2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering
Education for 130 Years
ASEE
Paper ID #37613

3D-Printed Piezoelectric Acoustic Energy Harvester

Michael A. Palmateer
Jacob Plesums
Ryan Santiago
Mr. Austin Miller
Dr. Reza Rashidi, SUNY University at Buffalo

Dr. Reza Rashidi is an Associate Professor at SUNY University at Buffalo. He was an Associate Professor at SUNY Alfred State when he supervised the project presented in this paper. He received his Ph.D degree in Mechanical Engineering (MEMS development) from the University of British Columbia in 2010 and completed his Postdoctoral Fellowship in Development of Biomedical Sensing Devices in the Department of Electrical and Computer Engineering at the University of British Columbia in 2011. He also received a minor degree in Engineering Management and Entrepreneurship from the University of British Columbia in 2009. He has over 16 years of industrial experience. Before joining Alfred State, Dr. Rashidi was a Senior Engineer at Siemens, where he worked on research projects from 2011 to 2016. His expertise is in the development of nano, micro and mini sensors and actuators in Biomedical Engineering and Energy applications. Dr. Rashidi was a recipient of several awards including the 2008 British Columbia Innovation award, administered by BC province, Canada. He has written over 30 research articles and is currently a reviewer and technical committee member of several journals and conferences worldwide.

3D-Printed Piezoelectric Acoustic Energy Harvester

Abstract

Energy harvesting has been widely researched in the past decade due to its significant usage for providing energy to remote areas and electronic devices. Harvesting energy from piezoelectric beams is one of the popular forms of energy conversion, enabling a wide range of applications. A team of four senior undergraduate students in a microfabrication course completed a project to develop a piezoelectric-based acoustic energy harvester. The students performed all development steps, including ideation, literature review, calculation, design, fabrication, assembly, testing, and writing. This paper investigates the plausibility of maximizing the generation of acoustically harvested energy by combining multiple generally known methods for harvesting acoustic energy from sound waves. One such method is using a Helmholtz resonator, a spherical device with one opening, which can create a region of considerable pressure variation when sound waves are directed inside. Another method for acoustic energy harvesting is utilizing the principles of resonance and antinodes in a cylindrical tube. Antinodes are areas of high sound pressure created by standing sound waves resonating through a cylindrical tube at specific frequencies. Our design combines these methods by placing a Helmholtz resonator at the closed end of a cylindrical tube to harvest energy from all areas of high pressure due to resonance; located at the antinodes along the cylinder. The open end of the cylinder expands outward in a parabolic fashion to increase the surface area for capturing as many incident sound waves as possible and directing them into the device. The acoustic energy harvester is fabricated using a three-dimensional (3D) print of the solid model constructed of PLA, a thermoplastic polyester. The device was tested using a speaker projecting known frequencies in the range of optimal frequencies of 600-2500Hz and a data acquisition card (DAQ) measuring voltages for each 100Hz increment. It was determined that the waveform amplitude of 12.13mV produced at 2300Hz was the highest compared to the ones taken at lower frequencies. This evidence proved that the device is more effective at higher frequencies.

Introduction

Course Structure

This paper and its associated project are major aspects of the Microfabrication course offered at the authors' institution. The course covers major microfabrication techniques from theory to practice, used to develop micro devices or components. This includes a hands-on laboratory segment of the course during which students work in groups with guidance from the instructor to fabricate MEMS (Micro-Electro-Mechanical Systems) from blank silicon wafers in a clean room. Students are expected to develop their own MEMS design and perform all lab processes on the silicon wafers, including CAD design, photolithography, doping, etching multiple layers, etc. The hands-on laboratory segment of the course provides students with a unique opportunity to work in a modern, clean room and physically perform the complex processes required to develop MEMS wafers from scratch.

As another assignment in this course, groups of students are expected to develop novel devices that utilize microsystem components for a particular application. This course segment requires students to design, fabricate, test, and document a novel design in an application, which is energy harvesting in this paper. There are publications from similar course projects performed in the past [1-6]. At the conclusion of this course, students are provided with a comprehensive understanding of the practical applications of MEMS devices and the processes available to manufacture these devices. This paper presents the results of a project that a group of students in the course performed to develop a novel piezoelectric-based acoustic device that harvests energy from ambient sound.

Student learning objectives in this course are defined as a student's ability to demonstrate skills after completing the course. At the end of the course, students will be able to do the following:

1. Demonstrate the ability to design various microfabrication processes
2. Classify common microelectromechanical devices
3. Categorize common sensing and actuating methods
4. Show an ability to function in the cleanroom in a safe and deliberate manner
5. Analyze their lab data and write an effective final laboratory report

The project assignment included in this course will address the first student learning objective of "demonstrate the ability to design various microfabrication processes." The course also supports some of the student outcomes at the program level, but the outcome of "an ability to design systems, components, or processes meeting specified needs for broadly defined engineering problems appropriate to the discipline" is primarily chosen to be assessed using the project assignment in this course. It also supports the program educational objective of "can function effectively in open-ended activities involving applications, design, analysis, and implementation."

Overview of Energy Harvesting and its Applications

It is common knowledge in the scientific community that energy loss is often an unavoidable consequence of reactions involving energy transfer. Engineers are constantly tackling the issue of making systems as energy efficient as possible to minimize losses, but over the last two decades, an incredibly useful tool for harnessing lost or ambient energy sources has emerged called energy harvesting. Energy harvesters are devices that utilize ambient energy sources in cases where this energy would usually be lost or unusable. Some examples include the use of thermoelectric energy harvesting techniques to capture wasted heat energy from the exhaust system of a vehicle [7], energy harvesting of centripetal forces generated by the movement of a car's wheel to power tire pressure sensors [8], or a sound barrier on a railway created to generate energy and absorb noise from passing trains to name a few [9].

The last example is possible due to acoustic energy harvesting, which can convert the stress due to sound wave vibrations into small amounts of usable energy. Some known methods for acoustic energy harvesting include the use of Helmholtz resonators, quarter-wavelength tube resonators, and acoustic metamaterial devices specifically made for manipulating incident sound waves [10]. These methods typically utilize resonant frequencies to maximize the harvested energy from areas of high sound pressure. Some devices can even vary the resonant frequencies of the energy harvester so that the device is in acoustic resonance as often as the design allows, generating maximal harvestable energy over a broader range of frequencies [11].

This paper explores utilizing sound resonance to generate and harvest as much vibrational energy as possible under the constraints of the design. This device could be mounted in any location experiencing frequent high-decibel noise, including on a vehicle, near a busy highway, within a concert hall, etc. For example, the energy harvested could be stored and used to power low-energy systems such as sensors and microelectronics in vehicles. The dimensions of the energy harvester can also be changed so the resonant frequencies of the device closely match whatever frequencies are experienced most often in the environment it is placed in. In this research's scope, the resonators' dimensions were selected to produce resonant frequencies in the range typically exhibited by road traffic noise (~600-2500Hz) [12].

Design

One commonly known method of generating resonance is utilizing a Helmholtz Resonator (*Fig. 1*), which creates a region of high sound pressure at the opening area of the resonator when sound waves are directed into it. The most vibrational sound energy can be harvested from these devices at their resonance frequencies, which can vary depending on the resonator’s dimensions [13, 14]. To harvest energy from a Helmholtz Resonator, a piezoelectric diaphragm sensitive to vibration can be placed inside the resonator cavity, or piezoelectric beams can be placed inside the resonator or along the resonator neck, which experiences the highest variation in pressure.

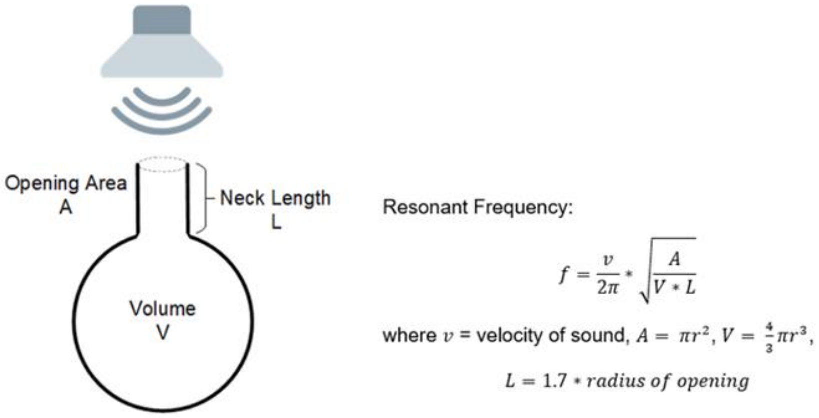


Figure 1 – Characteristics of a Spherical Helmholtz Resonator [13]

Another common method for creating resonance is using a cylindrical tube of a defined length, closed on one end or open on both ends. The resonance depends on the fundamental frequency of the cylinder, and areas of high pressure are created at antinodes along the length of the cylinder (*Fig. 2*) [15]. Piezoelectric beams can be placed at these antinodes where the pressure is highest to harvest vibrational energy from standing sound waves inside the cylindrical tube.

Our design aims to combine a cylindrical tube resonator with a Helmholtz Resonator to generate areas of high-pressure variation and vibration for energy harvesting. A Helmholtz Resonator can be placed at the closed end of a cylindrical tube where a high-pressure antinode is located, which could contribute to the pressure required to cause the resonance effect experienced by the Helmholtz Resonator (*Fig. 3*). Piezoelectric cantilever beams can be placed at antinodes along the length of the cylinder to generate energy when both the cylindrical tube and Helmholtz resonator are experiencing resonance [14, 16]. Combining both resonance-producing methods will ideally generate more vibration and, therefore, more harvestable energy than either method would. The entrance of the tube resonator expands parabolically, similar to the end of a trumpet, to capture and direct more incident sound waves into the tube resonator (*Fig. 3*).

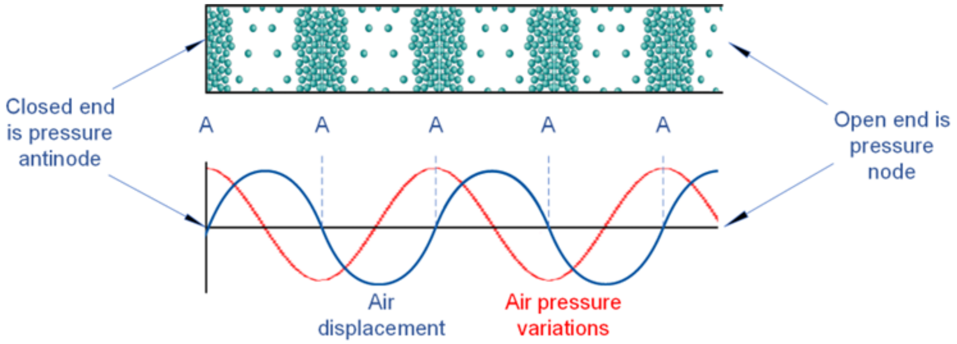


Figure 2 - Areas of High Pressure in a Cylindrical Air Column [15]

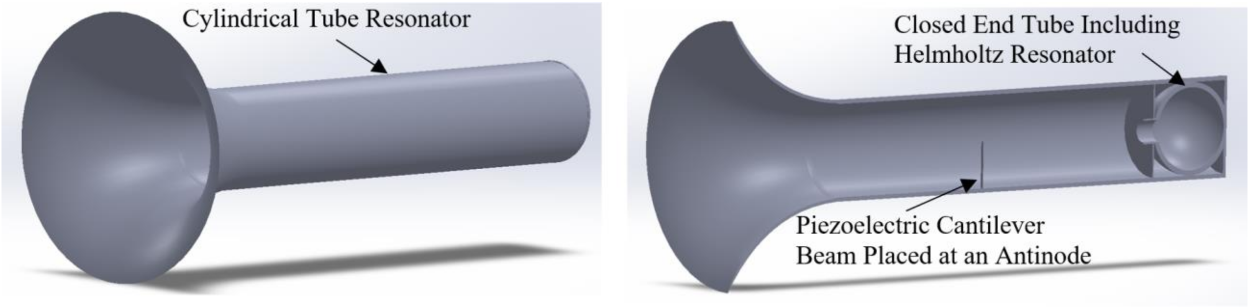
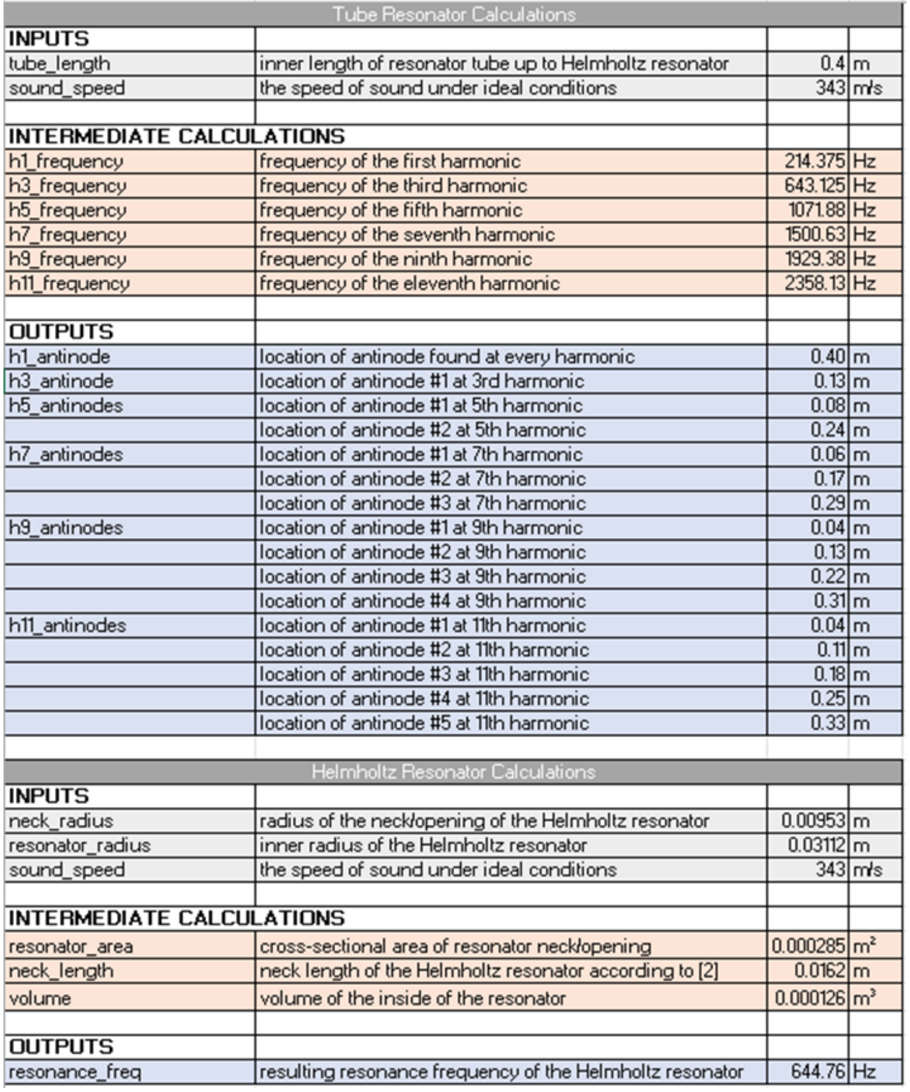


Figure 3 – Detailed 3D Model of Cylindrical Tube Resonator

The device’s dimensions can be found in *Fig. 4*. The inner resonator tube length up to the wall of the Helmholtz resonator was designed to be 400mm long to achieve the desired range of resonance frequencies (about 600-2500 Hz) within the first six harmonics. The piezoelectric beam was placed at 240mm inside the tube, which is the exact location of an antinode at the 5th harmonic of this device. The 5th harmonic results in a frequency of 1071.88 Hz and a wavelength of 320mm, which is within this application's target range of frequencies. This piezoelectric beam is constructed of APC 850 (APC International, Ltd., Mill Hall, PA) and has dimensions of 32mm long x 4.5mm wide x 0.5mm thick. A complete list of resonance frequencies and locations of antinodes can be found in *Table 1*.

The closed-end diameter, neck length, and neck radius dimensions were designed to match one of the resonance frequencies experienced by the tube resonator at any of its harmonics. This resulted in a resonance frequency of 644.76 Hz, closely resembling the 643.125 Hz frequency at the 3rd harmonic of the tube resonator. More details about how the Helmholtz frequency was calculated can be found in *Table 2*.

Table 1 - Calculations for the wavelength, frequency, and locations of antinodes at the first six odd harmonics for closed-end tubes. Locations of antinodes are measured from the front of the tube (x=0) to the face of the Helmholtz resonator at the end of the tube (x=0.4m). There are additional calculations for the resonance frequency of the Helmholtz resonator, given its fixed dimensions, which use information and formulas from [10] and [13].



Tube Resonator Calculations

INPUTS			
tube_length	inner length of resonator tube up to Helmholtz resonator	0.4	m
sound_speed	the speed of sound under ideal conditions	343	m/s
INTERMEDIATE CALCULATIONS			
h1_frequency	frequency of the first harmonic	214.375	Hz
h3_frequency	frequency of the third harmonic	643.125	Hz
h5_frequency	frequency of the fifth harmonic	1071.88	Hz
h7_frequency	frequency of the seventh harmonic	1500.63	Hz
h9_frequency	frequency of the ninth harmonic	1929.38	Hz
h11_frequency	frequency of the eleventh harmonic	2358.13	Hz
OUTPUTS			
h1_antinode	location of antinode found at every harmonic	0.40	m
h3_antinode	location of antinode #1 at 3rd harmonic	0.13	m
h5_antinodes	location of antinode #1 at 5th harmonic	0.08	m
	location of antinode #2 at 5th harmonic	0.24	m
h7_antinodes	location of antinode #1 at 7th harmonic	0.06	m
	location of antinode #2 at 7th harmonic	0.17	m
	location of antinode #3 at 7th harmonic	0.29	m
h9_antinodes	location of antinode #1 at 9th harmonic	0.04	m
	location of antinode #2 at 9th harmonic	0.13	m
	location of antinode #3 at 9th harmonic	0.22	m
	location of antinode #4 at 9th harmonic	0.31	m
h11_antinodes	location of antinode #1 at 11th harmonic	0.04	m
	location of antinode #2 at 11th harmonic	0.11	m
	location of antinode #3 at 11th harmonic	0.18	m
	location of antinode #4 at 11th harmonic	0.25	m
	location of antinode #5 at 11th harmonic	0.33	m

Helmholtz Resonator Calculations

INPUTS			
neck_radius	radius of the neck/opening of the Helmholtz resonator	0.00953	m
resonator_radius	inner radius of the Helmholtz resonator	0.03112	m
sound_speed	the speed of sound under ideal conditions	343	m/s
INTERMEDIATE CALCULATIONS			
resonator_area	cross-sectional area of resonator neck/opening	0.000285	m^2
neck_length	neck length of the Helmholtz resonator according to [2]	0.0162	m
volume	volume of the inside of the resonator	0.000126	m^3
OUTPUTS			
resonance_freq	resulting resonance frequency of the Helmholtz resonator	644.76	Hz

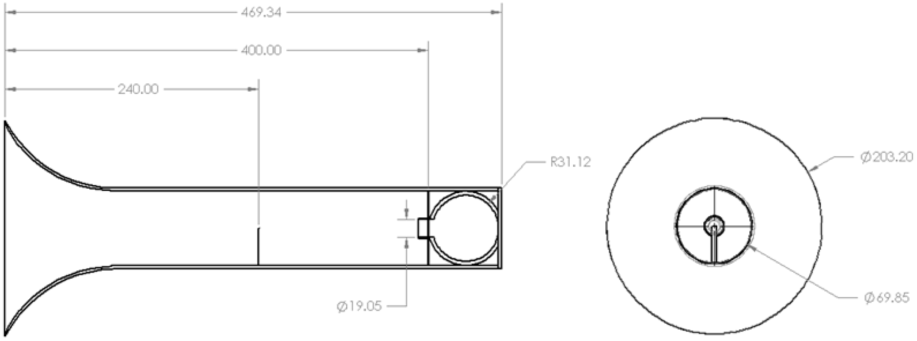


Figure 4 - Dimensioned Drawing of Acoustic Energy Harvester (Shown Dimensions are in Millimeters)

Table 2 – More information on how the locations of antinodes were calculated in Table 1. [17]

Antinodes occur when sin(kx) = ± 1 from equation $y = 2 * A * \sin(kx) * \cos(\omega * t)$
$\mathrm{kx} = \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}, \frac{7\pi}{2}, \ldots$
$\frac{2\pi}{\lambda} * \mathrm{x} = \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}, \frac{7\pi}{2}, \ldots$
$x = \frac{\lambda}{4}, \frac{3\lambda}{4}, \frac{5\lambda}{4}, \frac{7\lambda}{4}, \ldots$
where x = location of antinodes, k = 2π/λ, and λ = wavelength

Although this design does not accommodate this feature, an additional piezoelectric device such as a cantilever beam, ring, or diaphragm could be placed inside of the Helmholtz resonator for additional energy harvesting, as the inside of the resonator typically experiences the highest sound pressure during resonance, while the neck experiences the most particle velocity [10]. Since the neck of the Helmholtz resonator is an area of high-pressure variation, a second piezoelectric beam could be placed directly in front of its opening, which is also an antinode for every harmonic the tube resonator experiences. This means this beam would theoretically generate electricity whenever the tube resonator or Helmholtz resonator is at any of their resonance frequencies. Additional piezoelectric beams could also be placed at each antinode existing along the length of the cylindrical tube to maximize the ability to capture harvestable energy. Due to the time constraints involved considering that this project took place over the course of one college semester, additional piezoelectric devices were not included inside the Helmholtz resonator or along the cylindrical tube. Instead, one piezoelectric beam was placed in the most ideal location along the cylindrical cylinder, where it would be affected by the largest range of resonant frequencies while also being close enough to the Helmholtz resonator to be affected by the higher velocity air exiting the neck of the Helmholtz resonator upon resonance. This allowed for proof of concept while ensuring the project could be completed within the allotted timeframe.

The acoustic energy harvester is designed to capture and focus sound waves through its bell-shaped opening. The air inside the device becomes increasingly pressurized in the presence of higher-intensity sound, mainly when resonance occurs. The loudness (dB) and frequency (Hz) of the sound will cause the piezoelectric beams to vibrate more intensely and frequently and, as a result, will generate a voltage. The orientation of the device with reference to the origin of the sound is also essential, as the ability to capture sound waves is increasingly unlikely as the opening of the device faces farther away from the source of the noise.

Fabrication

The acoustic energy harvester was 3D printed in two separate halves using a Lulzbot Taz6 3D printer and PLA thermoplastic filament (Fig. 5a). Due to the lengthy print process to produce a high-quality prototype of this device, the standard quality was selected with a layer thickness of 0.3mm. Ideally, the finish should be as smooth and dense as possible to reflect sound waves efficiently instead of absorbing them, but in the interest of time and for simple prototypical testing, it was decided that standard print quality would be sufficient. The device will be tested using a speaker projecting sound waves in the frequency range of 600-2500Hz, which is a typical range for road traffic noise [12]. A small hole was left at the 240mm point of the resonator tube to allow for the mounting of a piezoelectric cantilever beam for testing.

Next, the piezoelectric beam was prepared and inserted into the device. This process began by finding a small, very thin piece of metal to support the beam to ensure it did not break during testing due to the fragile nature of piezoelectric materials. The support beam was then glued to the piezoelectric beam and left to set for about a half hour. Afterward, wires were soldered onto both sides of the beam to allow for energy harvesting and testing of voltage output for a range of incident sounds. The beam was then placed onto the mounting point, glued using a JB Weld plastic bonder, and left to cure (Fig. 5c, d). Finally, the mating surface was prepared, and both halves of the resonator were glued together (Fig. 5e).

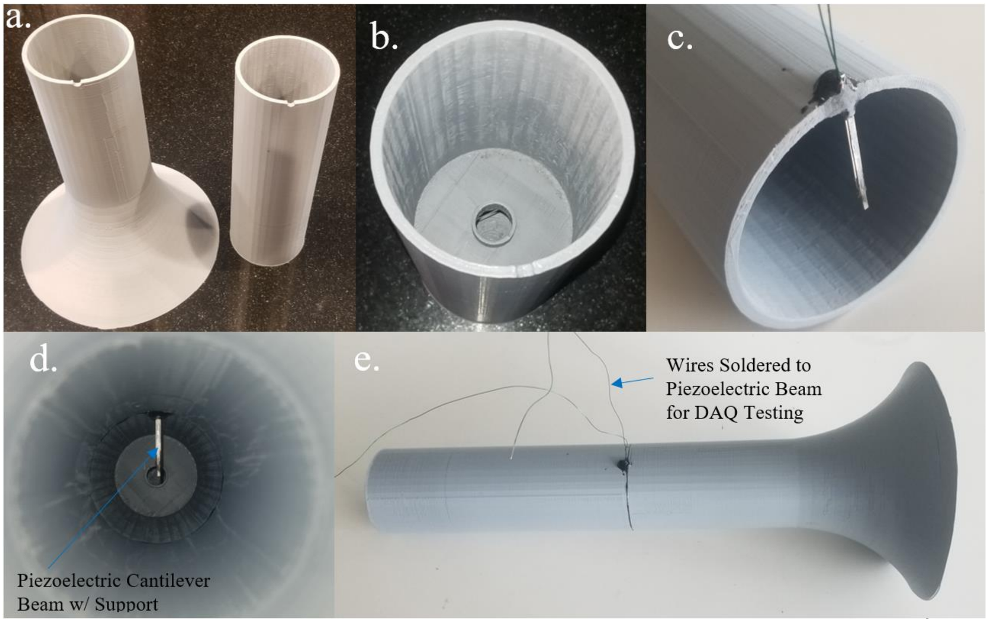


Figure 5 – The 3D-Printed Device with Pictures of the Piezoelectric Mounting and Assembly Process.

Results and Discussion

Technical Results

Testing was performed by interfacing the acoustic energy harvester with a National Instruments data acquisition device NI-6003 (DAQ) and a provided LabVIEW program meant to gather voltage data. A Bluetooth speaker was also positioned directly in front of the opening of the resonator to play sounds of varying frequencies into the device, which allowed for the determination of which frequencies were the most effective for generating energy in this design. Each trial run consisted of playing a constant tone at a known frequency using an online tone generator application [18].

Trial runs began at 600Hz and increased by 100Hz for every trial run up to a final value of 2500Hz. An additional trial run was performed at 643Hz to test the resonance frequency of the device and the validity of the calculations performed before testing began. The results of the data collected can be found in *Table 3*, which displays the amplitude of the produced waveform after the sound started playing. The waveforms produced in this case are the fluctuations in voltage values produced as a result of sound waves resonating back and forth inside the device. Plotted data for the most significant resonance harmonics tested can be found in *Fig. 6.* A graph comparing the maximum voltage amplitudes experienced at each harmonic tested can be found in *Fig. 7*.

When comparing the data collected in *Table 3* to the calculated resonant frequencies at every harmonic in *Table 1,* it appears that the calculated resonant frequency values may have been slightly inaccurate. Although the amplitude tends to be the highest near the calculated resonant frequencies, there is some variance by about 50-100Hz in the 3rd, 7th, and 9th harmonics. Data collected for the 5th and 11th harmonics was as expected, however, as the amplitude for these frequencies was higher than in the trials.

Table 3 - Tabulated average amplitude data for trials from 600Hz to 2500Hz.

Frequency (Hz)	Measured Voltage Amplitude (mV)
600	1.28
643	4.892
700	5.805
800	4.515
900	5.805
1000	4.606
1100	5.483
1200	4.837
1300	5.16
1400	4.838
1500	5.712
1600	6.45
1700	5.078
1800	4.192
1900	4.515
2000	4.515
2100	4.74
2200	7.573
2300	12.133
2400	5.475
2500	6.611

The most resonance can be observed at 2300Hz in the 11th harmonic, with an almost 12mV amplitude. The 2300Hz trial waveform in *Fig. 6* also indicates acoustic resonance, as the waveform displays much more intense fluctuation and an irregular wave pattern compared to every other trial run completed. These resonance patterns can also be observed in the 643Hz, 700Hz, and 1500Hz trials in *Fig. 6* to a smaller degree as the waveforms become more distorted. The differences in amplitude experienced at each trial run are displayed in *Fig. 7*, which shows the considerable increase in amplitude experienced in the 2300Hz trial compared to every other frequency tested. It is also worth noting the somewhat fluctuating nature of the voltage amplitude at every 100Hz increment, as observed in *Fig. 7*. This is most likely because as the varying frequencies being played into the resonator became closer or further in value from the harmonic frequencies of the resonator, the amount of resonance occurring at the location of the piezoelectric beam would fluctuate in intensity.

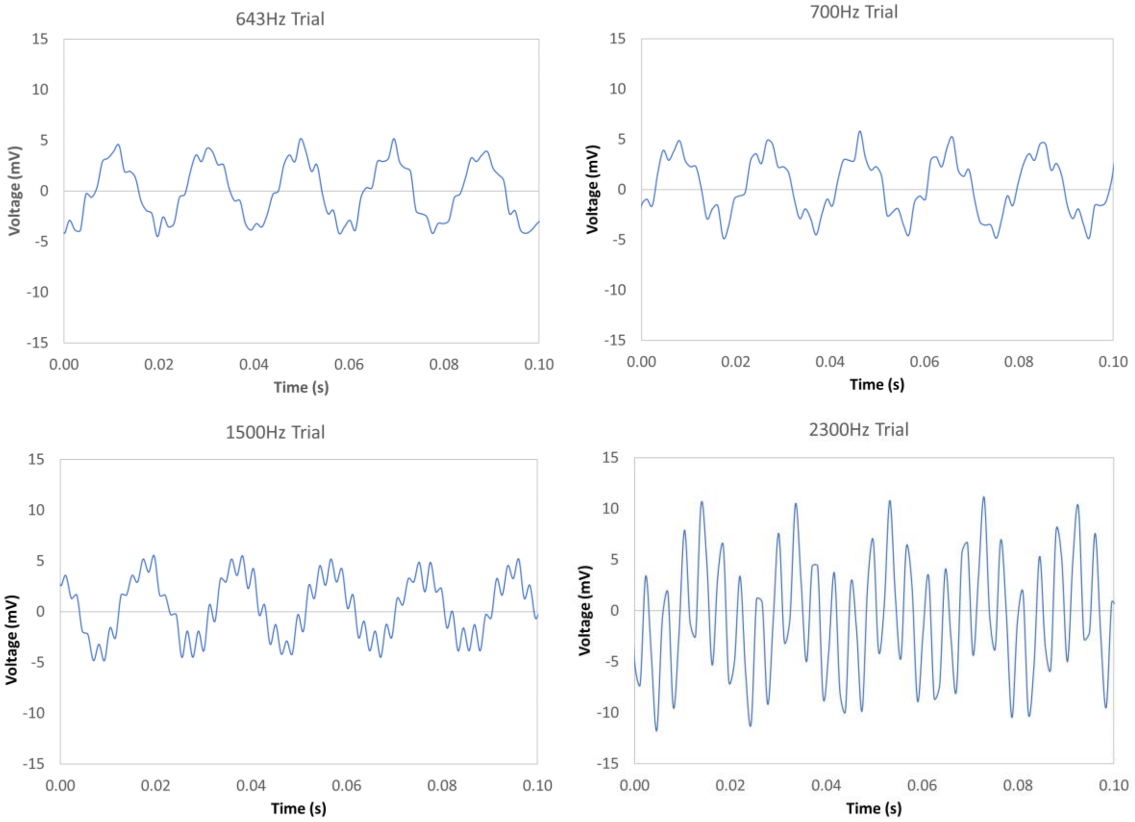


Figure 6 - Soundwave generated voltage over time at Select Resonance Frequencies.

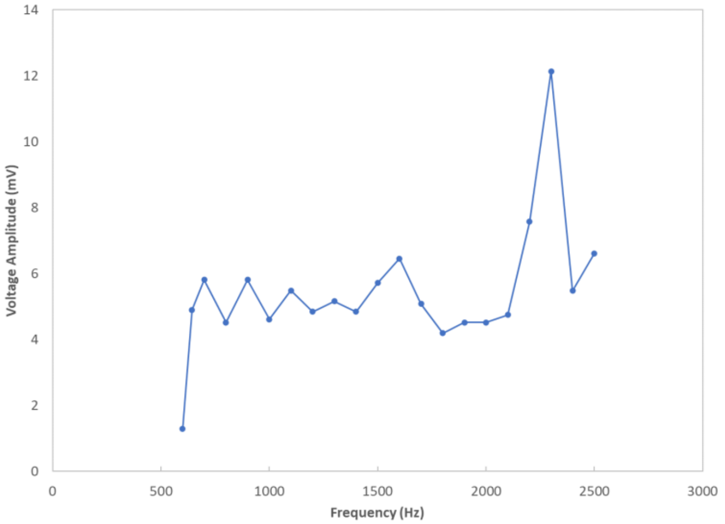


Figure 7 - Amplitude of soundwave generated voltage at resonance frequencies.

Any error in the calculation of harmonic resonant frequencies before the testing of the device can likely be attributed to the fact that the length of the resonance chamber used in these calculations was measured from the parabolic opening of the device to the outside face of the Helmholtz resonator within the device. The parabolic shape of the opening and the fact that the tube diameter was not constant over the entire length of the device likely meant that the actual harmonic frequencies for this device were slightly different than what was calculated beforehand. Evidence for this can be found when comparing the 643Hz and 700Hz trials in *Fig. 6*, as 643Hz was a calculated harmonic frequency; however, the 700Hz trial resulted in more resonance and, therefore, more harvestable energy.

Another noteworthy observation is that the waveform produced from the 2300Hz trial (*Fig. 6*) was the most defined and intense compared to any of the trials taken at lower frequencies, and the waveforms from the 2200Hz, 2400Hz, and 2500Hz trials displayed similar patterns of resonance not found in lower frequencies tested. This may be evidence that the device is more effective at higher frequencies than anticipated, as every trial was performed at a constant volume in decibels to ensure sound intensity did not vary from trial to trial. It may also be further evidence that the calculated ideal location for the piezoelectric beam was slightly incorrect, as previously mentioned.

One reason for this could be that at higher harmonics, there are more antinodes along the length of the tube (*Table 1*). This would mean that more areas of high pressure would exist within the device at the 11th harmonic frequency of about 2300Hz. Therefore, if the piezoelectric beam was not placed in the ideal spot due to miscalculation, it is likely that an antinode would have coincidentally fallen on the beam's location at higher harmonics. Another reason could be that the piezoelectric beam was stiffer than desired due to the metal support glued to it (*Fig. 5c*), which was done to ensure the beam did not flex too much and break during testing due to the brittle nature of the piezoelectric material used. In retrospect, this support beam likely resulted in lower energy output.

Applied Learning Results

This Microfabrication course was instrumental in providing undergraduate students with a complex understanding and appreciation of MEMS devices and the unique challenges involved in manufacturing them. Due to the expensive nature of the equipment and maintaining a clean room of the standard required to manufacture MEMS devices, only a few institutions in the country offer hands-on experiences such as those provided throughout this course. Students were given not only a lecture-style presentation of the major aspects of microfabrication but were also able to complete supervised weekly lab sessions in the clean room, which involved step-by-step, hands-on design and fabrication of microfluidic sensing devices over the course of a semester.

The course also allowed students to carry out a team-oriented project to develop a novel device using MEMS components in various applications; it was an energy harvester in the case of this paper. This included all steps of a development process, including ideation, literature review, design, fabrication, testing of a device, and rigid documentation of the entire process. The project was initiated by students with no prior experience in this field. The motivation to participate in the Microfabrication course was to explore the MEMS fabrication processes and to gain clean room experience for a job in the microsystem field. Groups of 3-5 students were formed at the beginning of the semester to perform the projects. The instructor introduced general ideas of the projects, and students were to perform a literature review in Google Scholar to find a potential idea and narrow it down to a novel idea.

Each group created a Gantt chart that included critical activities and milestones on the project and was designed to guarantee the completion of the project within the timelines. It included all steps of the project and allowed for redesign and refabrication per the experience from previous projects. The Gantt chart was revised based on the instructor's comments. Each group of students performed the work outside the regular class time and reported their weekly performance at the beginning of every lab session. The instructor reviewed the progress and made comments on the project. Students used CAD software, mostly SolidWorks, to design their work. Some groups of students performed a hand calculation to optimize their design, while others performed a simulation to properly design their idea before moving to the fabrication stage.

Due to the time limitation within a semester, the students were supposed to find ideas that required fewer fabrication steps and used common available prototyping machines like 3D printers. While some groups fabricated their design in the first shot, other groups found flaws in their design or fabrication and needed to redesign or refabricate their work. The groups created a testing setup to validate their device. The students were provided with a workshop on research paper writing by the instructor, and they submitted their work in three stages during the semester. After each step, the instructor commented on their write-up, and students submitted a revision. This allowed for flawless writing within a short amount of time. Even though a semester seems short for the students to perform such a project from scratch, the results presented in this paper indicate great success.

Microfabrication was one of the most challenging courses in the institution's engineering curriculum. It provided students with many unique learning experiences due to the general unavailability and novelty of courses of this nature, especially when offered as an elective course within a Mechanical Engineering degree instead of being exclusive to students studying degrees in microfabrication. At the conclusion of the semester, students taking this course were provided with an opportunity to evaluate the course in both the lecture and laboratory portions of the class. Twenty of twenty-three students enrolled in the course participated in the survey, yielding an 87% response rate. Table 4 shows the questions and the results from the survey. Each of the questions dealt with a characteristic of teaching excellence. The students were asked to indicate their rating for each question by filling in a bubble number from 1 (lowest) to 7 (highest). After processing the course evaluations of every student, an overall score of 6 out of 7 was reported for this course which shows the successful conduction of the course and its components. In addition to the quantitative survey results, the students were asked to provide qualitative feedback on two critical questions that would be helpful to the instructor as the information is used to improve the teaching style in the following years. Table 5 shows the most critical comments that the students provided. The comments indicate that the level of instruction was enough to motivate students to do their best work.

Table 4 - Student Course Evaluation Form and the qualitative results

Question	Average score out of 7
How would you rate the difficulty of this course?	4.5
1. Does the professor appear well-prepared for class?	6.4
2. How well does the professor communicate with students?	5.8
3. How well does the professor motivate students to do their best work?	5.9
4. How knowledgeable does the professor appear about the subject?	6.6
5. What is the professor's attitude toward the subject matter of the course?	6.4
6. Is the professor willing to use a variety of activities to promote student learning?	5.3
7. What was the professor's attitude toward the students?	6.4
8. How available is the professor for help outside of class?	5.8
9. How reasonable/fair are the professor's exams and/or other grading criteria?	5.8
10. To what extent are the professor's presentations generally thought provoking?	5.2
11. Feedback from the professor regarding grades is provided in a timely manner?	6.2
12. How would you rate the overall teaching effectiveness of the professor?	5.8
Average score of 12 questions	6.0

The course was assessed for the student outcome of "an ability to design systems, components, or processes meeting specified needs for broadly defined engineering problems appropriate to the discipline" using the project assignment. Rubrics were created to define the expectations for the project report and shared with the students. The project report was evaluated on a 100% scale. To satisfy the expectations, students must score 70% or higher for the project report. The percentage of students receiving 70% or higher grades was calculated. The percentages of >90%, >80%, >70%, and <60% were considered exceeding, meeting, minimally meeting, and not meeting expectations, respectively. Minimally meeting and not meeting expectations required changes made or plans to do something different in the future, closing the loop for continuous improvement. The assessment for the selected outcome showed that 83% of the students received a grade of 70% or higher; therefore, the outcome was met.

The Microfabrication course discussed here is a course that truly included the theory and hands-on components to challenge students on a subject that is usually taught at a graduate level. The course was taught in the senior year of the mechanical engineering technology program by an instructor with several years of experience in this field. Each course component was designed to provoke students to explore new ideas. While the lecture part of the course covered processes on this advanced subject, the student used the lab component to practice the design, fabrication, and testing of microfluidic sensing devices where most of the techniques discussed in the lectures were used. This lab component of the course was performed under the direct instruction of the professor. The project segment complemented the course by allowing the students to practice independently on novel ideas.

The projects were initiated by students from scratch, starting with ideation, followed by literature review, design, fabrication, and testing. The students presented the results in class and submitted a written report. This paper is a version of one of the reports. While such a course seemed heavy for undergraduate students, it had the most promising results. Students learned an advanced subject usually taught at graduate schools, while it was completely hands-on. Students performed both independent and dependent work in the class. As a result, they obtained enough knowledge to start working in the microfabrication industry. When the instructor discussed with the experts in the industry, they stated that the industry required engineers at all levels. While engineers with a master's or doctoral degree would work on the research and design part of such advanced devices, engineers with a bachelor's degree are needed to produce the devices in the industry. The industry currently lacks the latter group of engineers as only a small number of universities prepare undergraduate students with hands-on experience in microfabrication.

Table 5 – Qualitative Feedback from Students on the Course

What are the major strengths of the instructor and course?

1. It is an interesting course and requires attention to detail.
2. The instructor is enthusiastic and knowledgeable on the subject; he clearly enjoys this class and the subject matter. This course is clearly the instructor's forte.
3. The instructor provides interesting applications of the technologies we learn about.
4. The labs and projects are a new and fun experience. The lab work is helpful and attention-grabbing despite being long, clarifies instructions, and motivates us to continue research.
5. The instructor is always willing to work with students and give extra help in or out of class if necessary.
6. The instructor encourages group work outside of class, which is helpful with labs and homework.
7. The instructor is easily approachable about anything regarding the subject.
8. The instructor has a great attitude, understanding, and flexibility.
9. The instructor motivated students to do their best work.
10. The instructor offers good feedback and does his best to help students get higher grades if seeing they provide the effort.
11. The instructor gives fair tests.
12. The instructor is well-prepared for class every day.
13. There is a vast understanding of the process from the instructor, so it is easy to ask questions (provided they are understood correctly, however).
14. The instructor promotes discussion.
15. There are many sources for learning the topic, including lab, lecture, and project.
16. The instructor seems empathetic to the workload of senior students.

In what ways can this instructor improve the course?

1. The projects in this course are too ambitious.
2. The exams could focus more on asking what specific terms mean.
3. It would be helpful if the important information in the lectures and labs were emphasized.
4. Adding more homework to the assignments would help us understand this new subject.
5. The lectures could be slightly better thought provoking.
6. Adding a review section before the test would be helpful.
7. Talk individually to the students failing the course.
8. Post the assignment instructions significantly earlier than the due date.
9. Due to the heavy workload in this course, move the course to a year before the senior year when senior projects are not performed.

Conclusions

The Microfabrication course at the authors' institution was one of the most challenging, advanced, and up-to-date courses that undergraduate students could take to prepare for such an in-demand industry. In addition to homework and tests, the course also included three other major segments, including lectures, labs, and independent projects. A group of undergraduate students performed a project to develop a piezoelectric-based acoustic energy harvester. Energy harvesting is a subject that has drawn attention due to its great usage for providing energy in different applications. The students used the knowledge gained in the lectures and labs and performed all development steps, including ideation, literature review, calculation, design, fabrication, assembly, testing, and writing. This paper presents the results of the project that the students investigated the plausibility of maximizing the generation of acoustically harvested energy through a combination of multiple known methods for harvesting acoustic energy from sound waves.

After considering the testing results for this device, it can be viewed as a successful design due to the fact that a measurable increase in energy output occurred when incident sound waves were played into the device at various frequencies. If this device were to be redesigned, a few aspects could be changed to make the device more efficient in light of some of the data collected. Since there was some error involved in calculating the locations of antinodes, more precise positions could be calculated if the parabolic shape of the opening was accounted for when determining the resonance frequencies of the device. Additionally, more piezoelectric devices could be added to the design, such as at every predetermined antinode along the length of the cylinder or within the Helmholtz resonator, which would theoretically increase the maximum achievable power output of the system; however, due to time limitation in this course, proof of concept was demonstrated in this project. It would also be beneficial to downsize the device considerably to make it applicable across a broader range of applications if the resulting resonance frequencies can be kept within a reasonable range, as shortening the device makes the resonant frequencies increase along with the difference in frequency between each harmonic.

References

[1] Duell, T., Muehlbauer, M., Seitzinger, T., Westfall, J., & Rashidi, R. (2018, September). MEMS capacitive sensor for wound monitoring applications. In IOP conference series: materials science and engineering (Vol. 417, No. 1, p. 012040). IOP Publishing.

[2] Mbaye, A., Kreamer, C., Zink, L., Fredenburg, M., & Rashidi, R. (2018, September). 3D printed micro check valve for biomedical applications. In IOP Conference Series: Materials Science and Engineering (Vol. 417, No. 1, p. 012041). IOP Publishing.

[3] Cooke, I., DeClerck, B., Hallett, J., Miller, T., Mitchell, A., & Rashidi, R. (2019, November). A Magnetic and Shape Memory Alloy Actuated Gripper for Surgical Applications. In ASME International Mechanical Engineering Congress and Exposition (Vol. 59414, p. V004T05A035). American Society of Mechanical Engineers.

[4] Michelson, T., Rudnick, J., Baxter, J., & Rashidi, R. (2019, November). A novel ferrofluid-based valve-less pump. In ASME International Mechanical Engineering Congress and Exposition (Vol. 59445, p. V007T08A009). American Society of Mechanical Engineers.

[5] Rashidi, R., Alenezi, J., Czechowski, J., Niver, J., & Mohammad, S. (2019). Graphite-on-paper-based resistive sensing device for aqueous chemical identification. Chemical Papers, 73, 2845-2855.

[6] Rashidi, R., Summerville, N. C., & Nasri, M. (2018, October). A dual-purpose piezoelectric multi-beam energy harvesting and frequency measurement device for rotational applications. In 2018 IEEE MIT Undergraduate Research Technology Conference (URTC) (pp. 1-4). IEEE.

[7] Nesarajah, M., & Frey, G. (2017). Optimized Design of Thermoelectric Energy Harvesting Systems for Waste Heat Recovery from Exhaust Pipes. *Applied Sciences*, *7*(6), 634.

[8] Kubba, A., & Jiang, K. (2014). A Comprehensive Study on Technologies of Tyre Monitoring Systems and Possible Energy Solutions. *Sensors*, *14*(6), 10306–10345.

[9] Wang, Y., Zhu, X., Zhang, T., Bano, S., Pan, H., Qi, L., Zhang, Z., & Yuan, Y. (2018). A renewable low-frequency acoustic energy harvesting noise barrier for high-speed railways using a Helmholtz resonator and a PVDF film. *Applied Energy*, *230*, 52–61.

[10] Yuan, M., Cao, Z., Luo, J., & Chou, X. (2019). Recent Developments of Acoustic Energy Harvesting: A Review. *Micromachines, 10*(1), 48. MDPI AG. Retrieved from

[11] Liu, F., Phipps, A., Horowitz, S., Ngo, K., Cattafesta, L., Nishida, T., & Sheplak, M. (2008). Acoustic energy harvesting using an electromechanical Helmholtz resonator. *The Journal of the Acoustical Society of America*, *123*(4), 1983–1990.

[12] Wang, H., Cai, M., & Cui, H. (2019). Simulation and Analysis of Road Traffic Noise among Urban Buildings Using Spatial Subdivision-Based Beam Tracing Method. *International Journal of Environmental Research and Public Health*, *16*(14), 2491.

[13] Tang, P. K., & Sirignano, W. A. (1973). Theory of a generalized Helmholtz resonator. *Journal of Sound and Vibration*, *26*(2), 247–262.

[14] Komkin, A. I., Mironov, M. A., & Bykov, A. I. (2017). Sound absorption by a Helmholtz resonator. *Acoustical Physics*, *63*(4), 385–392.

[15] Li, B., Laviage, A. J., You, J. H., & Kim, Y.-J. (2012). Acoustic Energy Harvesting Using Quarter-Wavelength Straight-Tube Resonator. *Volume 12: Vibration, Acoustics, and Wave Propagation*.

[16] Li, B., You, J. H., & Kim, Y.-J. (2013). Low frequency acoustic energy harvesting using PZT piezoelectric plates in a straight tube resonator. *Smart Materials and Structures*, *22*(5), 055013.

[17] *Physics Tutorial: Closed-End Air Columns*. (2021). The Physics Classroom. https://www.physicsclassroom.com/class/sound/Lesson-5/Closed-End-Air-Columns

[18] *Online Tone Generator - generate pure tones of any frequency*. (2011). Szynalski.com. https://www.szynalski.com/tone-generator/