ACOUSTIC IMAGING WITH ELECTRONIC CIRCUITS

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Acoustic Imaging with Electronic Circuits

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Foreword

Early in 1977 we published as Supplement 9 to *Advances in Electronics and Electron Physics* a monograph entitled "Sequency Theory: Foundations and Applications" by Henning F. Harmuth. It shows his versatility that, a relatively short time later, we can present another monograph as a further supplement to this series.

The subject of acoustic imaging is a rather new one. While Dr. Harmuth restricts himself in this volume to the problem of the use of electrical circuits in producing acoustic images, the ample bibliography allows the student of the wider problem to dig deeper. The interest aroused by the earlier monograph makes it most likely that the present one will find a warm reception.

L. MARTON
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Preface

Nature uses acoustic waves to a much lesser extent than electromagnetic waves for the transmission of information. Our ears are sensitive up to a frequency of about 16 kHz, which means we can receive about 32,000 samples of a sound wave per second. On the other hand, a TV picture, with the standard of 625 lines and 25 frames per second, delivers $625^2 \times 25 = 9{,}765{,}625$ samples per second to our eyes; the number is still higher if the pictures are in color rather than in black and white. This shows that our eyes receive information at a rate of at least two or three orders of magnitude higher than our ears.

The large size of the sensor arrays required for the reception of acoustic waves seems to be the explanation for this different exploitation of acoustic and electromagnetic waves in nature. The sensor array for acoustic waves consists typically of two ears, while the sensor array for light waves in the human eye contains more than a hundred million sensors.

The scientific and practical development of image generation by acoustic rather than electromagnetic waves was doubtlessly handicapped by the lack of an example provided by nature. When the possibility and the potential of image generation by acoustic waves was finally recognized, the development was along the lines previously explored for electromagnetic waves. The acoustic lens was based on the optical lens, sonar followed radar, and acoustical holography was an offspring of optical holography.

Acoustic imaging with electronic circuits broke with the traditional pattern. This method was invented and developed without any example in optics or "electromagnetics." Indeed, the method could only be applied to optical imaging if the response time of the electronic circuits could be reduced by a factor of about 10^{-8}.

The transition from the first theoretical concept to the first experimental equipment was very fast, less than five years. This had much to do with the high state of development of our electronic technology. Equally important was the quick recognition of the potential of real time, reliable acoustic imaging for submarines. A. Cecelsky, a former submarine officer of the U.S. Navy, initiated the first development program within the Office of Naval Research; he was succeeded by M. A. Blizard, who continued the strong support until the first equipment was built. Credit for the successful

experimental work is also due to J. F. Ballon, R. D. Matulka, and D. D. Pizinger, all officers of the U.S. Navy assigned to the Office of Naval Research. C. McKinney of the Applied Research Laboratories of the University of Texas at Austin was of great help during the tests at the Lake Travis Test Station near Austin; the author is greatly indebted to him.

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* Equations are numbered consecutively within each of Sections 1.1 to 9.5. Reference to an equation in a different section is made by writing the number of the section in front of the number of the equation, e.g., Eq. (2.2-9) for Eq. (9) in Section 2.2.

Illustrations and tables are numbered consecutively within each section, with the number of the section given first, e.g., Fig. 5.4-2, Table 3.1-1.

References are characterized by the name of the (first) author, the year of publication, and a lower cased latin letter if more than one reference by the same (first) author is listed for the year.

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5. Practical Equipment

6. Multiplexing and Sidelobe Reduction

7. Implementation of Imaging by Digital Circuits

8. Special Effects Producible by Electronic Circuits

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1 Introduction

1.1 IMAGING WITH SOUND WAVES

There are currently four known methods for the generation of images by means of electromagnetic or acoustic waves. The oldest method uses lenses, which can be used for both electromagnetic and acoustic waves. Historically the second method is the echo principle used in radar and sonar; in the form of synthetic aperture radar and sonar, it produces images with an impressive resolution. The third method is holography; it was introduced theoretically by Gabor (1949, 1951) and implemented when the laser became available (Collier *et al.*, 1971; Kock, 1973). The fourth method uses two-dimensional, spatial electric filters; it was developed theoretically and experimentally during the last few years (Harmuth, 1976, 1977; Harmuth *et al.*, 1974). The first moving images by this method were obtained by J. Dierks of the Applied Research Laboratories of the University of Texas at the Lake Travis Test Station near Austin, Texas.

Refer to Fig. 1.1-1a to see what process is performed to generate an image by means of either electromagnetic or acoustic waves. Three wavefronts propagate from the points P1, P2, and P3 of the object plane to a

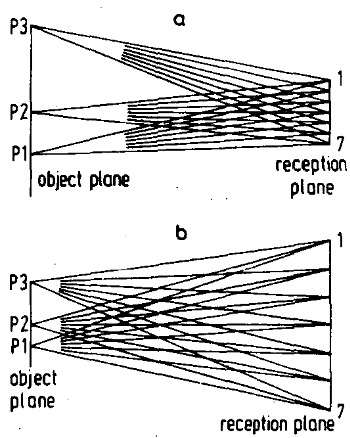

FIG. 1.1-1. Wavefronts generated at three points P1, P2, and P3 in the object plane and received at many points in the reception plane. (a) Reception plane smaller than object plane (telescope). (b) Reception plane larger than object plane (microscope).

reception plane. At every point of the reception plane one receives the sum of three wavefronts. The process of *imaging* means that this sum is decomposed into its components, so that one regains separately the amplitudes of the waves coming from P1, P2, and P3. Mathematically speaking, a linear transformation of the individual wavefronts originating in the object plane produces their sum in the reception plane; the inverse of this transformation reproduces the original wavefronts, which we call the image of the object plane. The various methods of image generation differ primarily in the way they produce the inverse transformation.

In Fig. 1.1-1a the reception plane is smaller than the object plane, while the opposite is true in Fig. 1.1-1b. We use the term *telescope* if the reception plane is smaller, and the term *microscope* if it is larger than the object plane.

The object planes in Fig. 1.1-1 need no further explanation, but it is not evident which physical structure can represent a reception plane. Figure 1.1-2

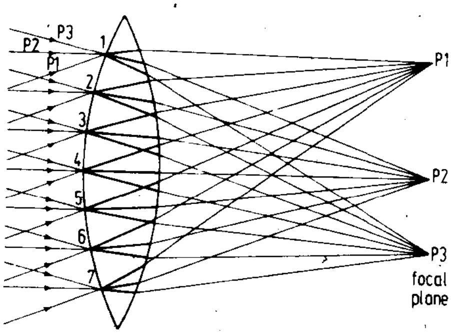

FIG. 1.1-2. Principle of the image generation by a lens.

shows a reception "plane" implemented by a lens. The points 1 to 7 on the reception planes in Fig. 1.1-1 are now the points 1 to 7 on the surface of the lens. The wavefronts from the three points P1, P2, and P3—which are assumed to be at infinite distance in order to have planar rather than spherical wavefronts at the lens—arrive as a sum at the points 1 to 7 but are separated by the lens into three image points in the focal plane.

We have used the term reception plane for the surface of the lens even though it is curved. Later, it will be seen that both the object plane and the reception plane may be curved, but this generalization will be tacitly ignored until needed.

The convex lens in Fig. 1.1-2 produces an image if the propagation velocity of the wavefront is slower in the lens than outside the lens. This is generally so for electromagnetic waves if the lens is made of glass and if it is surrounded by air. An acoustic wave propagates generally faster in a liquid than in a gas, and still faster in a solid. An acoustic lens in air is thus generally concave rather than convex, while an acoustic lens in water—the most important medium for acoustic imaging—may be either concave or convex, depending on the velocity of sound in the material of the lens.

The reception planes in Fig. 1.1-1 and the lens in Fig. 1.1-2 show seven receiving points, and the theory will be developed for a large but finite number of points. This is in contrast to most theoretical work on optical imaging, which assumes nondenumerably many points in order to be able to use differential calculus. This approach works in optics, even though a lens contains a finite number of glass molecules, the eye contains a finite number of light-sensitive cones, and a photographic film contains a finite number of light-sensitive molecules. The finite numbers are so large that the mathematical idealization is sufficiently accurate. This is no longer so in acoustic imaging with electronic circuits. The reception plane consists, in this case, of an array of hydrophones, and their number is conspicuously different from nondenumerably infinite.

Holographic acoustic images have not yet been produced satisfactorily,[1] but sonar images have been. The sonar images differ from our usual concept of an image, which is based on our experience with images formed by our eyes. Figure 1.1-3 shows the difference between the two kinds of images. The

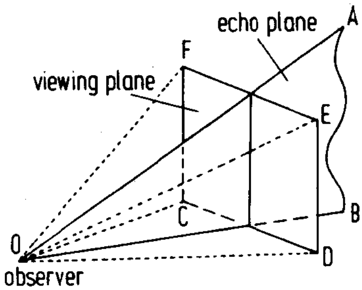

FIG. 1.1-3. The echo plane OAB of which the sonar principle produces images, and the viewing plane CDEF of which the eye and the lens produce images.

sonar principle produces an image of the *echo plane*, while the usual visual images, such as photographs or TV pictures, show an image of the *viewing*

[1] Imaging via acoustical holography using the boundary between a liquid and a gas or a crystal and a gas works theoretically, but its practical implementation proved difficult (Boutin and Mueller, 1967; Farrah *et al.*, 1970; Fritzler *et al.*, 1969; Goetz, 1970; Hildebrand and Brenden, 1972; Korpel and Desmares, 1969; Korpel and Whitman, 1969; Marom *et al.*, 1971; Metherel *et al.*, 1969; Mueller and Sheridan, 1966; Mueller and Keating, 1969; Mueller *et al.*, 1969; Mueller, 1971). The emphasis shifted to the implementation of the principle by electronic circuits; holography in this form has long been known in electrical engineering as synchronous demodulation (Booth and Sutton, 1974; Thorn *et al.*, 1974).

plane, which is perpendicular to the echo plane. Sonar images for medical diagnosis have been produced successfully (von Ramm and Thurstone, 1975; Kisslo and von Ramm, 1975).

1.2 Acoustic Lens versus Electronic Processing

Figure 1.1-2 shows an optical or acoustic lens that receives three planar wavefronts from the points P1, P2, and P3 at infinity. The lens concentrates the wavefronts in the three points P1, P2, and P3 in the focal plane. The propagation time of any part of a wavefront from its origin at infinity to its image point in the focal plane is the same, regardless of where the wavefront strikes the surface of the lens. The wavefront from point P1 at infinity requires more time to reach the point 1 on the surface of the lens than the points 2, 3, ..., 7. However, the propagation time from the surface of the lens to point P1 in the focal plane is shortest for the section of the wavefront striking the lens at point 1 and becomes increasingly larger for sections of the wavefront striking at the points 2, 3, ..., 7. The lens and the space between the lens and the focal plane act like many delay lines. There is a delay line for every point on the surface of the lens and for every angle of incidence. The heavy lines inside the lens in Fig. 1.1-2 show three "delay lines" originating at each one of the seven points on the surface of the lens.

Let us translate the action of the lens into electric circuits. In order to remain practical, we will use sound waves rather than light waves for illustration. The seven points on the surface of the lens in Fig. 1.1-2 are replaced by seven microphones or hydrophones in Fig. 1.2-1, which transform

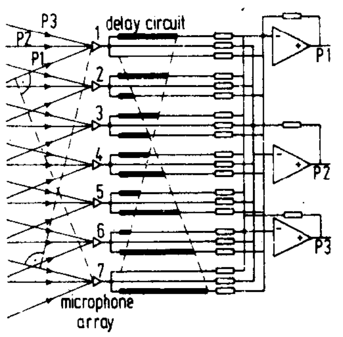

FIG. 1.2-1. Electric equivalent of an acoustic lens according to Fig. 1.1-2, using microphones, electric delay circuits, and summing amplifiers.

the acoustic oscillations into electric oscillations. Let us assume that the seven electromagnetic waves produced travel through the delay circuits shown with the same phase velocity as the acoustic wavefront traveled before reaching the microphones; the other parts of the electric circuit produce negligible delays. The traveling time of a wave from P1 at infinity, first as acoustic wave then as electromagnetic waves, to the output terminal P1 of the topmost summing amplifier, will thus be the same, regardless of which microphone received the sound wave.

The dashed lines in Fig. 1.2-1 are perpendicular to the line of propagation of the respective sound waves. One can readily see how these lines are used to determine the electric length of the delay circuits; the delay produced by these circuits is proportionate to their shown lengths.

Figure 1.2-1 shows seven microphones but only three points P1, P2, and P3 that are resolved. One will expect that an array of seven microphones can resolve seven points without ambiguity. This is shown in Fig. 1.2-2.

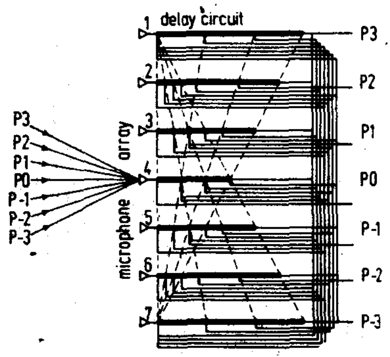

FIG. 1.2-2. Improved circuit of Fig. 1.2-1 yielding seven resolved points.

There are again seven microphones as in Fig. 1.2-1, but delay circuits with taps are connected to the microphones instead of a multitude of delay circuits. The location of the taps is determined by lines perpendicular to the lines of propagation from the points P-3, ... P3 to the microphone array. The resistors and summing amplifiers shown in Fig. 1.2-1 have been omitted in Fig. 1.2-2.

The image produced by the lens in Fig. 1.1-2 is a mirror image, since the sequence of the points P1, P2, and P3 in the focal plane is the reversed sequence of the points at infinity. The same holds true for Fig. 1.2-1. No such reversal occurs in Fig. 1.2-2. It is quite obvious that the location of the output terminals P1 to P3 in Fig. 1.2-1 or P-3 to P3 in Fig. 1.2-2 can be chosen at will. This possibility not only avoids side reversal but also provides a means to eliminate some of the distortions of the simple lens for wide viewing angles.

The imaging process in Fig. 1.1-2 is explained for one dimension only, but we extend it habitually to two dimensions by rotating the cut of the lens around the line from point 4 on the lens surface to P2 in the focal plane. This implies the use of polar coordinates. The choice of polar coordinates is based on technology. It is easier to compute and grind a lens in polar than in cartesian coordinates. The image is usually required to have a rectangular shape; e.g., modern photographs and TV screens are rectangular rather than circular, which favors cartesian coordinates.

The extension of electronic circuits from one to two dimensions can be done in polar coordinates too, but technology favors cartesian coordinates. Let us assume the circuit of Fig. 1.2-2 is mounted on a printed circuit card, without the microphones, but with the resistors and summing amplifiers that were left out in Fig. 1.2-2. The transition to two dimensions is accomplished by stacking seven cards vertically and another seven cards horizontally as shown in Fig. 1.2-3. The input terminals of the cards are the terminals 1 to 7

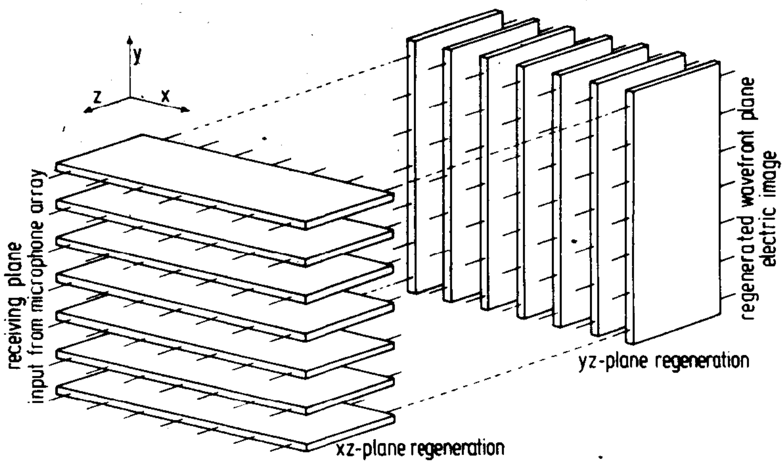

FIG. 1.2-3. Two-dimensional spatial processor or filter for image generation based on cartesian coordinates. The 7 × 7 voltages at the input terminals of the receiving plane are transformed instantaneously and linearly into 7 × 7 voltages at the output terminals of the regenerated wavefront plane.

in Fig. 1.2-2, the output terminals the points P-3 to P3, with the summing resistors and amplifiers added. The output terminals of the vertically stacked cards in Fig. 1.2-3 (xz-plane regeneration) are connected to the input terminals of the horizontally stacked cards (yz-plane regeneration) as indicated by the four dashed lines; the other connections are not shown, in order to avoid obscuring the picture.

A quadratic array of 7 × 7 microphones is connected to the input terminals of the vertical stack of cards in Fig. 1.2-3. The received acoustic wavefront is transformed by the microphones into a two-dimensional set or array of voltages, and the processor of Fig. 1.2-3 transforms this set of voltages into another set of voltages, which is the *electric image*. The next task is to transform the electric image into a visible optical image. Any electrooptical converter will do this. The best known converter is the television tube, but a light-emitting diode array could be used too.

Let us deviate for a moment and consider the implementation of the processor in Fig. 1.2-3 in polar coordinates. Figure 1.2-4 shows the arrange-

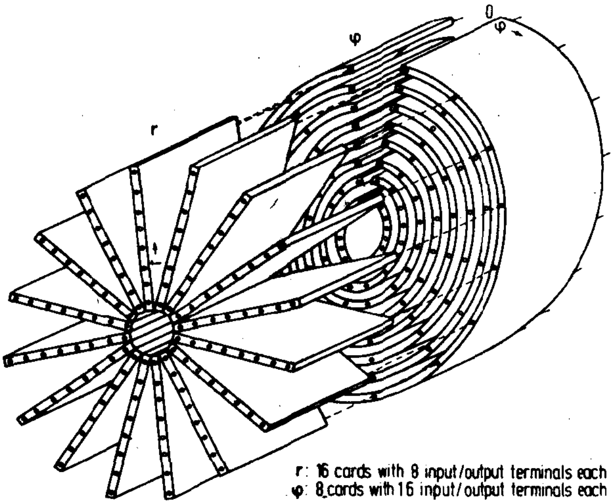

FIG. 1.2-4. Principle of circuit performing a two-dimensional spatial transform in polar coordinates. The cards denoted r contain the circuit of Fig. 1.2-2 but with 8 rather than 7 input and output terminals, while the cards denoted φ contain the same circuit but with 16 terminals.

ment of printed circuit cards according to Fig. 1.2-2 for polar coordinates. This illustration assumes an array of $8 \times 16 = 128$ microphones rather than $7 \times 7 = 49$ microphones as in Fig. 1.2-3. The microphones have to be mounted according to the pattern of polar rather than cartesian coordinates. The practical implementation of Fig. 1.2-4 appears much more complicated than that of Fig. 1.2-3, but this is not so. Both illustrations show only how the printed circuit cards have to be connected to the microphones, to each other, and to the electrooptical converter. The cards can all be fabricated in the usual way and mounted in the conventional printed circuit card hangers; only the wiring between the cards has to be done according to Figs. 1.2-3 and 1.2-4. The mechanical construction of the microphone array and of the electrooptical display differs. Figure 1.2-5 shows the arrangement of an essentially equal number of microphones in a polar array of $8 \times 16 = 128$ microphones and in a cartesian array of $10 \times 10 = 100$

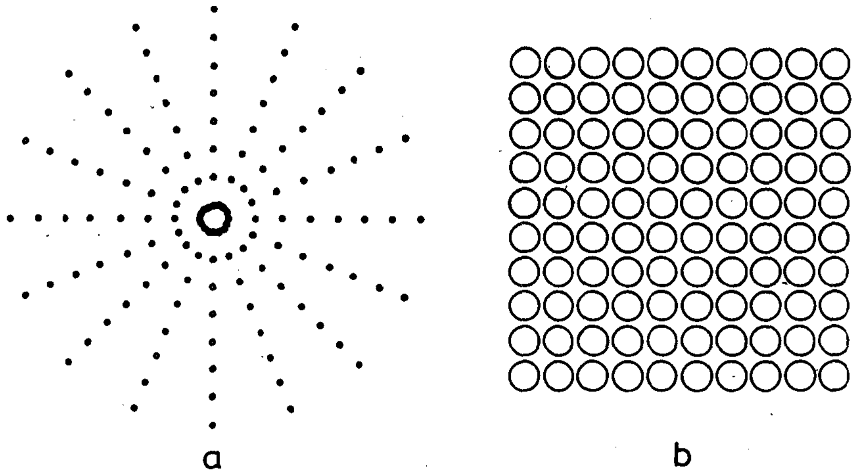

FIG. 1.2-5. Arrays with $8 \times 16 = 128$ microphones in polar coordinates (a), and with $10 \times 10 = 100$ microphones in cartesian coordinates (b).

microphones. The electrooptical converter should be constructed analogously. For a light-emitting diode display, one must mount the diodes like the microphones in Fig. 1.2-5. A cathode ray tube, as used in television, is scanning according to cartesian coordinates, but polar coordinate scanning is often used for radar displays.

The microphones in Fig. 1.2-5b cover the area of the array more uniformly than those in Fig. 1.2-5a. This translates practically into a uniform resolution of images based on cartesian coordinates, while polar coordinates favor a resolution that is better in the center than at the edges. The difference does not show up in optics, since optics is based, as pointed out before, on nondenumerably many points on the surface of the lens and in the focal plane of Fig. 1.1-2, which would imply nondenumerably many microphones in Fig. 1.2-5 and nondenumerably many terminals in Figs. 1.2-3 and 1.2-4. In principle, one cannot say whether uniform or nonuniform resolution is preferable. For photographs or TV pictures, we want generally uniform resolution. The eye, on the other hand, has conspicuously better resolution in the center than farther away from the center. The reason is obviously that we can move the eyes to get the best resolution where we want it, but we cannot change the resolution of a photograph or TV picture once it has been produced.

The construction of a microphone or hydrophone array according to Fig. 1.2-5b is preferable to that in Fig. 1.2-5a, since the microphones or hydrophones in the center of Fig. 1.2-5a must be very small. The use of cartesian coordinates is thus favored by the receptor array as well as by our