Photoacoustic Imaging
With
SimSonic

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Background and Overview

The focus of this project was the exploration of the photoacoustic imaging capabilities of the SimSonic2D software package. The photoacoustic effect is the physical basis for photoacoustic imaging; it refers to the generation of acoustic waves by the absorption of electromagnetic energy, such as optical or radio-frequency [1].

The object we chose to image was a cylinder with an infinite height and a finite radius. The imaging of the cylinder generally encompasses three main tasks: definition of transducer geometry, simulation, and signal processing. In simulation, we both define a pulse sequence and solve the forward problem for each pulse using SimSonic. For the task of signal processing, we iteratively apply a reconstruction algorithm to the signals and scan conversion to the pixel data in an effort to pictorially recreate the original object. We applied these imaging techniques to four different cases and observed the z radius. We say that the cylinder has an infinite height because that's what SimSonic2D assumes for a circular object.

We made several big assumptions when working on this problem. The first assumption was that our entire cylinder was uniformly illuminated. Next, we assumed that our entire cylinder possessed homogeneous acoustical properties. This means that our simulation ideally shouldn't have been affected by the differences throughout the cylinder. Additionally, we assume that the cylinder has different optical absorption characteristics than the background.

Originally, we wanted to apply exponential attenuation to the light penetration as the light beam propagated through the background medium. However, the SimSonic software made this very challenging to do, so this specification was omitted from the project requirements. It is important to note that there is no documentation on the photoacoustic imaging functionality of SimSonic, and that the majority of techniques employed in this project were developed primarily as a result of trial and error.

Definition of Transducer Geometry

The definition of the transducer geometry and imaging parameters can be found in two files: BuildSimul.m and Parameters.ini2D. BuildSimul.m contains code responsible for the creation of the cylinder, simulation map, and the photoacoustic map. In Parameters.ini2D one can find specification of the boundary conditions, perfectly matched layers (PML) parameters, and materials properties such as material density and pressure. In Parameters.ini2D, we also have a coefficient list. These coefficients were determined empirically through much trial and error. No documentation can be found on these coefficients.

The creation of the cylindrical shape can be accomplished with the help of the meshgrid and find commands in MATLAB after specifying the radius and dimensions (N1, N2). For the different cases explored, the general shape of the transducer stayed the same, but the number of cylinders, their size, and their orientation with respect to each other was changed.

Definition of Pulse Sequence

The pulse used to excite the cylinder is defined in BuildSimul.m. In doing photoacoustic imaging, we use a special type of signal that is represented by the PhotoacousticSignal.sgl file, which differs from the standard signal by several parameters, and is looked for in Parameters.ini2D. Upon creation, the photo signal is passed to SimSonic2DWriteSgl.m, which creates the PhotoacousticSignal.sgl file.

The signal is defined as a Gaussian Pulse having a center frequency of 4MHz, a pulse center time of 0.5 seconds, a bandwidth 6dB down from the center frequency, and duration of 6. Essentially, the laser pulse can be thought of as approximately a delta function.

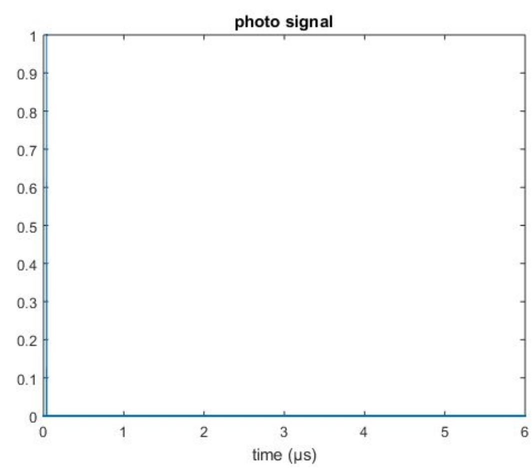


Figure 1: The photo signal used to irradiate the cylinder.

Solving the Forward Problem

Since the goal of our project is to simulate a cylinder, the forward problem is to use SimSonic2D simulation to create the signal.

In our scenario, the signal received from a cylinder surrounded by transducers will be identical at each transducer (assuming the cylinder is centered in the circular transducer array). Assuming the laser pulse is nearly instantaneous, we would model the cylinder as a sum of acoustic sources by Huygen's Principle. Therefore, the signal received by the transducers will be dependent on the solid angle intersection between a time-expanding sphere centered on the transducers with radius *c*t* and the object that absorbed the laser pulse.

In class, we did a similar problem in the homework with a sphere as the acoustic source, with the pressure wave being two triangular peaks with opposite amplitude and switching signs at the center of the sphere. With a cylinder, we would expect a similar response, although slightly altered. Since the pressure is proportional to the change of solid angle over time, we would expect the first peak to be larger in magnitude since the solid angle changes more rapidly intersecting a cylinder compared to a sphere. However, the second peak will be smaller in magnitude, since the solid angle will be decreasing slower after reaching the center of the cylinder. Lastly, we expect the signal to never go to zero since we are simulating an infinite cylinder and therefore there will always be an ever-decreasing signal arriving.

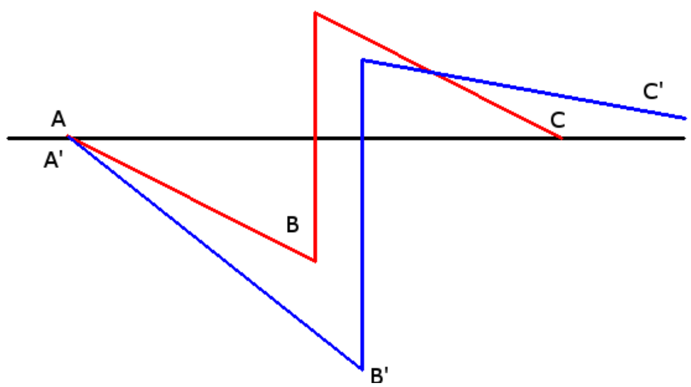


Figure 2: Comparison of sphere signal (red) compared to cylinder signal (blue). Point A and A' are the start of the signal, point B and B' are when the solid angle starts to decrease instead of increase, and C and C' are the endings of the signal.

Plugging it into the simulation, we receive a signal of what we theorized in Fig. (3). The oscillations at the end of the signal are artifacts of the simulation and finite step difference. In order to effectively create a uniform illumination of cylinder, we have to create a cylinder with an increasing absorption coefficient the further distance inside the cylinder, thereby accounting for the absorption of the material.

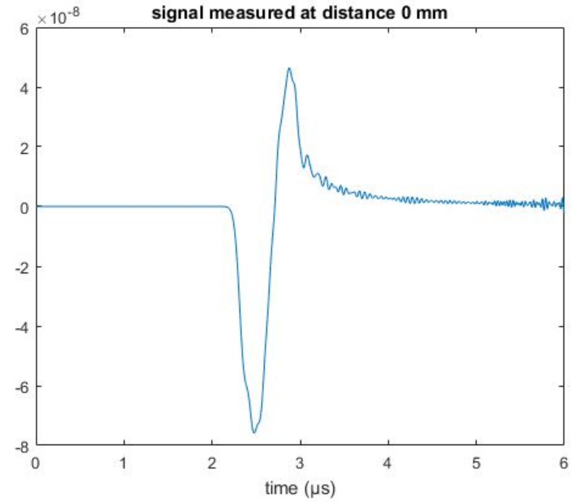


Figure 3: Signal received from simulation of a centered cylinder

Reconstruction Algorithm

To reconstruct the image, we use the derivation from the paper by Minghua Xu [2]. In this, we first recognize Green's function for ultrasonic waves. Assuming the transducers are far enough away from the sample we can use paraxial assumption. Also, assuming instant and uniform illumination, we know the initial conditions for pressure from the laser pulse onto the sample. Assuming the background does not absorb any light, the only boundary is therefore the absorption from the cylinder.

Finally, we can use the simple reconstruction equation below:

$$A(r) = C \int_{\varphi_0} d\varphi_0 \frac{1}{t} \frac{\partial p(r_0, t)}{\partial t}$$

In this equation, A(r) is the reconstruction point for given vector r, C is an arbitrary constant since we are only concerned about general shape, p is the pressure vector for given transducer, and t is for time. Lastly, we integrate over all of the transducers in the array.

To get the change in pressure over time, we use the Savitsky-Golay filter on the pressure received from the transducer. The Savitzky-Golay filter can smooth out and take the derivative of a signal, so it works much better than the MATLAB differential code.

For scan conversion in the reconstruction algorithm, we use two different vectors. One of the vectors is the 2-D location of each transducer while the second vector is the 2-D location of the reconstruction point. Therefore, we can calculate the time step "t" by subtracting the transducer location vector by the reconstruction location vector. Assuming the ultrasonic speed is constant throughout the medium, the time step is the difference in location divided by the ultrasound speed.

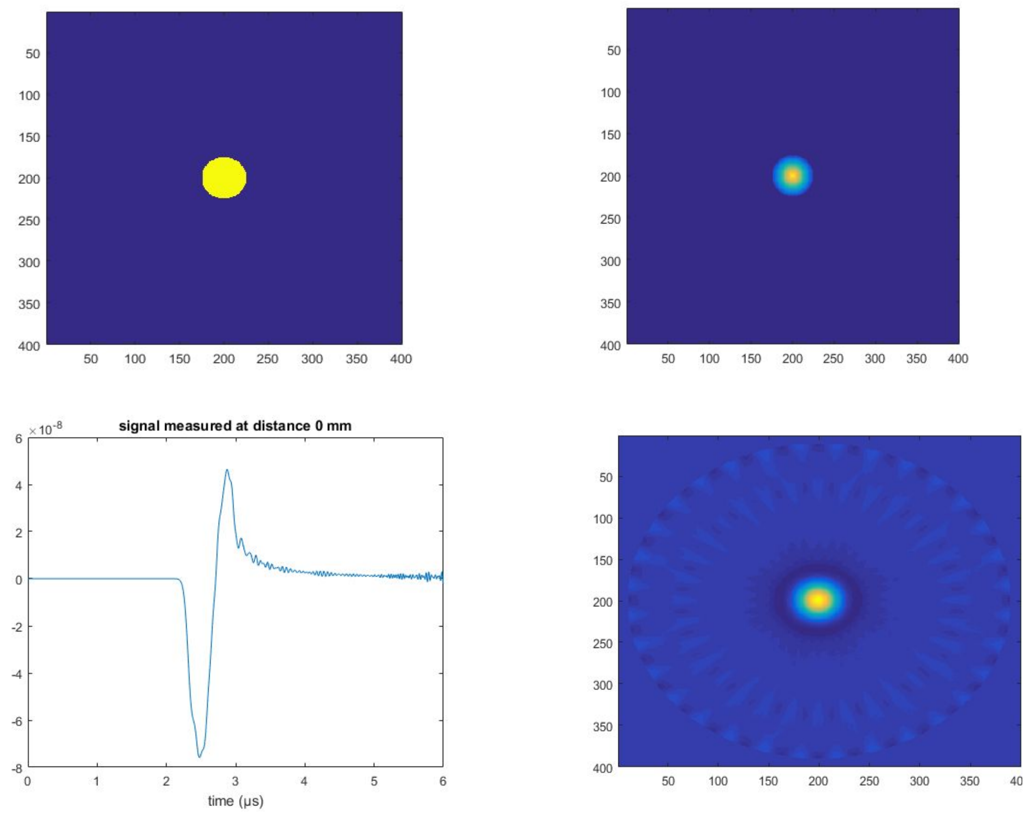
In MATLAB, we were able to create a code that ran the reconstruction algorithm provided. However, we ignored exact constants, such as the absorption coefficient, specific heat, etc. in order to just get an outline of the objects.

Results

In our simulation, we were able to reconstruct the shape of the cylinders simulated in SimSonic2D. In the figures below, we attempt multiple types of reconstruction to see how parameters affect the results. In all of our simulations, the total map size is 8mm x 8mm and the radius of the transducer array is 4mm with 32 total transducers. Each grid step has resolution .02 mm and our simulation runs for 6 microseconds. All material has index of water with the photomap having a gradient of absorption to more accurately simulate uniform illumination.

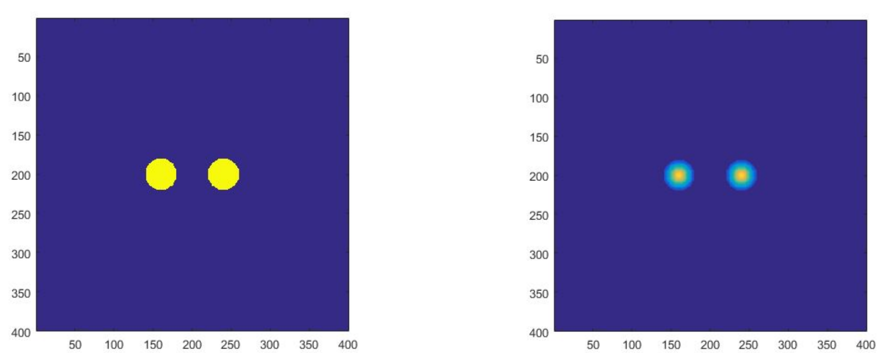
Result layout: First figure is the geometry of the map, second figure is the photomap, third is the signal received by the top middle transducer, and the last figure will be the reconstruction of the signals.

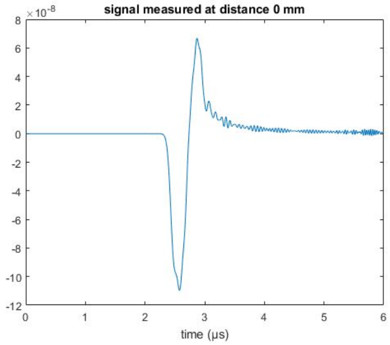
The Centered Cylinder

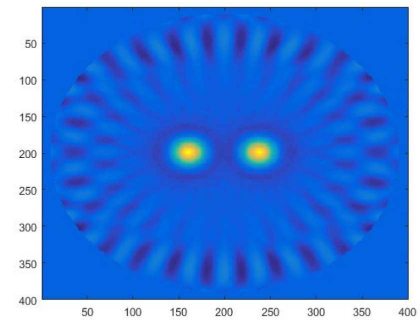


The simplest case for simulation is a cylinder in the center of the map. In reconstruction, it reconstructed approximately what we simulated. The interesting result is that the circle mimics the photomap in that the center is shown to have a higher absorption that the outside, which is what we simulated as well.

Two Cylinders

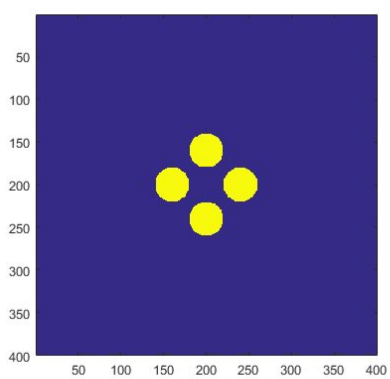


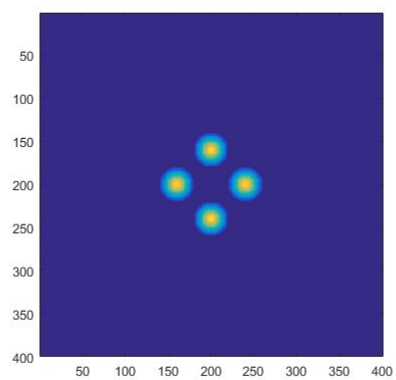


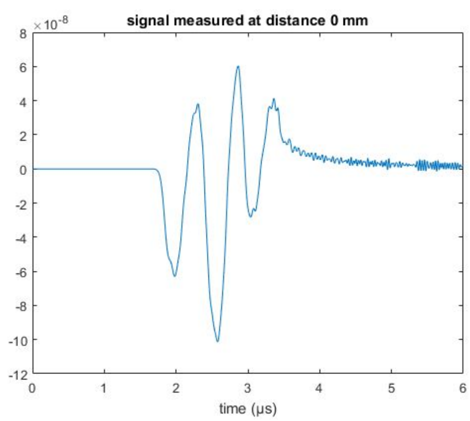


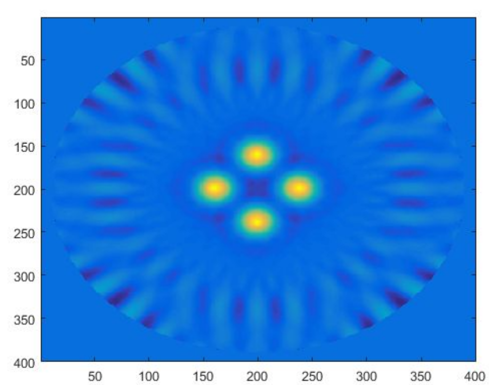
For two cylinders, we test if the reconstruction has sufficient resolution and if the accuracy decreases for non-centered cylinders. Although our signal looks the same from the topmost transducer, the other transducers in the circular array have enough resolution to identify each of the cylinders. The accuracy looks identical to the centered cylinder.

Four Cylinders









Our final trial tests the resolution of each direction as well as a more complex image with four cylinders. In the signal figure, the signal is more complex and the reconstruction algorithm still accurately predicts the location and size of each cylinder.

Conclusion

In SimSonic2D, we were able to simulate photoacoustic imaging of a cylinder and also reconstruct an image using a circular array of transducers. Since there is not much documentation on photoacoustic imaging in SimSonic2D, we were unclear how the laser pulse was implemented and also unsure how to create a photoacoustic map. What we did was create a very short laser pulse as well as have higher absorption coefficients the further inside the circle since that method seemed to mimic total uniform illumination correctly.

In our reconstruction, we successfully reconstructed a centered cylinder. After that, we also reconstructed two side-by-side cylinders as well as four side-by-side cylinders, each giving us accurate resolution and accuracy. In reconstructing, further in the cylinder is more defined than outside. This may be a vestige of the 2D nature of the simulation.

References
[1] Xu, M. (2006). *Photoacoustic imaging in biomedicine*. Retrieved May 12, 2017, from http://oilab.seas.wustl.edu/epub/2006MXu-PA-Review.pdf
[2] Xu, Minghua, and Lihong V. Wang. "Time-domain Reconstruction for Thermoacoustic Tomography in a Spherical Geometry." IEEE Transactions on Medical Imaging 21.7 (2002): 814-22. Web.