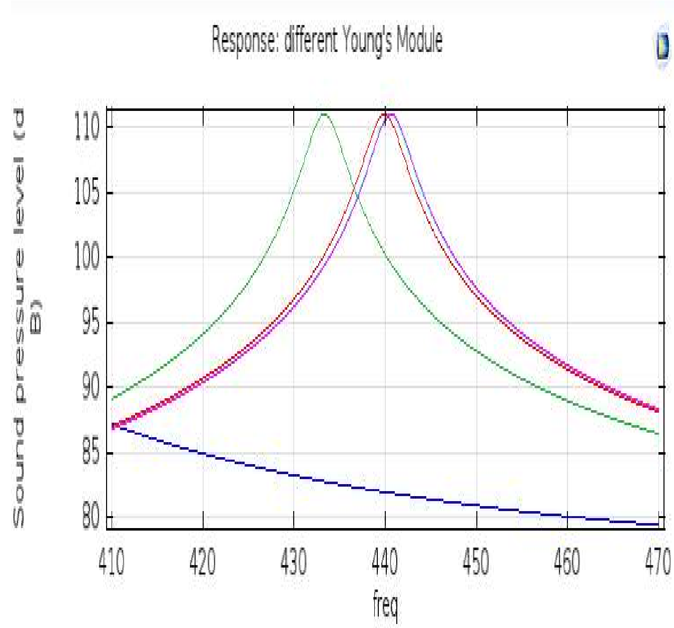
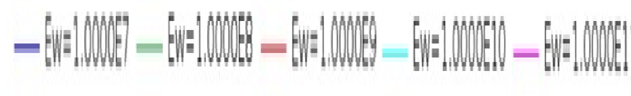


Figure 8: *Study 4: Frequency for Different young module(1e9)*



Based on figure.8, if Ew increases, the generated harmonics increase.

5. Conclusions

A pathological voice as any voice can be described as a disturbance, a transfer of energy, which travels through the air from one location to another location. It is distinguished by its property: density, Young's module, Poisson's ratio. Such physical properties describe the material itself not the wave. An alteration in the properties of the medium will cause a change in the speed.

A proposed model was presented in the present paper to simulate the fundamental frequency of /a/ alphabet, in order to compare its behavior for pathological and normal voices.

One of the most important findings is the fact that the resonant frequency could be shifted according to the values of inner radius and thickness, thus a pathological voice can be transformed to normal voice upon fine-tuning these parameters or adjusting damping forces.

The limitation of this model is that is capable of handling simple geometries however the voice apparatus is more complex. And it is only applicable under the cut off frequency.

In order to overcome these limitations, labial organ pipe model, and simulation of two or three dimensional systems are proposed.

In addition to that; more accurate result by using the end correction of effective length in case of open end.

It is necessary to mention that each adjustment is considered in isolation from the others. Nevertheless that this separate treatment of each adjustment is somewhat artificial, since make several adjustments simultaneously in real situation.

6. Acknowledgements

I would like to thank Mrs Mayda Bermudez for her valuable contribution and complete availability.

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