A STEERABLE AND VARIABLE FIRST-ORDER DIFFERENTIAL MICROPHONE ARRAY

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ABSTRACT

A new first-order differential microphone array with an infinitely steerable and variable beampattern is described. The microphone consists of 6 small pressure microphones flush-mounted on the surface of a 3/4" diameter rigid nylon sphere. The microphones are located on the surface at points where included octahedron vertices contact the spherical surface. By appropriately combining the three Cartesian orthogonal pairs with simple scalar weightings, a general first-order differential microphone beam (or beams) can be realized and directed to any angle in 4π steradian space. A working real-time version has been created and measured results from this microphone are shown. This microphone should be useful for surround sound recording/playback applications and to virtual reality audio applications.

1. INTRODUCTION

Variable beampattern differential microphones have been in existence now for more than 50 years. One of the first variable beampattern microphones was the Western Electric 639B unidirectional microphone. The 639B was introduced in the early 1940's and had a six-position switch to select a desired first-order pattern. Unidirectional differential microphones are commonly used in broadcast and public address applications since their inherent directivity is useful in reducing reverberation and noise pickup, as well as feedback in public address systems. Unidirectional microphones are also used extensively in stereo recording applications where two directional microphones are aimed in different directions (typically 90 degrees apart) for the left and right stereo signals.

Configurations of four cardioid microphones oriented along the normal to the surfaces of a tetrahedron have been proposed and used in the past [1, 2]. The major differences between these past systems and the one described in this paper is the use of omnidirectional microphones embedded in a rigid sphere and the use of precise DSP calibration and control of the beamforming and steering of the multiple first-order microphone beams.

2. DERIVATION OF THE ARRAY

A first-order differential microphone has a general directional pattern E that can be written as

$$E(\phi) = \alpha + (1 - \alpha)\cos(\phi) \quad (1)$$

where ϕ is the angle relative to the microphone dipole-axis and typically $0 \leq \alpha \leq 1$, so the response is normalized to have a maximum value of 1 at $\phi = 0°$. The magnitude of Eq. 1 is the parametric expression for the "limaçon of Pascal" algebraic curve. The two terms in Eq. 1 can be seen to be the sum of an omnidirectional sensor (first-term) and a first-order dipole sensor (second term), which is the general form of the first-order array. Early unidirectional microphones such as the Western Electric 639A&B were actually constructed by summing the outputs of an omnidirectional pressure sensor and a velocity ribbon sensor (essentially a pressure-differential sensor) [3]. One implicit property of Eq. 1 is that for $0 \leq \alpha \leq 1$, there is a maximum at $\phi = 0$ and a minimum at an angle between $\pi/2$ and π. When $\alpha = 0.5$, the parametric algebraic equation has a specific form which is called a cardioid.

The past discussion has shown that by appropriately combining the outputs of a dipole ($\cos(\phi)$ directivity) microphone and an omnidirectional microphone, any general first-order pattern can be obtained. However, the main lobe response is always located along the dipole axis. What is really desired is to electronically "steer" the first-order microphone to *any* general direction in 4π space. The problem therefore hinges on the ability of forming a dipole whose orientation can be set to any general direction.

A dipole microphone responds to the acoustic spatial pressure difference between two closely-spaced points in space. (By "closely-spaced" it is meant that the distance between spatial locations is much smaller that the acoustic wavelength.) In general, to obtain the spatial derivative along any direction one only needs to take the dot product of the acoustic pressure gradient with the unit vector in the desired direction. For general dipole orientation in a plane, only three closely-spaced noncolinear spatial pressure signals are needed. For general steering in three-dimensions a minimum of 4 closely-spaced pressure signals are required. The vectors that are defined by the lines that connect the 4 spatial locations must span the three-dimensional space so that the spatial acoustic pressure gradient can be measured or estimated.

For an incident plane-wave sound field with acoustic wavevector $\mathbf{k}$, the acoustic pressure can be written as,

$$p(\mathbf{k}, \mathbf{r}, t) = P_o \exp^{j(\omega t - \mathbf{k} \cdot \mathbf{r})} \tag{2}$$

where $\mathbf{r}$ is the position vector relative to the defined coordinate system origin, P_o is the plane-wave amplitude and ω is the angular frequency, and $\mid \mathbf{k} \mid = \omega / c$ where c is the speed of sound. If a dipole is formed by subtracting two omnidirectional sensors spaced by a distance $d = 2a$ then the output $\Delta p(ka, \phi)$ is,

$$\Delta p(ka, \phi) = p(\mathbf{k}, \mathbf{r}_1, t) - p(\mathbf{k}, \mathbf{r}_2, t) = -2jP_o \sin(ka \cos \phi). \tag{3}$$

Note that for compactness the time harmonic dependence has been omitted and the complex exponential term $\exp^{-jkr \cos \phi}$ has been conveniently removed by chosing the coordinate origin at the center of the microphones. For frequencies where $kd << \pi$ we can use the small angle approximation: $\sin(\theta) \approx \theta$, resulting in a microphone that has the standard dipole directivity $\cos \phi$. Implicit in the formation of dipole microphone outputs is the assumption that the microphone spacing d is much smaller than the acoustic wavelength over the frequency of operation.

To form a general first-order pattern all that is needed is to combine the output of the "steered" dipole with that of an omnidirectional output. However, from Eq. 3 it can be seen that there are two problems. First, the dipole output has a first-order high-pass frequency response. It would therefore be necessary to either high-pass filter the flat frequency response of an omnidirectional microphone, or to place a first-order lowpass filter on the dipole output to make the response flat. One problem with this approach is the concomitant phase differences between the omnidirectional microphone and the filtered dipole or, the phase difference between the filtered omnidirectional microphone and the dipole microphone. Secondly, there is a factor of j in Eq.3. To compensate for the $\pi/2$ phase shift, either the output of the omnidirectional element, or the dipole, would have to be filtered by a Hilbert allpass filter, which is well known to be acausal and of infinite length. With the difficulties listed above, it would seem somewhat problematic to realize the general steerable first-order differential microphone. However, there is an elegant way out of this dilemma: by first forming forward and backward facing cardioid signals for each microphone pair and summing these two outputs, an omnidirectional output that is in-phase having an identical high-pass frequency response to the dipole, can be obtained as elaborated below.

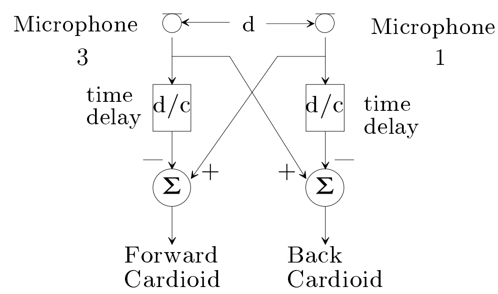

Figure 1: Diagram of combination of two omnidirectional microphones to obtain back-to-back cardioid microphones.

A simple modification of the differential combination of the omnidirectional microphones results in the formation of two outputs that have back-to-back cardioid beampatterns. The modification is to include a delay before the subtraction that is equal to the propagation time for sounds impinging along the microphone pair axis. The topology of this arrangement is shown in Figure 1 for one pair of microphones. To estimate the acoustic pressure gradient, one obvious realization is co-locate three orthogonal pairs of omnidirectional microphones along the cartesian axes. The forward cardioid microphone signals for the x-pair and y-pair and z-pair microphones can be written as,

$$\begin{aligned} C_{Fx}(ka, \phi) &= -2jP_o \sin[ka(1 + \cos \phi)] \\ C_{Fy}(ka, \phi) &= -2jP_o \sin[ka(1 + \sin \phi)] \\ C_{Fz}(ka, \theta) &= -2jP_o \sin[ka(1 + \sin \theta)] \end{aligned} \tag{4}$$

The back-facing cardioids can similarly be written by changing the sign of the second term in the brackets in Eqs 4.

If all forward and backward cardioids are averaged, the resulting output is,

$$E_{c-omni} = 1/6 \sum_{(x,y,z)} C_{F\{x,y,x\}} + C_{B\{x,y,z\}} \qquad (5)$$

For small ka, Eq. 5 has a frequency responses that is first-order highpass, and the directional patterns are that of an omnidirectional microphone. The subtraction of the forward and backward cardioids yield the desired dipole responses.

$$E_{\{x,y,z\}-dipole} = C_{F\{x,y,z\}} - C_{B\{x,y,z\}} \qquad (6)$$

The weighting for the x,y,z dipole signals to form a dipole steered to ψ in the azimuthal angle and χ in the depression angle are :

$$\mathbf{w} = \begin{bmatrix} \cos(\psi)\sin(\chi) \\ \sin(\psi)\sin(\chi) \\ \cos(\chi) \end{bmatrix} \qquad (7)$$

The steered dipole signal can therefore be written as,

$$E_d(\psi,\chi) = \mathbf{w}^T \cdot \mathbf{d} \qquad (8)$$

where,

$$\mathbf{d} = \begin{bmatrix} E_{x-dipole} \\ E_{y-dipole} \\ E_{z-dipole} \end{bmatrix} \qquad (9)$$

The synthesized first-order differential microphone is obtained by combining the steered-dipole and the omnidirectional microphone with the appropriate weightings for the desired first-order differential beampattern.

3. MICROPHONE REALIZATION

A six element microphone array was constructed to investigate the feasibility of realising a 4π steerable and controllable beampattern first-order differential microphone using standard inexpensive pressure microphones. For mechanical strength it was decided to install the six microphones flush with the surface of a small (3/4" diameter) hard nylon sphere. Another advantage to using the hard sphere is that the effects of diffraction and scattering from a rigid sphere are well known and easily calculated. For planewave incidence, the solution for the acoustic field variables can be written down in exact form (integral equation) and can be decomposed into a general series solution involving spherical Hankel functions and Legendre polynomials [4]. The acoustic pressure on the surface of the rigid sphere for an incident monochromatic planewave can be written for very small values of ka ($ka << \pi$) as,

$$p(ka,\theta) \approx P_o(1 + \frac{3}{2} jka\cos\theta) \qquad (10)$$

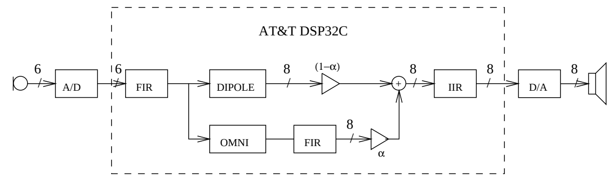

Figure 2: Block diagram of the DSP processing used to form an infinitely steerable first-order differential microphone.

where, θ is the rotation angle between the incident wave an the angular position on the sphere where the pressure is calculated and a is the sphere radius. One interesting observation that can be made in examining Eq. 10 is that the equivalent spacing between a pair of diametrically placed microphones for a planar sound wave incident along the microphone pair axis is $3a$ and *not* $2a$. This difference is important in the construction of the forward and backward cardioid signals.

4. DSP IMPLEMENTATION

A DSP (Digital Signal Processing) implementation was realized on an eight channel Signalogic Sig32C DSP-32C PC DSP board. The A/D and D/A converters can be externally clocked and this feature was a requirement since the sampling rate is set by the dimensions of the spherical probe. The size of the spherical baffle was chosen so that the frequency response of the microphone could exceed 5kHz and so that it could be made from existing materials. For a rigid spherical baffle of 0.75 inch (1.9 cm) diameter the time delay between opposing microphones is 83.31 microseconds. The sampling rate corresponding to a period of 83.31 microseconds is 12.003 kHz. This sampling rate is very close to one of the standard rates that is selectable on the Sig32C board. The individual microphone elements were Sennheiser KE4-211 omnidirectional elements. These microphones have an essentially flat frequency response up to 20 kHz (well beyond the designed operational frequency range of the differential microphone array). A functional block diagram of the DSP realization of the steerable first-order differential microphone is shown in Figure 2.

4.1. EXPERIMENTAL DATA

The first experiment was performed to determine the appropriate sampling rate so that the forward and back cardioids are appropriately formed. A simple measurement that can verify the sampling rate is the on-axis

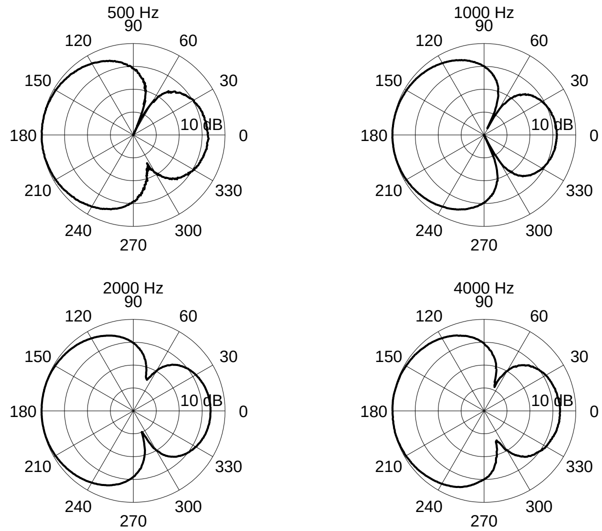

Figure 3: Measured hypercardioid beampatterns for 0.5, 1.0, 2.0, and 4.0 kHz.

frequency response of the synthesized dipole and omnidirectional microphones. If the microphones are accurately calibrated and the sampling rate is close to the diffraction time delay due to the rigid spherical baffle, then the dipole and omnidirectional responses should be very close. Measurements of the x, y, and z-pairs showed good matching ($\pm$ 1 dB) in frequency responses between the dipoles and the synthesized omnidirectional response. Figure 3 shows the measured hypercardioid beampatterns (α=0.25). The measured data that have been shown above are essentially from a single pair of microphones ("z-pair").

As a final series of plots, Figure 4 shows the measured beampatterns for a 30° steered first-order microphone with various beampatterns measured at 1.5 kHz. The beampatterns were measured sequentially and combined onto a single polar axes plot. The patterns were generated by varying α (Eq. 1) to give beampatterns between dipole and cardioid with nulls varying in roughly 10° increments. This variation is obtained by varying α between 0 and 0.5. The 3 dB beamwidth variation in Figure 4 is approximately from 90° to 130° For values of $0.5 \leq \alpha \leq 1.0$, the beamwidth moves from 130° to 360°.

5. CONCLUSIONS

An infinitely steerable first-order differential microphone constructed from inexpensive pressure microphones has been described. The synthesized beampattern is also infinitely variable within the constraints of first-order differential microphone realizations. A minimum of three pressure microphones are required to steer in 2-D and four microphones to steer in 3-D.

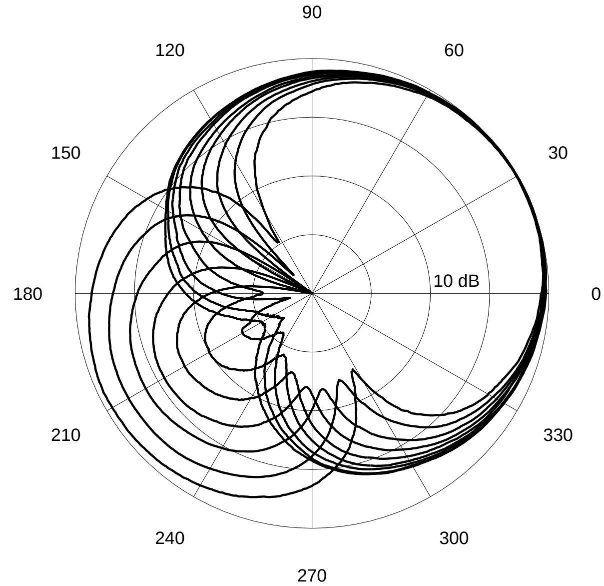

Figure 4: Measured beampatterns at 1.5 kHz for various synthesized first-order differential microphones steered to 30° .

Preliminary listening tests using six synthesized cardioid beams steered in 60 degree intervals in a plane indicate that the microphone can be used to generate realistic surround sound fields. Further work is planned to investigate the usefulness of the microphone array processing described here to virtual sound field applications.

6. REFERENCES

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