Vibration of piezoelectric micro cantilever beam array

Chuming Zhao
Department of Mechanical Engineering,
University of Michigan,
Ann Arbor, MI, 48105, USA
chumingz@umich.edu

***Abstract*— A Completely Implantable Artificial Organ of Corti (CIAO) was designed and fabricated to improve the current commercial cochlear implant. Piezoelectric cantilever beams with certain resonant frequencies are designed. Laser Doppler Vibrometer is employed to measure the vibration of the beams to confirm the resonances. A study of mimicking the sound what a patient could actually hear using the device is performed.**

***Keywords*— Cochlear implant; piezoelectric; vibration; resonant frequency**

I. Introduction

Cochlear implants are effect treatment for sensorial hearing loss. Current commercially available cochlear implants use microphone to pick up sound signal and use digital signal processing techniques to decompose signal into multiple frequency filtered bands. The signals are transmitted into electrode array implanted in scala tympani inside cochlea through radio frequency unit. While cochlear implant delivers significant hearing functionality to patents, it still faces the challenges of low battery life and high device latency. This work presents a part of the attempt to build a Completely Implantable Artificial Organ of Corti (CIAO) which is designed to address these issues.

A piezoelectric cantilever array functions just like the organ of Corti which transduces mechanical vibration into electrical voltage. The cantilever lengths are selected such that a certain resonances in fluid should be achieved to correspond to the tonotopic location in the guinea pig where that cantilever is to be implanted. Because of the imperfection of the fabrication process, it is important to be able to experimentally confirm the resonances in air and in water.

After acquire the vibration behavior of the beam, the device response could be characterized. More interesting discovers could be found like simulating what the patients would actually hear using the CIAO device. This could be achieved after we find out the impulse response and convolve it with the input sound signal.

II. Experimental Setup

Because of the reciprocal nature of the piezoelectric material, we should be getting mechanical vibration if we drive the device electrically. A chirp is sent into the CIAO device. The input signal lasts 1s and 500,000 samples are taken. Laser Doppler Vibrometer (LDV) with a sensitivity of 10mm/s/V is employed to measure the velocity of the cantilever beams. Figure 1 shows the experimental set up.

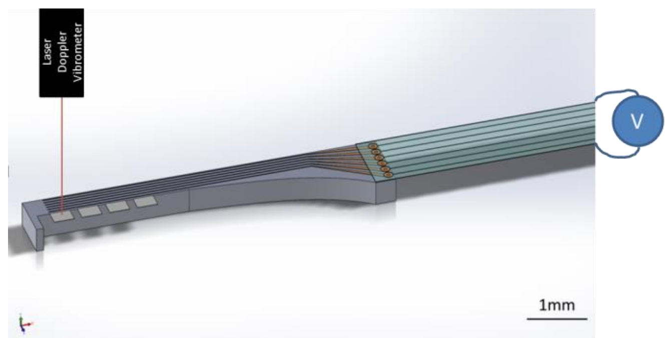

Figure 1, Illustration for Experimental Setup

III. Data processing

A. Voltage input

A sinusoidal voltage chirp input with frequency from 30kHz to 200kHz with amplitude of 1V is sent into the CIAO device. Figure 2 shows the data of the input signal in time domain.

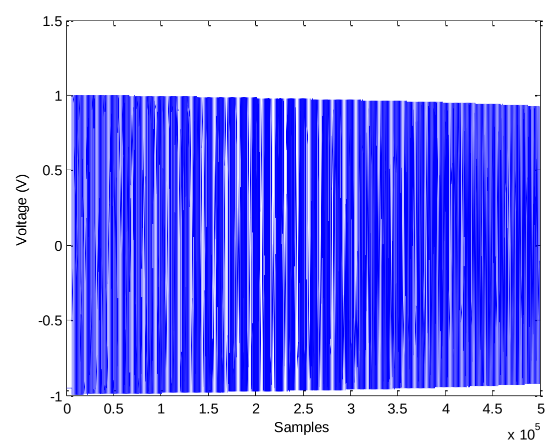

Figure 2, Input chirp in time domain

FFT of the input signal is performed and shown in Figure 3.

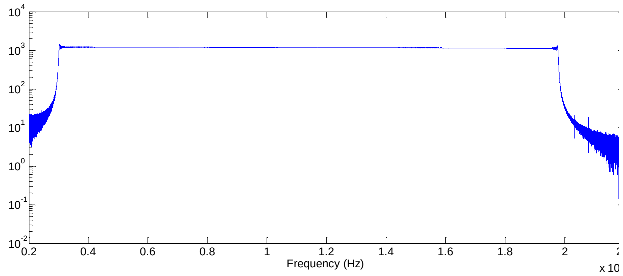

Figure 3, FFT of the input signal.

B. LDV Output

Beam vibration velocity is measured using LDV and shown in Figure 4.

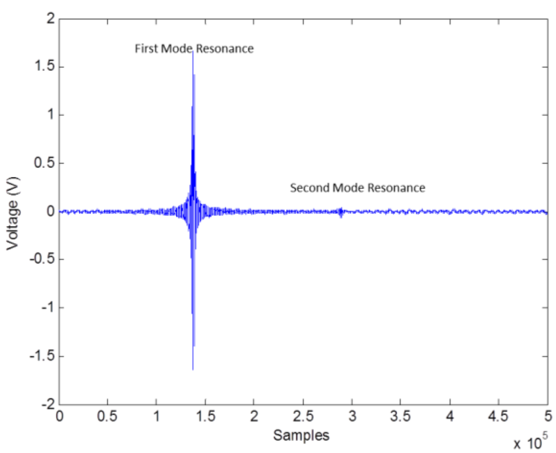

Figure 4, LDV output in time domain.

It can be seen in Figure 4 that there are two peaks, indicating the first mode and second mode resonances. Figure 5 illustrates the mode shape for the two modes.

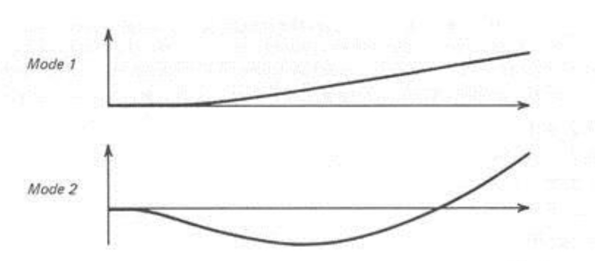

Figure 5, Mode shapes for the first and second mode

FFT is performed to analyze the resonant frequencies and shown in Figure 6.

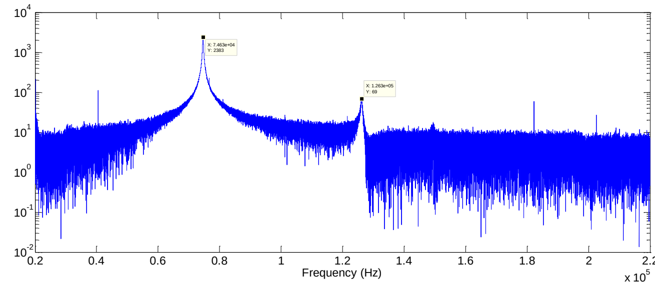

Figure 6, FFT of the LDV output

It can be seen in the Figure 6 that the first peak happens when frequency is 74.6kHz and second peak is at 126.3kHz.

IV. Noise Analysis

Noise analysis is very important for my experiments since it is so small, delicate and precise. Noise spectral density is studied by performing the Power Spectral Density (PSD). I took the worst signal (the weakest I took) and performed the PSD and a pure noise (without input and just measure the output). In order to find the noise floor, Welch method was employed to calculate the autospectral pectral density. Welch method is the most common method for computing PSD which is defined as

$$G_{xx}^{W}(k) = \frac{S_P}{M} \sum_{m=0}^{M} Y_{w,m} X_{w,m}^{*}$$

Where

$$X_{w,m} = DFT[x_m(n) \cdot w(n)]$$

and *w* is a window function

Four sets of noise data were taken and autocorrelation is performed when calculating the Welch PSD. Then a actual signal is taken and performed similar analysis. The PSD for both noise and signal are plotted in Figure 7. As can be seen in the Figure 7. The signal is above the noise floor, and the best signal to ratio (SNR) is around SNR=10^6. But after 2kHz, the signal was nearly as big as noise floor. It is because the chirp only goes as high as 20kHz.

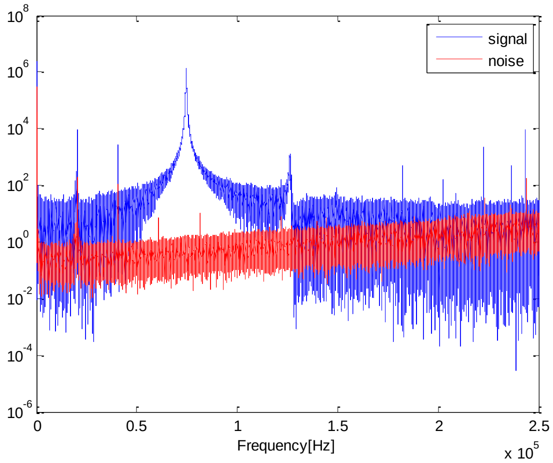

Figure 7. PSD for signal and noise using Welch Method

V. Transfer Function (Impulse Response)

After the first process report, more data was taken by submerging the probe under the water (this is more similar to the actual environment inside the cochlea). Since the resonance for the cantilever will be much lower in the water, compared in the air, a chirp with 10kHz -100kHz was used to excite the device.

Impulse response was trying to get. However, since the device was very delicate, instead of hitting the cantilever in any kind, which will destroy the device, alternate method was necessary. After talking to Prof. Balzano, I believe by finding the transfer function of the frequency response of a chirp (f) and the chirp itself (c) in frequency domain, it would give me the impulse response (h). Because $h*c=f$ or $H\cdot C=F$, where H,C,F are the Fourier Transforms of the h,c,f . H is the impulse response and is also the transform function of chirp response and chirp itself $H=\frac{F}{C}$. Based on the deconvolution theory, $(h*c)+\varepsilon=f$, where ε is uncorrelated noise. I modified the LabView program and collected the transfer function H. I collected 50 data and did the average, which eliminates some uncorrelated random noise. Figure 8 shows the transfer function H for all four beams excited under water.

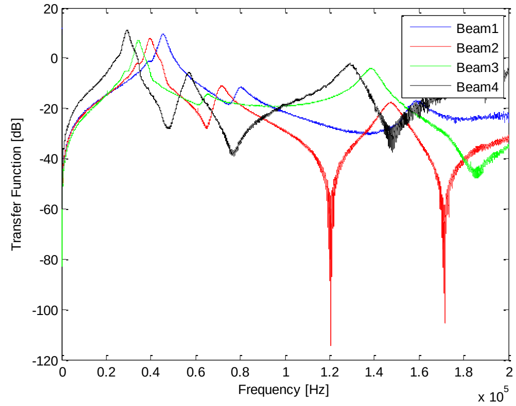

Figure 8. Transfer functions (Impulse Response) for four beams

After we found out the transfer function of all the beams, we could proceed to the impulse response (IR) of the whole system. Assume it is linear system and the impulse response is the superposition of the IR of the four beams (The actual IR might be more complicated than this, but it is not the focus of this study), the IR could be obtained. However, this specific cochlear implant (or CIAO implant) is designed at 20kHz~50kHz for a guinea pig, which has a higher audible range, compared to human being (20~20kHz). In order to mimic the sound a patient could hear, I manually downsampled the IR. I took every 100 sample and obtained a new simulated IR as shown both in the frequency domain and time domain in the Figure 9. Now the desired range is 200Hz~500Hz. (This is not typical downsampling in time domain, but rather in the frequency domain. The purpose is simply shift the peak range to a lower frequency range)

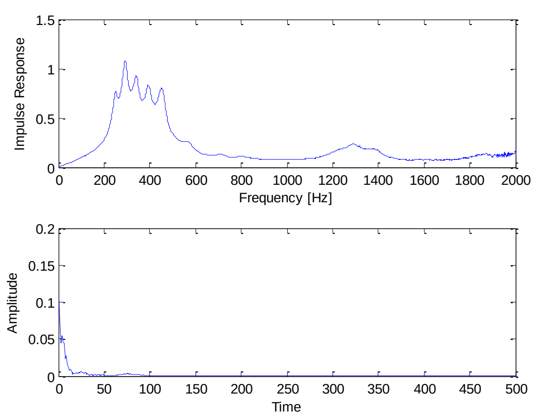

Figure 9 Downsampled impulse response in frequency domain (upper) and time domain (lower)

VI. Convolution with Sound Signal

After I got the IR in time domain, I convolved IR with a chirp starting from 20Hz. Spectrograms of the chirp itself and the convolution of chirp with IR are shown in Figure 10.

As can be seen in Figure 10, the output signal is much weaker (less red) in the higher frequency range. The IR acts as a bandpass filter (or low pass filter) which confirms with our expectation due to the nature of the IR.

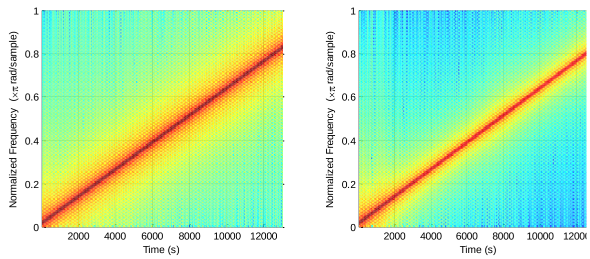

Figure 10. Spectrogram for a chirp (Left) and for the chirp convolved with IR (right)

Therefore, it is expected that the patient would probably hear better in the lower frequency range (especially within 200~400Hz range) if he/she uses the CIAO implant. The good news is this range could be expanded using more piezoelectric cantilevers. Therefore there would be subtle difference if you listen really carefully or look at the spectrogram. A similar approach is done using the marySong. The song can be found in the attachment.

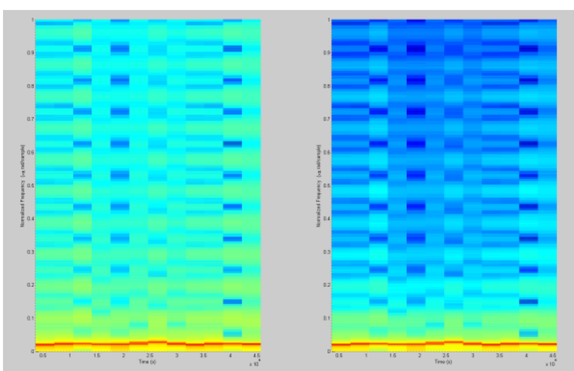

Figure 11. Spectrogram for marySong (Left) and for the marySong convolved with IR (right)

From the Figure above, we could find that the signals give us similar results in the lower frequency range but when it comes to the higher frequency range, the CIAO can't do as good as it does in the lower frequency domain.

VII. Challenges and difficulties

The device is extremely delicate and the measurement is super sensitive. It takes a lot of time just to get a signal from LDV. I broke some devices during measurements. I know it is not so relevant to the DSP, but I think a picture of the actual CIAO device, shown in Figure 12, may help readers understand the difficulties of the measurement. However once I could get a right signal, taking data and post processing is relatively easier.

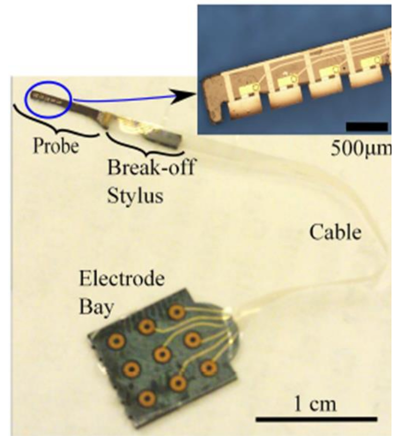

Figure 12, actual CIAO device fabricated using MicroElectricalMechanical System (MEMS) technique

VIII. Discussion and Conclusion

I only intended to find the resonances of the micro cantilever beams and do some filtering at first when I finalize the project idea. However during the time I work with the data, I realize maybe I could do more. In progress report 1, I had some confusion on how to find the impulse response, which allows me to simulate the sound a patient could hear with CIAO implant could actually hear, by convolving with sound signal. In progress 2, I figured out a way to compute the impulse response. After that, I found the the next step would be to find a predefined sound input signal and convolve with the transfer function H . Spectrograms for both the input signal and the signal generated by impulse response and input signal are done to compare the two. The output is similar to the input sound especially in the lower frequency domain. There are not too much difference when listening to the marySong and deformed marySong, which proves the CIAO cochlear implant is a very good one, or CIAO works for those who want to listen marySong! (Although the reality might not be so ideal!)

IX. Summary

In summary, the in class tools I used are FFT, IFFT, spectrogram, downsampling, convolving with impulse response to simulate what a patient would actually hear. The non-class DSP tool is Welch Method to estimate Power Density Spectrum. I understand the Welch PSD is not fundamentally counted as non-class DSP tool, but I've studied the mathematical and physical meaning behind it and didn't use the pwelch tool in matlab.

X. REFERENCE

Oppenheim, Alan V., Ronald W. Schafer, and John R. Buck. *Discrete-time signal processing*. Vol. 2. Englewood Cliffs: Prentice-hall, 1989.

Brandt, Anders. *Noise and vibration analysis: signal analysis and experimental procedures*. John Wiley & Sons, 2011.

Knisely, Katherine, and Karl Grosh. "A MEMS AlN transducer array for use as a cochlear implant." *Applications of Ferroelectric and Workshop on the Piezoresponse Force Microscopy (ISAF/PFM), 2013 IEEE International Symposium on the*. IEEE, 2013.