

Hearing Loss: Piezo-polymers Nano-fibers for Bio-medical Applications

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***ABSTRACT-* Hearing loss happens when hair cells inside the cochlea are damaged. About one third of the people in United States have some degree of hearing loss. This can possibly be solved by replacing those damaged hair cells with polyvinylidene fluoride (PVDF) nanofibers. PVDF is a highly non-reactive and pure thermoplastic fluoropolymer produced by the polymerization of vinylidene difluoride. PVDF have great piezoelectric properties, meaning that it has the ability to generate an electric charge in response to an applied mechanical stress. In this research, I used a computer program to simulate a cylindrical cantilever, which resembles a hair cell in the cochlea, and analyze the response of the frequencies by changing parameter values (length and diameter). Here, I report that I was able to analytically verify that the frequencies obtain from the computer program are similar with those obtain using an equation that I was able to derive. I also simulated two different conditions of the fiber to obtain the current that each fiber produce when stimulated in the audible frequency range of 250 – 2500 Hz.**

INTRODUCTION

On average, three of every one thousand people in the United States are functionally deaf. Though more than half became deaf relatively late in life; fewer than one out of every thousand people in the United States became deaf before 18 years of age [3]. There are many reasons for hearing loss, but the most common reason is known as “sensorineural” hearing loss, where hair cells in the cochlea are damage. Aging and prolonged exposure to loud noise may cause wear and tear on the hairs or nerve cells in the cochlea that send electrical signals to the brain. When these hair cells are damaged or missing, electrical signals are not transmitted as efficiently, and hearing loss occurs [2]. Currently there are no medical or surgical methods of replacing or repairing hair cells in the cochlea. However, hearing loss can be treated with hearing aids or cochlear

implants.

Unfortunately, cochlear implants are invasive, expensive, and its parts need to be replaced often. Advance research in nanotechnology can potentially be a solution to replace damage hair cells in the cochlea. My work consists of using COMSOL MultiPhysics version 5.1 to simulate a cylindrical cantilever, which resembles a hair cell in the cochlea.

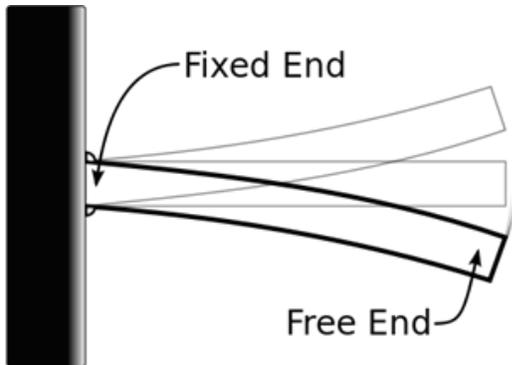


Figure 1 – This picture shows cantilever beam fixed at one end and free on the other end. This cantilever beam can be model in COMSOL as a hair cell.

Vladsinger, Oscillating cantilever beam, 2009, Cantilever Beam. Web. June 2015

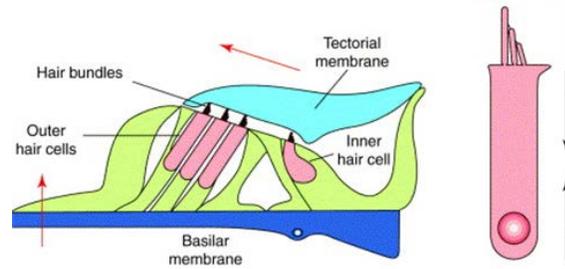


Figure 2 – This is how a human hair cell actually looks like. A cantilever beam is structurally similar to a human hair cell.

Fettiplace, Robert, Clues to the cochlear amplifier from the turtle ear, 2001, Science Direct. Web. June 2015

I'm using COMSOL to simulate a cylindrical cantilever because COMSOL is be able to account for coupled or multiphysics phenomena and you can further expand the simulation platform with dedicated physics interfaces and tools for electrical, mechanical, fluid flow, and chemical applications. The purpose of simulating a cylindrical cantilever in COMSOL is to analyze the response of the frequencies by changing parameter values (length and diameter) of the cantilever. We can also obtain the current of the fiber by stimulating the fiber in the audible frequency range of 250 – 2500 Hz. These results will help the rest of the group to spin nanofibers with specific dimensions

that can naturally respond to the audible frequency and send electrical signals to the brain.

BACKGROUND

A cochlear implant is a small, complex electronic device that can provide a sense of sound to a person who is profoundly deaf or severely hard-of-hearing. The implant consists of an external portion that sits behind the ear and a second portion that is surgically placed under the skin [4]. Cochlear implants bypass damaged portions of the ear and directly stimulate the auditory nerve. Signals generated by the implant are sent to the auditory nerve of the brain, which recognizes the signals as sound [4]. Unfortunately, cochlear implants are very expensive, and not a lot of people can afford a surgery. The total cost ranges from \$50,000 to \$100,000 for those without health insurance. Also, cochlear implants require continual maintenance, and some of its parts need to be replaced often, which at the time of replacement, the patient will need to go under surgery again.



Figure 3 – This picture shows how a cochlear implant looks and how it works.

Cochlea implant, London Cochlear Implant Clinic, Web. June 2015

Nanoscience and nanotechnology are the study and application of extremely small things and can be used across all the other science fields, such as chemistry, biology, physics, materials science, and engineering [1]. This technology has allowed many researchers to experiment and improve technologies that are already being used. For nano-biomedical implants, this type of technology can potentially open new doors and create a solution for those expensive surgeries. The development of a polymer electrode based piezoelectric cochlear implant device with PVDF is the most sensitive piezoelectric polymer being used to create this nanofiber [5].

PVDF is a semi-crystalline polymer that consists of four crystalline phases. It is a non-reactive and pure thermoplastic fluoropolymer produced by the polymerization of vinylidene difluoride. PVDF is used in applications requiring highest purity, strength, and resistance to solvents, acids, bases, and heat. Furthermore, PVDF has a low density of where E is the Young's Modulus of $2.5974e^9$ GPa, ρ is density of $1.78g/cm^3$, d is the diameter, and L is the length.

well known that proper mechanical stretching and electrical poling are necessary to achieve good piezoelectricity. Piezoelectricity is important for this application because piezoelectric-effect is the ability to generate an electric charge in response to applied mechanical stress, and this charge can send an electrical signal to the brain. One way to create PVDF nanofibers is by electrospinning, a process that uses an electrical charge to draw very fine (micro or nano scale) fibers from the PVDF solution. During electrospinning, the diameters of the fibers could be controlled by adjusting various electrospinning parameters, such as PVDF concentration, electrospinning voltage, needle-to-collector distance, and x-y stage moving speed.

Increasing the stage-moving speed could produce thinner PVDF fibers, however higher speed (more than 90mm/s) would terminate the electrospinning process, making the fiber discontinuous.

The objective of this research is to simulate a cylindrical cantilever, which resembles a hair cell in the cochlea, and analyze the response of the frequencies by changing parameter values (length and diameter). In addition, analytically verify the frequencies obtained from COMSOL that will send an electrical signal to the brain in the audible frequency range of 250 – 2500Hz. Furthermore, measure the current of the fiber when stimulated in the audible frequency range.

EXPERIMENT

Using COMSOL I was able to simulate a cylindrical cantilever. This was accomplished by these procedures.

Procedures:

1. Open COMSOL from the desktop.
2. Select "Model Wizard" (which will guide you to select your geometry, physics, etc.)
3. Select "3D dimension model" and click next.

4. Under physics, select “Piezoelectric devices” which is under structural mechanics. After selecting the physics click add and then click on study.

5. In the study window select “Eigen-frequency”. This type of study corresponds to the natural frequencies of vibration. Then click done, this will bring you to the COMSOL desktop.

Once you reach the COMSOL desktop follow the next instructions:

6. In Model builder right-click in “Global Definition” and add Parameters.

7. Under Parameter settings add diameter (D) = 100 nm and length (L) = 100 μm .

8. Click on Geometry and set the units to μm .

9. To create a nanofiber right click in Geometry and select “cylinder”.

10. Under the cylinder settings, type D/2 for Radius and L for length then click Build All Objects.

11. Right-click on “materials” and under User-Defined Library selected “(PZT-5H)(Kynar 460)” this is the material that we created with similar PVDF properties.

12. Right-click on “Solid Mechanics” and select “Fixed Constraint” and manually select one side of the cylinder where you want it to be fixed.

13. Right-click on “Electrostatics” and select “Terminal” and under terminal settings in terminal type select Voltage and set the Voltage equal to zero.

14. Once again, right-click on “Electrostatics” and select “Floating potential” and under settings select all boundaries expect the one side that is set as Terminal.

15. Next, right click in mesh and select Free Quad. Manually select top and bottom parts of the cylinder and set the minimum element size to D/3. After, right click in mesh again and select Swept and select Remaining, under element size select a finer swept and click Build All. I did this type of mesh because the default mesh, tetrahedral, has a lot of elements and the aspect ratio is big, therefor using a free quad and then a swept makes the mesh have less elements and it is faster for COMSOL to simulate.

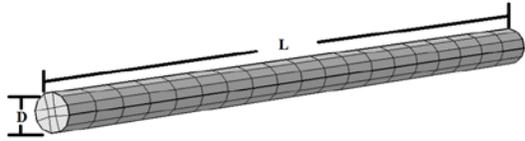


Figure 4 – This is how the cylindrical cantilever should look after the mesh is completed.

16. Under Study in Eigen-frequency, click compute and wait for the simulation to converge.

17. Under Results, click Mode Shape and you will see the results of the Eigen-Frequency.

1. Furthermore, to study the frequency in different dimensions go back up in the settings window and right-click in “study” and add a parametric sweep and add parameter values for diameter and length.

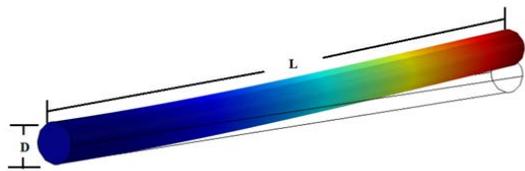


Figure 5 – Shows the displacement of the cylindrical cantilever at its first natural frequency.

After setting up different parameter values for the diameter and length, we were able to obtain the frequency output at different dimensions from COMSOL. To verify that we were obtaining the right frequencies at different dimensions we were also able to derive an equation for frequency for a cylindrical cantilever, where frequency is:

$$f = \frac{1.875^2}{8 * \pi} \left(\sqrt{\frac{E}{\rho}} \right) \left(\frac{d}{L^2} \right)$$

where E is the Young’s Modulus, ρ is density, d is the diameter of the cylinder, and L is the length of the cylinder.

I was able to derive this equation from the Free Vibration of a Cantilever Beam[11] a mathematical analysis for a cantilever beam with a rectangular cross section, where the frequency equation of a rectangular beam is:

$$f = \frac{1.875^2}{2 * \pi} \left(\sqrt{\frac{EI}{\rho AL^4}} \right)$$

where E is the Young’s Modulus, I is the moment of inertia of a rectangular cross section:

$$I = \frac{bd^3}{12}$$

where b and d are the breadth and width of the beam cross section, A is the area of a rectangle, and L is the length.

In the case of a cylindrical cantilever I was able to use this equation using the respective moment of inertia of a circular cross section and the area of a circle. That is to say that the frequency equation of a cylindrical cantilever is:

$$f = \frac{1.875^2}{2 * \pi} \left(\sqrt{\frac{EI}{\rho AL^4}} \right)$$

where E is the Young's Modulus, I is the moment of inertia of a circular cross section:

$$I = \frac{\pi}{64} d^4$$

where d is the diameter, A is the area of a circle, and L is the length. Plug in for I and A in the equation and that gives us:

$$f = \frac{1.875^2}{2 * \pi} \left(\sqrt{\frac{E \frac{\pi}{64} d^4}{\rho \frac{\pi}{4} d^2 L^4}} \right)$$

after deriving this equation we are able to obtain the frequency for a cylindrical cantilever which is:

$$f = \frac{1.875^2}{8 * \pi} \left(\sqrt{\frac{E}{\rho}} \right) \left(\frac{d}{L^2} \right)$$

Furthermore, to obtain the current from the fiber I simulated two different models. One model was fixed at the base of the cylinder and displaced at the top and the other model was only displaced at the base. I simulated these two models because that is how the hair cells behave in the cochlea. To obtain the current from the fiber, start from step 7. Under parameter settings add displacement values of .1, .3, .5 μm . Skip to step 12 and for one model leave step 12 the same but for the model delete this step. Proceed to step 16 and delete Eigen-frequency, right-click in study and add Frequency Domain. Under frequency domain settings, add the audible frequency range of 250 – 2500 Hz. Once again, right-click in study and add a parametric sweep and add the parameter values for length (L) = 10, 20 μm , diameter (d) = 100, 200 nm, and displacement (DP) = .1, .3, .5 μm . After setting up our parameter values click on study and wait for the simulation to converge. In results right-click in “Derived Values” and select “Surface Integration”. Under settings click on “Expression“ and write “abs(imag(es.JdZ))” which will calculate the absolute current at the base. After click on “Evaluate” and wait for the simulation to converge.

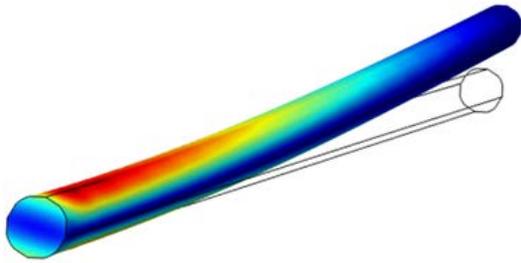


Figure 6 – Shows the nanofiber fixed at the base and displaced at the top when stimulated at the audible frequency range.

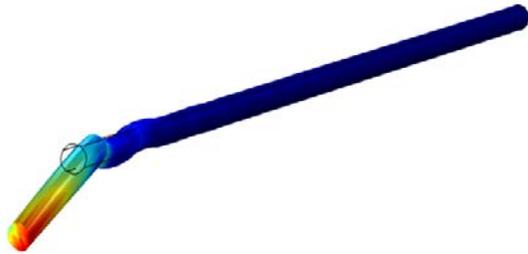


Figure 7 – Shows the nanofiber displaced at the base when stimulated at the audible frequency range.

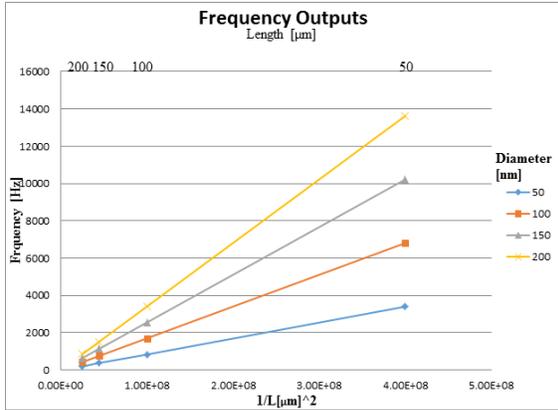
RESULTS AND DISCUSSION

Frequency output from COMSOL

I used COMSOL to simulate the cylindrical cantilever and I was able to obtain the frequencies at different dimensions.

Table 1 – This table shows the frequencies obtained from COMSOL at different dimensions.

3D Cylindrical Cantilever				
	Diameter [nm]			
Length [μm]	50	100	150	200
50	3403.2 Hz	6811.1 Hz	10221 Hz	13633 Hz
100	834.72 Hz	1701.7 Hz	2553.3 Hz	3405.5 Hz
150	379.74 Hz	755.18 Hz	1133.9 Hz	1512.6 Hz
200	182.06 Hz	415.93 Hz	635.99 Hz	850.89 Hz



Graph 1 – Shows the frequency output from COMSOL of the cylindrical cantilever with corresponding lengths and diameters.

Table 1 and Graph 1 show the different frequency outputs at different lengths and widths. Each solid line in the graph represent different diameters ranging from 50 to 200 nm. Each point belongs to its corresponding frequency with its respective length and diameter.

Frequency output from equation

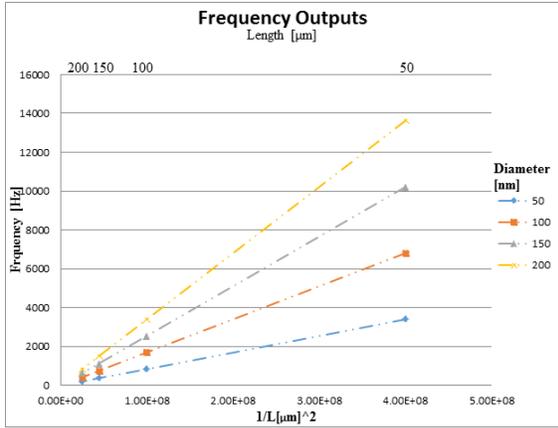
We were also able to derive an equation and use this equation to analytically verify the frequencies that were obtaining from COMSOL. The equation for frequency for a cylindrical cantilever is:

$$f = \frac{1.875^2}{8 * \pi} \left(\sqrt{\frac{E}{\rho}} \right) \left(\frac{d}{L^2} \right)$$

where E is the Young’s Modulus of $2.5974e^9$ GPa, ρ is density of $1.78g/cm^3$, d is the diameter, and L is the length.

Table 2 - This table shows the frequencies obtained from the equation at different dimensions.

Cylindrical Cantilever				
	Diameter [nm]			
Length [μm]	50	100	150	200
50	3404.9 Hz	6814.6 Hz	10226.2 Hz	13639.9 Hz
100	835.1 Hz	1702.6 Hz	2554.6 Hz	3407.2 Hz
150	379.9 Hz	755.6 Hz	1134.5 Hz	1513.4 Hz
200	182.2 Hz	416.1 Hz	636.3 Hz	851.3 Hz



Graph 2 – Shows the frequency output from the equation of the cylindrical cantilever with corresponding lengths and diameters.

Table 2 and Graph 2 show the different frequency outputs at different lengths and widths. Each dotted line in the graph represent different diameters ranging from 50 to 200 nm. Each point belongs to its corresponding frequency with its respective length and diameter.

Further work needs to be done in COMSOL to obtain the frequency when the fiber is submerged in a liquid and analyze how it reacts and how the frequency varies when it is not submerged and when it is.

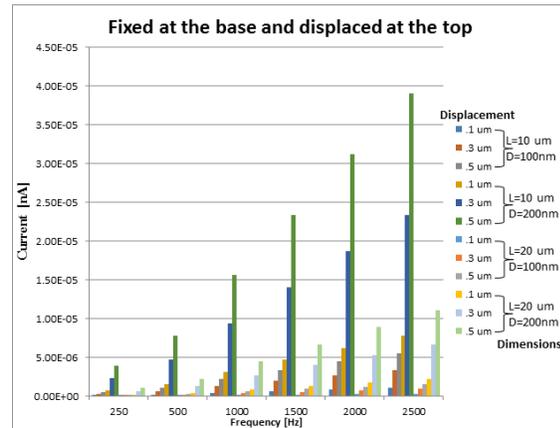
To obtain the current I simulated two different models. One model was fixed at the base and displaced at the top and the other model was just displaced at the base.

Each model was stimulated at the audible frequency range and displace at .1, .3, and .5 μm .

To obtain the current I simulated two different models. One model was fixed at the base and displaced at the top and the other model was just displaced at the base. Each model was stimulated at the audible frequency range and displace at .1, .3, and .5 μm .

Current output: Cylindrical cantilever fixed at the base and displaced at the top

By using COMSOL I was able to obtain the current from the fiber when stimulated at the audible frequency range of 250 – 2500 Hz.

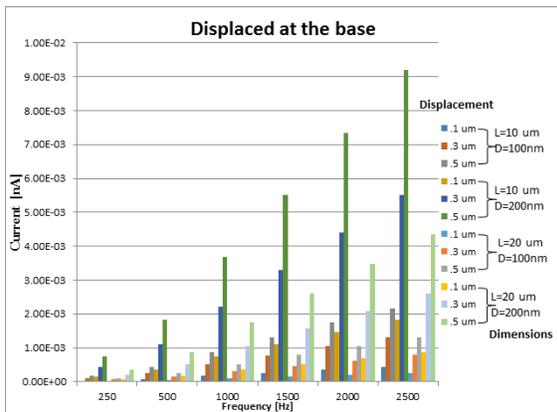


Graph 3 – Shows the current at different frequencies and we are able to see that the dimensions with high current are those with length of 10 μm and diameter of 200 nm. There is a high current when the

displacement is at $.5 \mu\text{m}$.

Current output: Cylindrical cantilever displaced at the base

By using COMSOL I was also able to obtain the current from the fiber when displaced at the base and stimulated at the audible frequency range of 250 – 2500 Hz.



Graph 4 – Shows the current at different frequencies and we are able to see that the dimensions with a significant high current are those with length of $10 \mu\text{m}$ and diameter of 200 nm . There is also a great increase in current when the displacement is at $.5 \mu\text{m}$.

CONCLUSION

After deriving the frequency equation of a cylindrical cross section to analytically verify the frequencies that I was obtaining from COMSOL, I am able to determine that the frequencies are correct. With this equation we are able to plug in

any diameter and length and get the frequency for each respective dimension.

That is to say, that instead of using COMSOL to simulate the response frequency for each dimension, we can now use the equation that I derived to estimate the frequency output that will send an electrical signal to the brain in the audible frequency range of 250 – 2500 Hz. Also after simulating two different models of the fiber, one which was only displaced at the base and the other fixed at the base and displaced at the top, I can conclude that the dimensions with the largest current response are those with a length of $10 \mu\text{m}$ and a diameter of 200 nm with a displacement of $.5 \mu\text{m}$.

ACKNOWLEDGEMENT

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