Photoacoustic imaging using acoustic reflectors to enhance planar arrays

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Abstract. Planar sensor arrays have advantages when used for photoacoustic imaging: they do not require the imaging target to be enclosed, and they are easier to manufacture than curved arrays. However, planar arrays have a limited view of the acoustic field due to their finite size; therefore, not all of the acoustic waves emitted from a photoacoustic source can be recorded. This loss of data results in artifacts in the reconstructed photoacoustic image. A detection array configuration which combines a planar Fabry–Pérot sensor with perpendicular acoustic reflectors is described and experimentally implemented. This retains the detection advantages of the planar sensor while increasing the effective detection aperture in order to improve the reconstructed photoacoustic image.

Keywords: photoacoustic imaging; limited aperture; reflectors; image reconstruction; Fabry–Pérot ultrasound sensors.

1 Introduction

Planar sensor arrays used for photoacoustic (PA) imaging, e.g., interferometric optical sensors,1 or capacitive micromachined ultrasonic transducers,2 are often easier to fabricate (and interrogate), than curved or spherical arrays. However, their planarity also leads to a disadvantage: with a finite-sized planar sensor array, it is not possible to exactly measure sufficient data to recover the image anywhere in the imaged region. In other words, there is no “visible region” (see Fig. 1). This “limited aperture,” “limited view,” or “partial data” problem results in blurring and artifacts in the reconstructed image.

Several techniques have been investigated to overcome the limited aperture problem. One approach is to introduce additional edges into the initial pressure distribution so that they are “visible” to the sensor array. Gateau et al.4 proposed to do this by using speckle illumination to give the fluence more structure, and Wang et al.,5 by using focused ultrasound to increase the Grüneisen parameter within the focal region (as it is typically temperature dependent). To obtain the full image, both methods require numerous partial images to be measured, which make these techniques slow. The limitations of both procedures are related to the extent to which they can form sharp features within the initial pressure distribution. Frikel and Quinto6,7 show that windowing the data (apodising) can ameliorate the presence of sharp image artifacts, but it does not help to recover the missing edges. A more general approach, which is not specific to this type of artifact, could be to frame the image reconstruction in such a way that additional information about the image (priors) can be directly incorporated. For example, a total-variation penalty term could be used to promote piecewise constant features in the image,8 or vessel filtering9 could be used to reduce artifacts, although there must be vessel-like structures present for this to work. This paper takes a different approach and examines the use of multiple acoustic reflectors to increase the effective aperture by redirecting the sound waves that would otherwise have missed it, onto the sensor array. This allows parts of the image to be recovered that would otherwise be invisible; for example, edges that are close to perpendicular to the sensor plane. Huang et al.10 also used an acoustic reflector positioned at about a 45 deg angle to a linear sensor array to extend its effective aperture and assist with the recovery of boundaries perpendicular to the sensor. As the exact angle of the reflector was unknown, it was adjusted during the image reconstruction to maximize the sharpness of the image. The acceptance angle of their piezoelectric transducer limited the improvement achievable. Li et al.11 extended this work by investigating the use of two reflectors, one at each end of the array and each making a 30 deg angle with it. A limitation of this technique is that the entire object being scanned has to fit in the volume between the reflectors and the sensor. Increasing the reflector angles so that they are perpendicular to the array allows part of an object to be imaged while the remainder stays outside the imaging region, this would be beneficial in breast or small animal imaging. Using numerical simulations, Cox et al.12 demonstrated that this arrangement could be used to extend the sensor’s effective aperture and gave a fast exact reconstruction algorithm for this case. This paper presents an experimental validation of this approach.

The layout of the paper is as follows. Section 2 describes the use of acoustic reflectors to increase the effective aperture of the sensor. In Sec. 3, numerical simulations of this technique are presented. An experimental configuration for implementing this technique based on an optically addressed planar Fabry–Pérot (FP) ultrasound sensor is introduced in Sec. 4 and the images obtained using this scheme are presented in Sec. 5. Finally, a discussion of the limitations and practical capabilities of using acoustic reflectors to extend the effective aperture of the sensor is presented in Sec. 6.
3 Numerical Simulations

Two separate groups of simulations were conducted to investigate the increase in the effective aperture with the presence of reflectors. The first group of simulations demonstrated the qualitative improvements in the image, the second group investigated the quantitative improvement in the reconstructed images as the acquisition time (and, therefore, the number of reflections acquired) increased.

3.1 Simulation Investigating Qualitative Improvement in Two-Dimensional Knotted Phantom

Two two-dimensional (2-D) simulations were conducted to investigate the increase in the effective aperture that could be gained using perpendicular reflectors. In one simulation, there were no reflectors (free-space propagation); in the other, reflectors were present. The simulations consisted of modeling the acoustic wave propagation and detection by a sensor array using a $k$-space pseudospectral time-domain acoustic propagation model, $k$-Wave. In the first simulation, where no reflectors were present, absorbing boundary conditions were applied to all sides of the computational domain, simulating free-space propagation. For the second simulation, the reflections were simulated by first mirroring the domain about its right-hand edge (Fig. 3), and then setting the acoustic model to have periodic boundary conditions on the vertical sides, so that pressure waves leaving the domain at one wall will reappear at the other wall across the domain. Data were acquired increased.

For both simulations, zero-mean random Gaussian noise was added to give a signal-to-noise ratio of 40 dB. A
frequency-dependent absorption coefficient, $\alpha = a\omega^2$, was used, with $a = 2.17 \times 10^{-3}$ dB MHz$^{-2}$ cm$^{-1}$, to simulate propagation in distilled water, matching the experimental conditions investigated later. The acoustic field at the sensor array was recorded for 380 $\mu$s, which ensured that the majority of the acoustic energy had left the domain by the end of the simulation. (In the simulation where reflectors are present, the ratio of the sum of the acoustic pressure initially squared across the domain to that at the end of the simulation was $1.45 \times 10^{-5}$.) The grid size for the free-space simulation was $129 \times 129$ with a step size of 100 $\mu$m, supporting spatial frequencies up to 7.34 MHz, with a temporal step size of 19.9 ns. The reverberant simulation had a grid size of $258 \times 129$ with a step size of 100 $\mu$m. The nonabsorbing sound speed and density for both simulations was 1482 ms$^{-1}$ and 1000 kgm$^{-3}$, respectively, to simulate the phantom being in de-ionized water at 20°C.

The simulated time series over the first 60 $\mu$s (a) without reflectors and (b) with reflectors can be seen in Fig. 4; the reflections are clearly visible. Figure 5 shows (a) the true initial pressure distribution, (b) the image reconstructed without reflections present, and (c) the image reconstructed with reflections present. Clearly, there is an improvement in the image that includes the reflections; more of the features are visible in the image, and there are fewer artifacts. Most notably, the visibility of features that are tending toward being perpendicular to the sensor is considerably improved when reflections are used in the reconstructions.

### 3.2 Improvement in Reconstruction with Number of Reflections

To investigate the relationship between the improvement in the reconstructed image and the number of reflections recorded, a number of simulations were conducted using the same model and choices of parameters as above. In each simulation, an initial pressure distribution consisting of a single disk was simulated. These were placed at different locations within the domain to investigate the spatial dependence of the improvement in reconstruction (see Fig. 6). Each simulation was run for a total of 247 $\mu$s, which is a sufficient time for an acoustic wave to traverse the domain 20 times ($20 \times$ diagonal of domain/speed of sound within the domain), corresponding to a minimum of 20 reflections being recorded at the array for all spatial locations. For each source location, 20 reconstructions were performed, with the duration of the time series used in the reconstruction truncated between 5% and 100% of the total duration. By doing this, reconstructed
images that incorporated different numbers of reflections were produced.

Each reconstructed image was compared to the initial pressure distribution by calculating the sum of the square difference (SSD) between them. This was normalized with respect to the SSD value for the first reconstruction where no reflections are present to give an error metric. In Fig. 7, the log₁₀ of the error metric is plotted against the log₁₀ of the duration of the time series (corresponding to the number of reflections) used in reconstruction. As the number of reflections included in the reconstruction increases, the error metric decreases, meaning that the reconstructions become closer to the initial pressure distribution, for all spatial locations. The error metric for reconstructions of disks closer to the sensor decreases more slowly with an increase in the number of reflections, as would be expected since more of the radiating acoustic wave is directly captured by the sensor. Minimal improvement in the reconstruction is achieved by collecting more than 10 reflections (Fig. 7 is plotted on a log scale). This is also expected, as the waves propagating in directions almost parallel to the detector will need to traverse the domain many times before reaching the detector array and both geometric spreading and absorption will reduce their amplitude, reducing the improvement in the reconstruction after a finite number of reflections.

4 Experimental Configuration

This section describes the experimental configuration used to investigate the use of perpendicular reflectors in extending the effective aperture of a sensor.

The acoustic reflectors consisted of four borosilicate crown (BK 7) glass prisms glued together to form a 1 cm³ hollow cube faced with glass reflectors on the four vertical sides. This reflector arrangement was directly placed on the sensor surface. Prisms were chosen to reduce the effect of secondary acoustic reflections from the exterior wall of the glass re-transmitting into the water, being recorded, and corrupting the image. Glass being optically transparent had the advantage that it allowed the direct illumination of the region of interest; using opaque reflectors makes it difficult to achieve an even distribution of light inside the cavity. A minor limitation of using glass is that it is not perfectly acoustically reflecting; based on a sound speed and density of 5660 ms⁻¹ and 2500 kgm⁻³ for glass, 1482 ms⁻¹ and 1000 kgm⁻³ for water, the pressure reflection coefficient for waves at a normal incidence to the boundary is R = 0.81. The reconstruction and simulation described in Secs. 2 and 3 assumed that the walls are 100% reflective, R = 1. This is further discussed in Sec. 6.

The acoustic sensor consisted of a 20-µm thick FP polymer film sensor with a −3 dB bandwidth of approximately 40 MHz. The FP is addressed by a focused beam that is scanned from point to point across the sensor surface to synthesize a planar array. Using an acoustic sensor based on the FP allows the array to have a small element size without a decrease in the sensitivity. Elements with a smaller size more closely approximate the assumption in the reconstruction of omnidirectionality, which is beneficial when using acoustic reflectors due to the high angles of the later reflected waves. The acoustic reflector was directly placed on top of the sensor. The photoacoustic signal was generated using a fiber coupled Q-Switched Nd:YAG laser with a pulse duration of 10 ns that was backward mode coupled into the system as shown in Fig. 8.

Two phantoms were imaged with the acoustic reflectors present. The first phantom consisted of a tube (microbore extension line, MX590, Smiths Medical) that was knotted [see Fig. 9(a)]. The loop that this formed had both edges that are directly detectable by the sensor (with angles that are close to parallel to the sensor) and edges that would not be (with angles that are close to perpendicular to the sensor). This choice of phantom was made in order to demonstrate that including reflections will allow more of the edges to be reconstructed, corresponding to an effectively larger sensor aperture. The tube was filled with India ink diluted to 1% concentration so that the illuminating light can penetrate throughout
the diameter of the tube and not be solely absorbed at the surface of the ink.

The second phantom consisted of a polymer ribbon, ∼0.6 mm wide and 100-μm thick. This was twisted several times and held in place by gluing it between two acrylic armatures of a custom mount [see Fig. 9(b)]. The twisted plane nature of the phantom means that along the phantom’s length its angle relative to the sensor changes. By imaging this phantom, the maximum angle of the side of the phantom relative to the sensor that can be reconstructed is found; from this the effective aperture of the sensor could be determined.

The chosen phantom was placed inside the acoustically reflecting cavity, which was placed on top of the FP sensor and filled with deionized water. A scan area of $11 \times 12$ mm was selected, which deliberately overlapped the walls, so that the exact position of the walls could be obtained from the measured data. In this way, the region of interest was defined, and measurements from outside this region were discarded pre-reconstruction. A step size of 100 μm was chosen as a compromise between a high spatial sampling and a dataset of easily manageable size. All wave components with frequencies below 7.5 MHz were spatially sampled at least two points per wavelength, which although below the 40 MHz bandwidth of the sensor, are not significantly lower than the highest frequencies expected in the signal. By inspecting the time series, it was found that the last reflections that were above the noise floor were observed at 22.6 μs; this defined the length of each acquired time series and thus the length of data used in the reconstruction.

5 Experimental Results

5.1 Time Series Data

Figure 10 shows the time series recorded following the illumination of the twist phantom. Reflections from the side walls of the reflector can be seen in the time series just as in the simulation (indicated by the arrows in Fig. 10).

5.2 Tube Phantom

To investigate the influence of a few reflections compared to many on the reconstructions, two reconstructions were produced corresponding to a short measurement time (very few reflections) and a longer measurement time (several reflections). To replicate the case where only a few reflections are present, data after $t_{\text{max}} = 6.8$ μs was removed, the dataset was then zero padded and the transition between the data and the zeroes was smoothed using a Blackman window on the time series. This means that some reflections were still present but it approximated to the case without reflecting walls. In the second reconstruction, all of the data were used. Both cases are exactly reconstructed in the same way using the algorithm described in Sec. 5.

In Fig. 11, maximum intensity projections (MIPs) of the reconstructions for both cases can be seen, rendered in...
Amira® (FEI Visualization Sciences Group). In the case where the data are reconstructed with all of the reflections present, it can be seen that the rear loop of the tube and part of the tube at a steep angle from the sensor are visible. In the case where fewer reflections are present, these features are not clearly defined and there are more artifacts.

A 2-D MIP of the image of the loop in side profile was used to give an estimate of how much the additional reflections increase the effective aperture. Lines connecting the last well-reconstructed points on each side of the loop image were extended until they crossed the plane of the sensor array. The effective aperture was then defined as the distance between the intersections with this plane (see Fig. 12). The case where only some of the reflections are present gives an effective aperture of 27.8 mm, whereas the case where all the reflections are present gives an effective aperture of 39.1 mm. This represents an increase in the linear aperture of ∼40%. For a square-based cavity, both linear directions will see the same increase. This demonstrates an increase in the effective area of almost 100%.

5.3 Twisted Ribbon Phantom

The ribbon was positioned so that its length ran parallel to the sensor array in one axis. Images of the twisted ribbon phantom were reconstructed using short and long duration time series, as with the tube phantom [see Figs. 13(a) and 13(b), respectively]. In both cases, not all of the ribbon is recovered: the acoustic waves emanating from parts of the absorber that are perpendicular to the sensor array are not recorded, therefore, those edges do not appear in the images. In the case where fewer reflections are present, it can be seen that less of the ribbon is reconstructed. The reconstruction that uses fewer reflections is better on one side as the ribbon was placed close to one of the walls which resulted in the acoustic waves emitted by the portion of the ribbon tending toward the wall not being directly received.

The improvement in reconstruction with the presence of reflections is also seen when the reconstruction is stepped through as a series of slices along the length of the ribbon (see Fig. 14). In the case where all the reflections are present, the ribbons sides are recovered at angles closer to perpendicular...
to the sensor than in the case where fewer reflections are present. This is seen in Fig. 14 by the ribbon being clearly visible in the fourth slice down in column c but not in column b.

The increase in the effective aperture length with more reflections is determined from the maximum recoverable angle of the ribbon to the sensor in the reconstruction. The maximum angle of the ribbon relative to the sensor that is stably reconstructed was found by stepping through the reconstruction a slice at a time until the ribbon was no longer visible. The slice before this corresponds to the last stably reconstructed edge of the phantom. The effective aperture was determined from this slice by thresholding the image and then applying a Hough transform. The Hough transform detects the straight line formed by the ribbon in the reconstruction slice and outputs its position and angle. Using this position and angle information, a line perpendicular to the ribbon was extrapolated from the center of the ribbon (see Fig. 15). Where this extrapolated line met the sensor plane was determined to be the effective aperture, which in this case was 14.3 mm. This represents a 43% increase in the aperture length.

6 Discussion

Due to the nature of acoustic propagation, the ultrasonic pulses emitted by the photoacoustic source will propagate in all directions. While the reflectors help in collecting more of this field than would have otherwise been collected, those parts traveling parallel or close to parallel to the sensor will not reach the sensor for a long time. Furthermore,
because of the geometrical spreading (and absorption) that the waves undergo, the later arrivals will be significantly reduced in amplitude. (Some of the effects of attenuation could be compensated for using time variant filtering, though care must be taken to ensure high frequency noise components are not excessively amplified.) The proportion of the total pressure field that is collected will, therefore, be ultimately limited by the finite noise floor of the detector and not the finite size of the sensor array. This reflector and sensor configuration, while offering an improvement over a planar sensor, still does not have a region where the initial pressure field is fully recoverable; there is still no “visible” region; however, it does represent an improvement.

As well as attenuation due to absorption and spreading, the loss at the reflectors should be considered. The image reconstruction algorithm was based on the assumption that the reflectors had a pressure reflection coefficient of 1, i.e., they are 100% reflective. In practice, waves normally incident to reflectors will experience a reflection coefficient \( R \) < 1. Silicon and tungsten carbide have high acoustic impedances and reflection coefficients of 0.92 (velocity of 11820 m/s and density of 3160 kg/m\(^3\) \( \times \) 0.97 (velocity of 6655 m/s and density of 15,000 kg/m\(^3\) \( \times \)), respectively, but are optically opaque which complicates the illumination of the sample. A water-air boundary has a pressure reflection coefficient of \(-1\), and the reconstruction algorithm could be adapted to this case, but in implementing such a boundary it would be necessary to use a membrane to contain the water, and the water-membrane-air boundary only exhibits this ideal behavior over a narrow range of frequencies. As PA is inherently broadband, this is a drawback. In these experiments, borosilicate glass was used; it has quite a large acoustic impedance (\( R = 0.81 \)) and it is optically transparent, which allows the sample to be illuminated from all sides. At incident angles above 25.6 deg relative to the normal of the reflecting boundary, the waves will undergo total internal reflection, matching the \(|R| = 1\) assumption of the perfect reflecting boundary used in the reconstruction. However, these waves will undergo a phase change on reflection, so their contributions to the final reconstructed image will be blurred to some extent. For the majority of reflected waves with incident angles greater than 25.6 deg relative to the normal to the boundary, the phase shift in the reflected wave is \(\approx 340\) deg. As this phase shift remains relatively constant for a range of reflection angles, it may be possible to compensate for it in later arrivals by introducing a virtual boundary offset in the positions of the walls used in the reconstruction by a distance equivalent to the phase shift. This is not implemented on the results presented here, but is left as future work.

Waves traveling at steeper angles will arrive at later times and will, therefore, either be significantly attenuated or not detected at all.

A further assumption implicit in the image reconstruction was that the reflectors were perpendicular to the sensor array. In these experiments, the uncertainty in the perpendicularity of the walls was estimated using digital calipers to be approximately \(1\) deg. This will affect the acoustic path of the reflected waves and the location of their contributions to the final reconstruction. This is demonstrated in Fig. 16 for two reflections. An initial pressure source \( p_0 \) is reflected in wall A which is at a slight angle \( \epsilon \) to vertical, producing a reconstruction in position 1 (which would be subsequently introduced into the true domains reconstruction). When the first reflection is subsequently reflected at wall B this produces a reconstruction at position 2. The subsequent reflections’ contribution to the reconstruction become erroneously placed further away.

The erroneous placement of the contribution to the reconstructed pressure field \( (x_{\text{error}}, y_{\text{error}}) \) following the \( m \)th reflection due to the wall being at an angle \( \epsilon \) away from perpendicular can be described by the following equation for an even number of reflections (assuming the first reflection occurs from the tilted wall):

\[
\begin{bmatrix}
  x_{m, \text{error}} \\
  y_{m, \text{error}}
\end{bmatrix} = \left\{(R_0 R_{\epsilon})^{m/2} \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} + \sum_{i=0}^{(m/2)-1} (R_0 R_{\epsilon})^i \begin{bmatrix} 2d \\ 0 \end{bmatrix} \right\} \mod(2d), \quad (1)
\]

where \( R_0 \) and \( R_{\epsilon} \) are the reflection matrices for the walls when they are normal and angled by \( \epsilon \) away from normal toward the sensor defined as

\[
R_{\epsilon} = \begin{bmatrix} \cos(\epsilon) & -\sin(\epsilon) \\ \sin(\epsilon) & \cos(\epsilon) \end{bmatrix}
\]

Fig. 15 Reconstruction of ribbon at the steepest angle that was fully recoverable. Dashed line runs perpendicular to the ribbon, denoting the maximum aperture.

Fig. 16 Diagram depicting the propagation of misplacement of reconstructions of the initial pressure source \((p_0)\) caused by an error in the angle of a wall \((\epsilon)\), for the first two reflections. The diagram shows the placement of the reconstructed field due to a reflection at wall A to be at point 1. The subsequent reflection at wall B produces the reconstruction at point 2. Due to the symmetry of this technique, these misplaced reconstructions from each reflection will also occur in the original sensors domain. Also shown are the virtual domains (gray shaded area either side of original domain).
\[
R_0 = \begin{bmatrix}
-1 & 0 \\
0 & 1
\end{bmatrix},
\]
\[
R_x = \begin{bmatrix}
\sin^2 \epsilon - \cos^2 \epsilon & 2 \sin \epsilon \cos \epsilon \\
2 \sin \epsilon \cos \epsilon & \cos^2 \epsilon - \sin^2 \epsilon
\end{bmatrix}.
\]
(2)

The mod\(_{(2d)}\) in Eq. (1) indicates that the modulo operation applies only to the \(x\) component, i.e., it restricts the reconstructed image sources to the region \(0 \leq x < 2d\). However, the final reconstructed image must lie between the reflectors, in the region \(0 \leq x \leq d\); therefore, those reconstructed sources for which \(x_{\text{error}} > d\) must subsequently be folded back into the image region:

\[
\begin{bmatrix}
x_{\text{error}}^m \\
y_{\text{error}}^m
\end{bmatrix} = R_0 \left( \begin{bmatrix}
x_{\text{error}}^m \\
y_{\text{error}}^m
\end{bmatrix} - \begin{bmatrix}
d \\
0
\end{bmatrix} \right) + \begin{bmatrix}
d \\
0
\end{bmatrix}.
\]
(3)

Using this analytical solution, the location of the contribution to the reconstruction from each reflection can be found, as shown in Fig. 17, for a wall with an angle of 1 deg away from perpendicular for the first 20 reflections. For the first two reflections, the contributions are within 100 \(\mu\)m of the placement of the initial \(p_0\), this rises to 1 mm for four reflections and increases significantly after this. Evaluating the time series data from the experimental measurements, a maximum of three reflections are observed. The error in the placement of the contribution due to the reflections can be estimated as 300 \(\mu\)m. Because the spatial sampling size of the images produced is 100 \(\mu\)m, this represents a significant uncertainty. It is clear that the angle of the wall relative to the sensor is very important in terms of the gain in the effective aperture length. Using alternate manufacturing techniques, such as milling out the reflective cavity from a solid block of material, to construct the reflector could significantly reduce this error and improve the resolution of the final reconstruction.

It should be noted that this technique is resilient to the practical limitations discussed above and can be successfully implemented to extend the aperture of planar sensors.

7 Conclusion

It has been experimentally demonstrated that using acoustic reflectors perpendicular to a planar sensor array can extend the effective detection aperture of the array, and thereby improve the quality of the photoacoustic images. Extending the effective aperture allows the sensor array to capture a larger solid angle of the emitted acoustic field, which in turn allows the recovery of features in the initial pressure distribution that are not visible to the planar sensor alone. The estimated increase in effective aperture is \(\sim 40\%\) in each direction, which is an increase in the effective area of the sensor array by approximately 100%. While this is a significant improvement, full view reconstructions are still not possible using this technique, as extending the aperture does not create a “visible” region. Furthermore, the benefit of recording more and more reflections decreases due to the geometric spreading of the wavefield. In summary, using acoustic reflectors is a cost-effective and easily implementable way of increasing the effective detection aperture of a planar array, which can result in improved photoacoustic images.

Acknowledgments

This work was supported by Engineering and Physical Sciences Research Council (EPSRC) and European Union project FAMOS (FP7 ICT, Contract No. 317744).

References


Fig. 17 Plot of the contributions to the reconstruction for the first 20 reflections where one wall is 1 deg away from perpendicular in a reflective cavity 10 mm long. The circle represents the initial location, the cross and triangles represent contributions from the odd and even reflections, respectively.

Biographies of the authors are not available.