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PHY 312

Acoustic Levitation

Introduction

In order to advance the research on targeting cancer cells, we must develop an efficient method of isolating circulating tumor cells (CTC) from blood cultures. If the isolation of CTCs from blood samples are effective, doctors can better analyz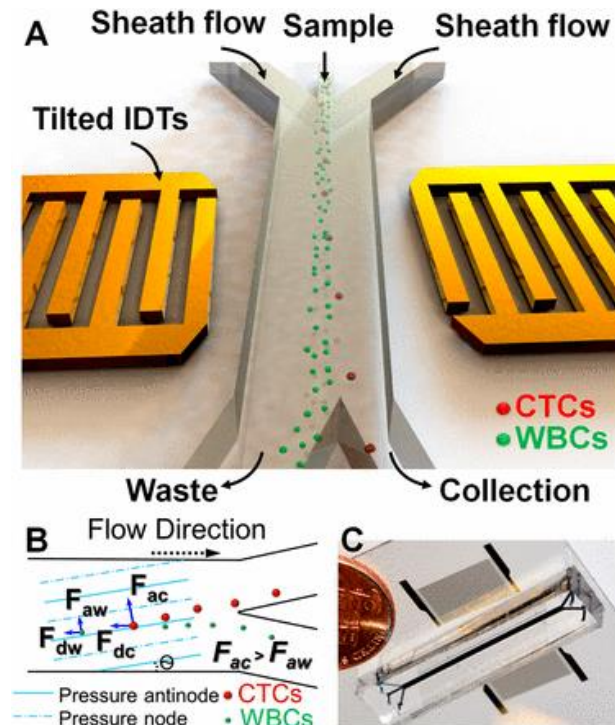e the response of patients to various treatments. Recently, researchers have successfully used acoustic levitation to isolate tumor cells from peripheral blood. Since CTCs are physically smaller than white blood cells, "CTCs experience a larger acoustic radiation force (F_{ac}) than WBC (F_{aw})." [1] Thus, the acoustic radiation forces act as filters while collecting CTCs in this diagram (left). Using similar techniques and design, there are numerous of biological applications that acoustic levitation can provide.

Figure 1: Separation of circulating tumor cells and white blood cells using acoustic levitation.[1]

In our project, we aim to build a successful levitation device using ultrasonic waves to trap objects such as water droplets in the nodes. We also plan to design an efficient circuit so future researchers can adjust the components of the levitation device with ease.

How it works?

      Acoustic levitation is the process of using sound waves to levitate small objects. Sound

waves travel through air by compressing and decompressing air particles, thereby creating

pressure points in the medium. The superposition of the emitted sound waves and of the reflected

waves produce standing waves with pressure nodes. When the sound waves induce enough

acoustic pressure, the propagating sound waves will be able to levitate certain objects. The

acoustic pressure nodes are separated by half wavelength of the emitted sound. In the diagram

(below), objects are levitated in the antinodes while the pressure nodes change from high
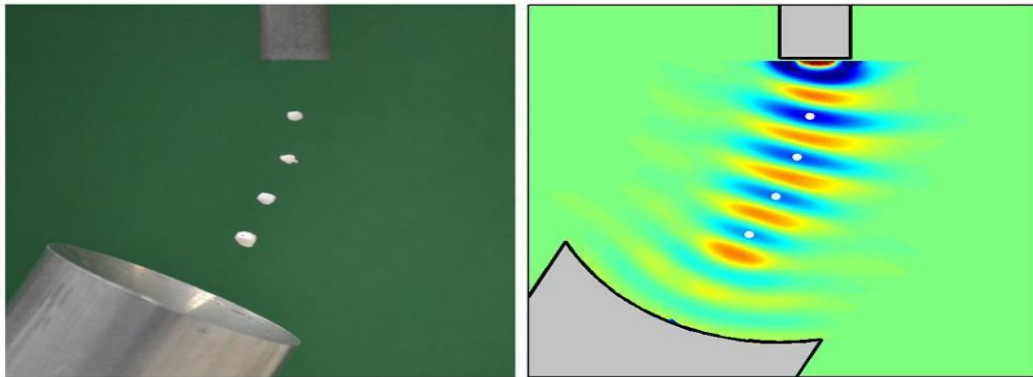
pressure to low pressure and vice versa.

Figure 2: Levitation of expanded polystyrene particles and the simulated standing wave pattern. [2]

Overview of Experiment

Our experiment revolves around three components: the ultrasonic transducer, the design of the circuit, and the concave reflector. The resona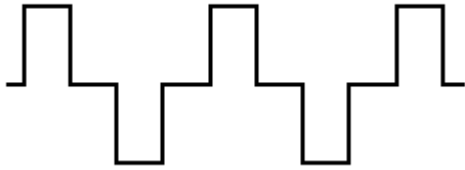nt frequency of the Hesentec Rank D ultrasonic transducer is 28 kHz. The electronic circuit is designed to output a large amount of voltage to the transducer while maintaining the ability to fine-tune the frequency. Although it is not most efficient, the output waveform is that

Figure 3: A modified sine wave.

of a modified sine wave. Using Fourier analysis, the modified sine wave will output 76% of the power to the fundamental while the square wave only outputs 55% of the power. [3] So, a modified sine wave seems to be our best option considering our selection of logic chips. Instead of a flat reflector, we mold a concave reflector so the reflection of the sound waves would theoretically converge to a focal point. Ultimately, the parabolic shape of the reflector reduces the energy loss through the propagating sound waves.

Circuit Design

At the beginning of the circuit, we have a timer chip (NE555) that outputs a pulse we need. The frequency of the pulse is eight times faster than the transducer and we can fine-tune the pulse by using a 4.7kΩ resistor, a 10kΩ pot, a 1kΩ pot, and a 470 pF capacitor. The 10kΩ pot is our coarse tuner and the 1kΩ pot is our fine tuner. The pulse, then, goes into the binary counter logic chip (74HC193). The counter generates three waveforms: Q0, Q1, and Q2. Each waveform is equivalent to half the frequency of the previous waveform as shown in the image below.
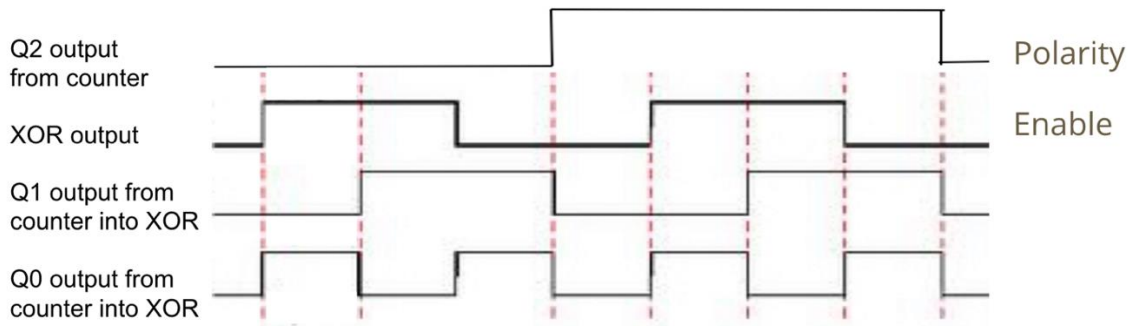
Q2 output from counter — Polarity

XOR output — Enable

Q1 output from counter into XOR

Q0 output from counter into XOR

Figure 4: The four waveforms we use to generate a modified sine wave.

From the counter chip, we feed Q0 and Q1 into an XOR gate (74HC86N) to get our enable waveform. The output Q2 becomes our polarity waveform. The MOSFET drivers (MPC14E11) takes in the enable and the polarity waveform and outputs two channels that are connected to the H-bridge. The enable and polarity channels control the logic going into the H-bridge accordingly to create the intended modified sine wave. The enable controls which side the current flows through in the H-bridge. The polarity controls which power MOSFET transistor to turn on.

Right before putting the logic into the H-bridge, we included a voltage divider and a transistor. The reason is because the P-type MOSFET transistors in the H-bridge tend to stay on when the logic voltage is above 15V. If the P-type MOSFETS stay on, then it will short the circuit when the other side of the H-bridge should be on. So, the voltage divider ensures the top part of the H-bridge is functioning appropriately. The transistor we used for the voltage divider is an N-type transistor. Theoretically, an NPN transistor should work but we believe the logic was not going through fast enough since the oscilloscope showed some diagonal lines in the square waves.
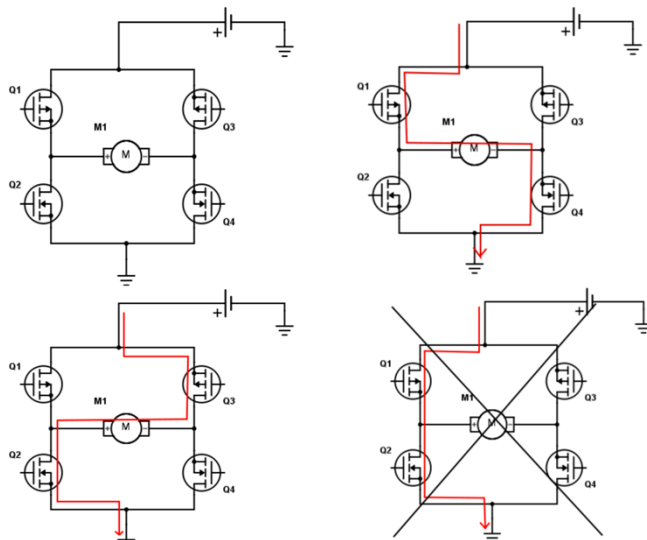
Figure 5: Display of how current should flow through the H-bridge.

The diagram (left) shows the structure of our H-bridge. At the top are two P-type power MOSFET transistors (IRF9640) connected to high voltage and the bottom are two N-type MOSFET transistors (IRF640) connected to ground. We want the current to go through the transducer in the middle. If the current goes through the two MOSFET transistors on the same side, then we will cause a short circuit.
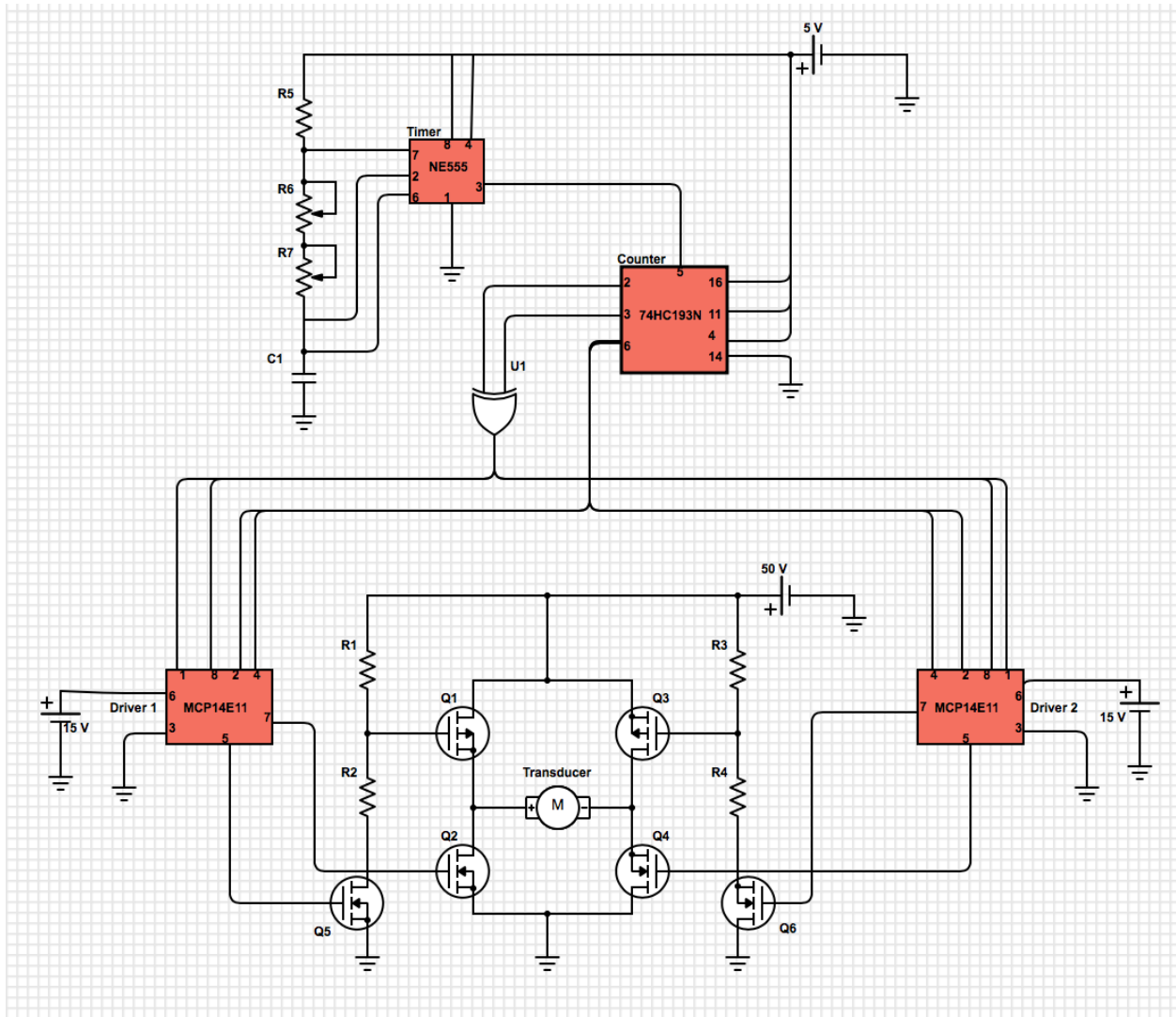
Figure 5: Full Circuit Diagram

The image above shows a complete circuit diagram we used. The resistors, R1, R2, R3, and R4, depend on the amount of voltage we power our transducer. Since we used 52V, the resistance of R1 and R3 is 200Ω and the resistance of R2 and R4 is 1kΩ. In addition to the diagram above, we also used 0.10 micro Farad capacitors for every logic chip to decrease the amount of spikes in our waveforms.

Making the Reflector

At first, we made a negative of the reflector using an 8cm diameter cylinder. One side of the cylinder was wrapped by a balloon and the other side was glue to a glass disk using silicone. Then, we drilled a hole through the glass disk and filled the inside with water until we achieved the curvature we wanted. We taped another same size cylinder to the negative and filled it will Plaster of Paris. In order to get the best curvature, we inverted the mold while the plaster is still curing to use the water pressure in forming the parabolic shape. After the plaster cured, we used the reflector and were able to levitate bits of tissue but nothing more.

Later, we use the same technique as before and mold a 16cm diameter cylinder. The concave part of the reflector ends up having a smoother surface with a depth of 2.3cm. With more precise measurements and finer parabolic shape, we calculate a focal length of 7.0cm.
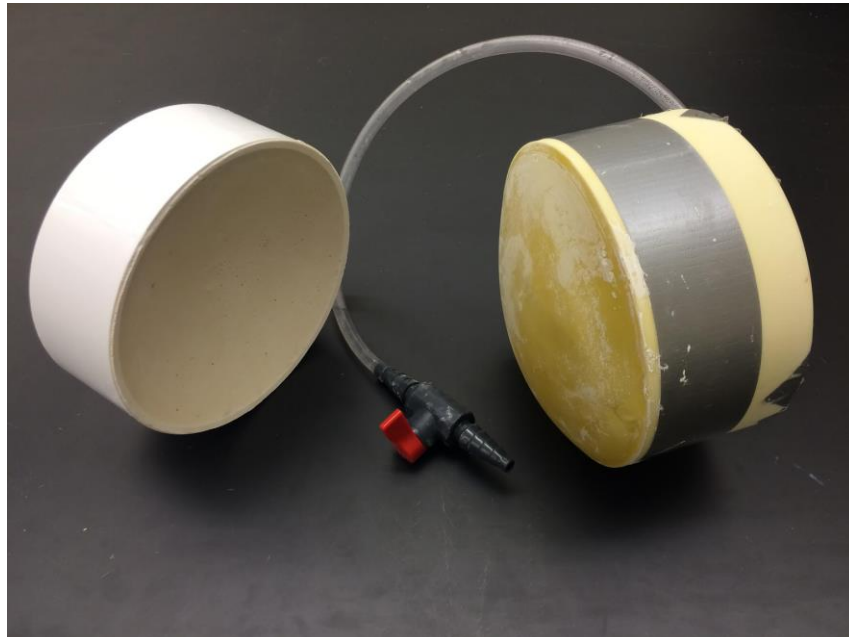

Figure 6: The final 16cm diameter reflector and its negative
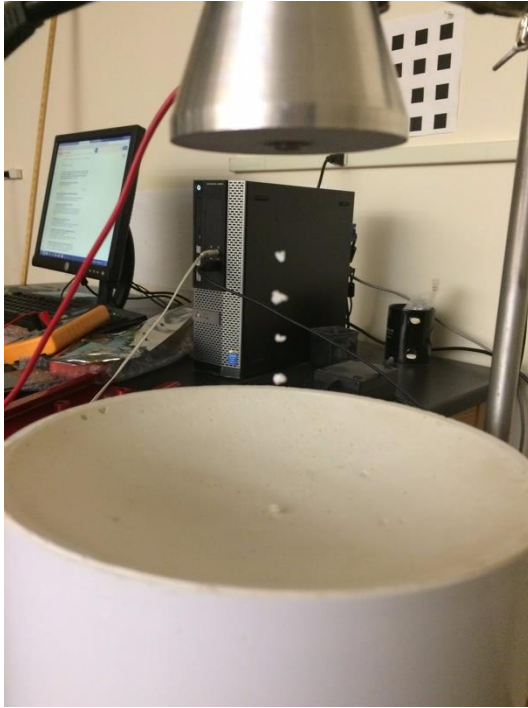
Results

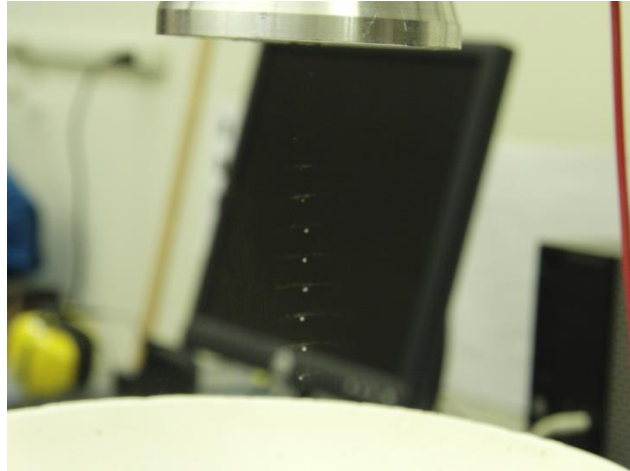Figure 9: Levitation of water droplets at half of a wavelength apart.

Figure 8: Levitation of Styrofoam bits at roughly one wavelength apart.

At 30V, we waved a small piece of paper between the ultrasonic transducer and the reflector. We could see obvious nodes where the paper was attracted to but it it did not have enough power to levitate anything.

When we increased the voltage to 45V, we were able to levitate tiny pieces of tissue and Styrofoam bits. Considering the limitations of our circuitry, we determined that the maximum voltage our circuit can handle was 52V before the P-type MOSFET transistors starts getting too hot. The maximum current we got at this voltage is 0.41 amps. At maximum power, we measure the heaviest object it can levitate was a 0.1g piece of balsa wood.

The distance for optimum levitation is 12cm from the center of the reflector to the center of the transducer (parabolic depth included in this distance). The longest duration we power the transducer is 20-25 minutes. Since the resonant frequency is at roughly 28kHz, the wavelength is 1.2cm. In Figure 8, we levitated bits of Styrofoam that were separated by the distance of a wavelength. In Figure 9, we levitated water droplets that are half of a wavelength apart.

Conclusion

We achieved our initial goal to levitate water droplets. However, improvements can be made to the circuit so that we can let the levitation run longer without the circuit or the transducer getting too hot. We also want to make the circuit susceptible to higher voltages in order to output more power from the transducer. Considering efficiency, we should improve the modified sine wave, determine the optimal parabolic shape of the reflector, and make the focal distance proportional to the wavelength. Once these improvements take effect, we should be able to levitate salt water and witness the crystallization while the water evaporates. As for future researchers, our device may be useful for chemical reactions that require a containerless environment.

References

[1]   Li, Peng. (2015). Acoustic Separation of Circulating Tumor Cells. *Proceedings of the National Academy of Sciences of the United States of America.* (http://www.pnas.org/content/112/16/4970.full)

[2]   Andrade M. A. B. , Perez N, Adamowski J. C. (2015). Particle manipulation by a non-resonant acoustic levitator. *Applied Physics Letters,* pp. 106.

[3]   Hahn, James H. (2006) Modified Sine Wave Inverter Enhanced. *Power Electronics Technology*, pp. 22. (http://powerelectronics.com/site-files/powerelectronics.com/files/archive/powerelectronics.com/mag/608PET21.pdf)

PS: I must give credit to Phyo Lin for generating beautiful images of the H-bridge (Figure 5) and the whole circuit diagram (Figure 6).