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MICROPHONE ARRAYS USING TANGENTIAL VELOCITY SENSORS

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Abstract: *We introduce a new class of 3D microphone arrays that use symmetrical arrangements of tangential velocity sensors. Use of velocity sensors allows these arrays to recover spherical harmonics of a given degree with less low-frequency boost than when using pressure sensors only. As an example we present a symmetrical array of twelve velocity sensors that resolves the eight harmonics of degrees 1 and 2. A second-order spherical microphone can now be constructed by combining this array with one or more pressure sensors that provide the missing harmonic of degree 0.*

Key words: microphone array, dipole sensors, regular polyhedra, spherical harmonics

1 INTRODUCTION

Following its invention in the 1970s, the Ambisonic Soundfield Microphone [1] was for many years the only microphone capable of single-point 3-D capture of a sound field, and then only with first order directional resolution. Recently there has been much interest in producing a second-order or higher-order successor (see for example [2], [3], [4], [5] and [6]), several of the recent designs being based on a 1975 paper by Gerzon [7] which proposed spherical arrays of microphone capsules to sample the sound field at points arranged in a good 'integration rule' on the sphere.

However while mathematically elegant, there appear to be practical difficulties in implementing the 'integration rule' approach. After explaining some of the problems, we propose the use of dipole[1] sensors mounted tangentially on the surface of a sphere, in order to recover first and higher degree[2] spherical harmonics. We present and analyse several symmetrical arrays of this type.

2 ENHANCING DIRECTIVITY

A fundamental problem that besets the designer of a high-order microphone is that while pressure sensors provide the zero-degree component ("W") of a sound field, and velocity sensors can provide the three first degree components ("X", "Y", "Z"), we know of no physical principle that directly retrieves a spherical harmonic of second or higher degree.

A method of obtaining a second order response by differencing the outputs of two closely-spaced first-order sensors was disclosed in Blumlein's 1936 patent [8]. The differencing incurs a 6dB/8ve loss of low frequencies however, thus requiring bass boost in an equalizer (shown as a passive shelf filter in Blumlein's patent).

The 'Blumlein Difference Technique' can be applied repeatedly but each time the order of response is increased by one, a further 6dB/8ve boost is needed. This result applies equally to the capsule arrays considered by Blumlein and to the spherical arrays that have been considered recently.

The "integration rule" principle as given by Gerzon [7] can be summarized as follows. The outputs of a spherical array of pressure sensors are firstly given a weighting as prescribed by the integration rule. (The weights may be all equal in the case of a completely symmetrical array.) A degree zero ("W") directional output is obtained simply by taking the sum of the weighted sensor outputs. A harmonic output of first or higher degree is obtained by applying to each weighted sensor output a further weighting proportional to the value of the harmonic at the sensor, before summing the weighted sensor outputs. This will produce an output having the correct directionality (subject to the integration rule being good enough) but deficient in bass. An *n*th degree harmonic obtained in this way requires equalization (bass boost) of, asymptotically, $6\times n$ dB/8ve. Figure 1 (taken from Gerzon [7]) shows a signal processing structure for a first-order microphone, the "Matrix" implementing the weighted summations referred to above.

[1] Also known as "velocity", "pressure gradient" or "figure-of-eight" sensors.

[2] We use the term "degree" in relation to an individual harmonic, and "order" to refer to the maximum degree of harmonic that is retrieved by a microphone that may retrieve harmonics of several different degrees.

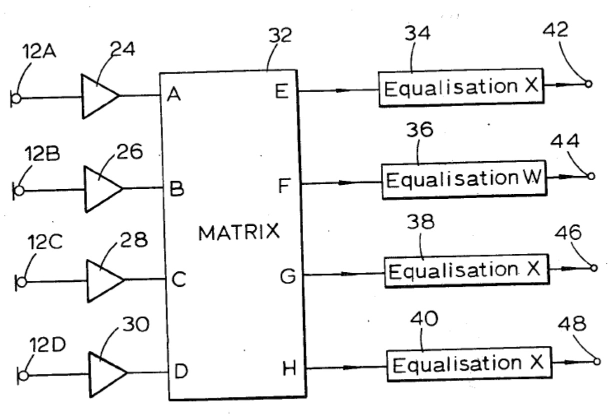

Figure 1: Extraction of harmonics from a spherical array (from Gerzon [7]).

3 SPHERICAL ARRAY OPTIONS

The need for, for example, a 12dB/8ve bass boost in order to produce a second order output from pressure sensors makes it difficult to construct a studio quality microphone using the principle just described [2].

A larger sphere radius lowers the 'knee' frequency below which boost must be applied, and so lowers the total amount of boost. However, larger spheres will result in anomalies at high frequencies (roughly, frequencies at which the spacing between adjacent capsules is comparable with a wavelength) and in practice the boost will be required over most of the audio frequency range.

As the signals to be boosted are obtained using a matrix that subtracts larger but nearly equal signals, the requirement to boost not only increases noise but also magnifies modulation noise and nonlinear effects, and makes capsule matching extremely critical [2].

If first order capsules can be used in place of pressure sensors, then the required boost is reduced by 6dB/8ve, so now is 'only' 6dB/8ve for a second order output (c.f. figure 1 of [4]).

First order capsules are directional, and it would be natural to point the directional capsules radially outwards from the centre of the sphere. This however raises the question of whether the sphere exists physically and is solid, or whether the microphones are in an 'open' arrangement on the surface of a conceptual sphere.

Equalisations for the solid sphere and for the open (or 'free field') spherical arrangement have been quoted in [2], [4], [6] and several other recent publications. It can be shown that the equalization for the solid sphere takes the form of simple analogue filters: [3]

Degree 0	$s + 1$
Degree 1	$s + 2 + 2/s$
Degree 2	$s + 4 + 9/s + 9/s^2$

where the Laplace transform variable s is scaled appropriately.[4,]

The unequalised response of degree 2 is a cascade of a first-order HF rolloff and a 2nd order LF rolloff with a Q of 1.01. The corresponding time response is thus well damped. This contrasts with the open sphere case, in which the HF response has 'wiggles', caused by a discrete event in the unequalised impulse response corresponding to the propagation time for an impulse to cross the diameter of the sphere. These wiggles are minimized by the use of cardioid capsules ([4], [6]) but are nevertheless visible in plots such as figure 1 of [4], and cannot of course be equalized exactly by simple analogue means.

Another problem to be faced with the open sphere is that capsules are not in practice acoustically transparent, so an analytic treatment is much more complicated and one may need finite element techniques to solve the acoustic scattering problem. Moreover a reasonably dense spherical array of non-transparent capsules is in danger of creating a cavity resonance with the volume of air within the sphere, requiring very precise equalization if the audio transient response is not to be adversely affected.

Can cardioid capsules be mounted on the surface of a solid sphere, pointing radially outwards? Yes one can mount them so, but they then cease to have a cardioid response! A cardioid capsule senses a combination of pressure and velocity. The radial component of velocity is however constrained to be zero by the solid surface, so capsules that have a cardioid when in free space become equivalent to pressure sensors when mounted radially on a spherical surface.

On balance the authors see advantages in using a solid sphere. As discussed, we also wish to make use of the velocity sensitivity of first order sensors in order to reduce the need for bass boost. If the radial component of velocity is constrained to be zero on the surface of a solid sphere, we are led to consider orientating the sensors to respond to tangential velocity. That is, the sensors point in directions parallel to the surface rather than radially outwards.

4 SYMMETRY

For a small number of pressure sensors it has seemed sensible to make use of the symmetries of the Platonic solids, i.e. tetrahedral, cubic (or octahedral) and

[3] These analogue equalizations are exact, and can be derived from the more complicated expressions usually quoted that use spherical Bessel functions and/or Hankel functions. They were known in 1896 to Lord Rayleigh, who derived them in relation to the dual (or reciprocal) problem of sound radiating from a spherical surface, with angular dependence given by spherical harmonics. See [9] §323.

[4] I.e. the unit of time is taken as the time taken for sound to travel a distance equal to the radius of the sphere.

dodecahedral (or icosahedral) symmetry. as this can reduce the number of sensors required for a given performance. For example, if one adds together the outputs of twelve pressure sensors mounted at the centres of a faces of a dodecahedron, a zeroth-order "W" signal is recovered with no contamination from any incident harmonics of degree one through five. To achieve the same result by solving simultaneous equations on the outputs of a 'random' array, at least thirty-six sensors would in general be required.

If the thirty-six (or more) randomly placed sensors were recessed into the surface of a sphere, so that they had no effect on the sound field, it would be simple to derive the equations that would need to be solved in order to isolate the different harmonics. However if the sensors do present significant acoustic obstruction, a non-symmetrical array requires sophisticated analysis; alternatively the relevant equations may be determined empirically by measurement. Whichever method is used, the derivation has to be repeated for each frequency.

In contrast, if symmetry arguments can be used to isolate the different harmonics, then capsules presenting real acoustic obstruction can be used, provided that the underlying symmetry of the array is not broken. The matrix (in figure 1) required to separate the different harmonics is independent of frequency, only the equalizations being dependent on the precise acoustic behaviour of the capsules. Moreover, one needs a separate equalization only for each degree of harmonic, not for each individual harmonic. Thus, for a second order microphone, only three different equalizations need to be determined.

How then can we make use of symmetry with velocity sensors ? If one could use an 'XY' sensor, i.e. a sensor having uniform two-dimensional sensitivity within the plane tangent to the surface of the sphere, the symmetry would be retained. However a conventional velocity sensor, such as a figure-of-eight microphone, has a preferred axis, and placing such sensors at the centres of the faces of a regular polyhedron would destroy the polyhedral symmetry.

Accordingly, the authors have proposed [10] that each capsule be associated with an edge rather than with a face or a vertex of a polyhedron, the edge providing a natural direction so that the directional sensors need not break the symmetry.

5 EDGE MOUNTED SENSORS

As the regular tetrahedron is the simplest platonic solid, we start by considering velocity sensors whose directions are aligned with the six edges of a regular tetrahedron. The arrangement is indicated in figure 2, the thin lines therein indicating the correspondence between each edge and its respective sensor. Each sensor is shown as a thin disc, suggestive of the diaphragm of a capacitor figure-of-eight microphone, so that the axis along which it senses velocity is in a direction perpendicular to the plane of the disc. As shown, the sensor is orientated such that the plane of the disc includes the corresponding edge of the tetrahedron, so the axis direction is perpendicular to the edge.

A variation is to mount the sensors so their axis directions are parallel to the respective edges of the tetrahedron or other reference polyhedron. Such a parallel arrangement is equivalent to a perpendicular arrangement using the dual polyhedron, but as the regular tetrahedron is self-dual, the perpendicular and parallel orientations are equivalent in this case.

The polyhedron need not exist physically of course, instead merely acting as a reference, and in accordance with previous reasoning the capsules might be mounted on the surface of a sphere enclosing the polyhedron.

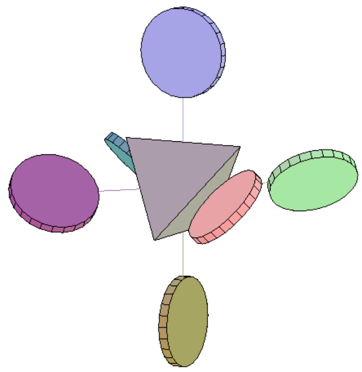

Figure 2: Sensors on the edges of a tetrahedron

6 SPHERICAL HARMONIC PERFORMANCE

We now consider the response of the array of figure 2 to a sound field whose pressure is expressed as a sum of spherical harmonics on a solid sphere on which the capsules are mounted. Table 1 lists the nine harmonics of degree up to two, normalized to unit power averaged over the sphere and labelled W', X', Y', Z', R', S', T', U' and V'. For brevity we shall now drop the primes, which have been used in table 1 to indicate that the normalization is different from that proposed by Furse and Malham [11]. The expression given for pressure is valid only on the surface of the unit sphere $x^2 + y^2 + z^2 = 1$. Also shown is the pressure gradient, corresponding to the fact that a velocity sensor is equivalent to a pressure gradient sensor with an internal bass boost. Again, only the tangential component of gradient has validity in the current context, because the radial component is constrained to be zero on the surface of the sphere.

Deg	Sym	Pressure ϕ	Gradient $\left(\frac{\partial}{\partial x}\phi, \frac{\partial}{\partial y}\phi, \frac{\partial}{\partial z}\phi\right)$
0	W'	1	$(0, 0, 0)$
1	X'	$\sqrt{3}\, x$	$(\sqrt{3}, 0, 0)$
	Y'	$\sqrt{3}\, y$	$(0, \sqrt{3}, 0)$
	Z'	$z\sqrt{3}$	$(0, 0, \sqrt{3})$
2	R'	$\frac{\sqrt{5}\,(3z^2-1)}{2}$	$(0, 0, 3z\sqrt{5})$
	S'	$\sqrt{15}\, x\, z$	$(\sqrt{15}\, z, 0, \sqrt{15}\, x)$
	T'	$\sqrt{15}\, y\, z$	$(0, \sqrt{15}\, z, \sqrt{15}\, y)$
	U'	$\frac{\sqrt{15}\,(x^2-y^2)}{2}$	$(\sqrt{15}\, x, -\sqrt{15}\, y, 0)$
	V'	$\sqrt{15}\, x\, y$	$(\sqrt{15}\, y, \sqrt{15}\, x, 0)$

Table 1 Spherical harmonic values and gradients

With suitable choice of coordinate axes and numbering of the capsules shown in figure 2, we can now tabulate the positions and the capsules and the direction cosines of the axes for the capsules, as shown in table 2

Capsule #	Position *x, y, z*	Direction cosines *u, v, w*
1	0, 1, 0	$-\frac{\sqrt{2}}{2}, 0, \frac{\sqrt{2}}{2}$
2	0, 0, 1	$\frac{\sqrt{2}}{2}, -\frac{\sqrt{2}}{2}, 0$
3	1, 0, 0	$0, \frac{\sqrt{2}}{2}, -\frac{\sqrt{2}}{2}$
4	0, 0, -1	$\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}, 0$
5	-1, 0, 0	$0, \frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}$
6	0, -1, 0	$-\frac{\sqrt{2}}{2}, 0, -\frac{\sqrt{2}}{2}$

Table 2 Capsule positions and axis directions

By taking scalar products of the direction cosines in table 2 with the pressure gradients in table 1, we can derive the responses $resp_1$ $resp_2$, … $resp_6$ of the six capsules as:

$$\begin{bmatrix} resp_1 \\ resp_2 \\ resp_3 \\ resp_4 \\ resp_5 \\ resp_6 \end{bmatrix} = A \,.\begin{bmatrix} w \\ x \\ y \\ z \\ r \\ s \\ t \\ u \\ v \end{bmatrix}$$

where

$$A = \begin{bmatrix}
0 & 0 & -\frac{\sqrt{6}}{2} & -\frac{\sqrt{6}}{2} & 0 & -\frac{\sqrt{15}\sqrt{2}}{2} & 0 & 0 & -\frac{\sqrt{15}\sqrt{2}}{2} \\
0 & -\frac{\sqrt{6}}{2} & \frac{\sqrt{6}}{2} & 0 & 0 & \frac{\sqrt{15}\sqrt{2}}{2} & -\frac{\sqrt{15}\sqrt{2}}{2} & 0 & 0 \\
0 & 0 & -\frac{\sqrt{6}}{2} & \frac{\sqrt{6}}{2} & 0 & -\frac{\sqrt{15}\sqrt{2}}{2} & 0 & 0 & \frac{\sqrt{15}\sqrt{2}}{2} \\
0 & -\frac{\sqrt{6}}{2} & 0 & -\frac{\sqrt{6}}{2} & 0 & 0 & -\frac{\sqrt{15}\sqrt{2}}{2} & 0 & -\frac{\sqrt{15}\sqrt{2}}{2} \\
0 & -\frac{\sqrt{6}}{2} & -\frac{\sqrt{6}}{2} & 0 & 0 & -\frac{\sqrt{15}\sqrt{2}}{2} & -\frac{\sqrt{15}\sqrt{2}}{2} & 0 & 0 \\
0 & -\frac{\sqrt{6}}{2} & 0 & \frac{\sqrt{6}}{2} & 0 & 0 & -\frac{\sqrt{15}\sqrt{2}}{2} & 0 & \frac{\sqrt{15}\sqrt{2}}{2}
\end{bmatrix}$$

Of course, we cannot expect six capsules to resolve nine independent harmonics, so it is unsurprising to see some linear dependencies, or even zero columns, in this matrix A. The first column indicates zero response to W, as would be expected with velocity sensors only. The fifth and eighth columns indicate a zero response to the second-degree harmonics R and U. Further inspection shows that the response to S (sixth column) is a scaled copy of the response to Y (third column), and similarly with T and X, and with V and Z. So though we are considering nine linearly independent excitations, we receive only three linearly independent outputs from these six capsules !

Therefore no second degree harmonics can sensibly be retrieved from this array; and the retrieved first degree harmonics X, Y and Z will be contaminated by second degree harmonics.

Retrieval and contamination can be assessed more readily by inspection of the matrix A^TA:

$$A^T A = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 6 & 0 & 0 & 0 & 0 & 6\sqrt{5} & 0 & 0 \\
0 & 0 & 6 & 0 & 0 & 6\sqrt{5} & 0 & 0 & 0 \\
0 & 0 & 0 & 6 & 0 & 0 & 0 & 0 & 6\sqrt{5} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 6\sqrt{5} & 0 & 0 & 30 & 0 & 0 & 0 \\
0 & 6\sqrt{5} & 0 & 0 & 0 & 0 & 30 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 6\sqrt{5} & 0 & 0 & 0 & 0 & 30
\end{bmatrix}$$

This matrix can be considered to represent a straightforward attempt to recover each harmonic by taking the scalar product of the array output with the output that obtains when the array is excited by that harmonic alone. The diagonal elements in A^TA represent the strengths of the recovered harmonics, while the off-diagonal elements represent contamination from 'unwanted' harmonics when this is done.

The contamination can be eliminated if the capsules are given a 'twist' of 45 degrees, i.e. rotated to a direction midway between the parallel and perpendicular orientations discussed earlier, as shown in figure 3. The direction of twist may be chosen as clockwise or anticlockwise, but should be consistent between the capsules.

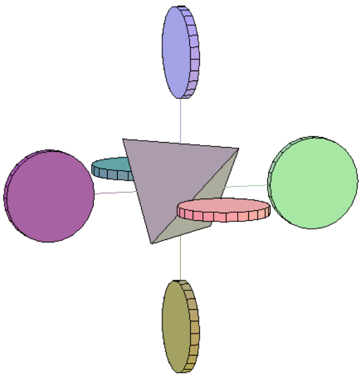

Figure 3: Tetrahedral arrangement with 'twist' of 45°

With this arrangement, the matrix $A^T A$ becomes:

$$A^T A = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 6 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 6 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 30 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 30 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 30 \end{bmatrix}$$

The diagonal elements with value '6' represent the response to the first-degree harmonics X, Y and Z, while those with value '30' represent the response to the second-degree harmonics S, T and V. The array is 'blind' to harmonics R and U. The absence of off-diagonal elements indicates lack of contamination between first and second-order harmonics.

An alternative interpretation of figure 3 is that the capsules lie at the centres of the faces of a cube. However the arrangement does not have hexahedral (cubic) symmetry when the directionality of the capsules is taken into account.

We now consider arrangements that are based on the cube as a reference polyhedron. Figure 4 shows cubical arrangements of twelve sensors, using perpendicular (top) and parallel (bottom) alignment of capsule axes relative to the edges of the cube. (These are equivalent to, respectively, parallel and perpendicular arrangements relative to the twelve edges of a regular octahedron.)

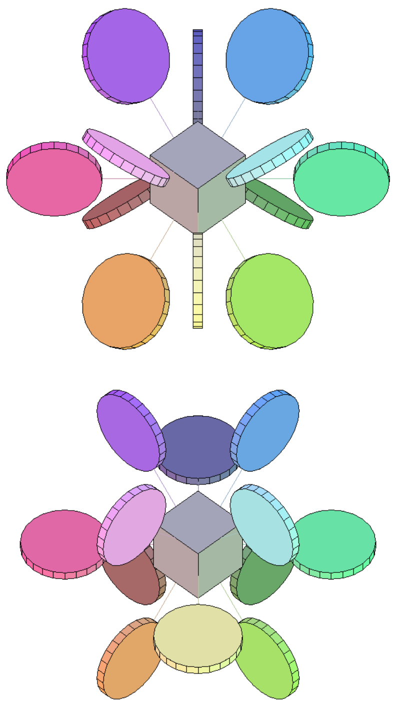

Figure 4: Sensors on the edges of a cube

With twelve capsules we might hope to resolve all eight harmonics of first and second degrees, but on computing $A^T A$ for these two arrays, we find, respectively,

$$A^T A = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 12 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 12 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 12 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 60 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 60 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 60 \end{bmatrix}$$

and

$$A^T A = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 12 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 12 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 12 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 90 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 90 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

In each case the three diagonal entries with the value "12" refer to the first-degree sensitivity (showing a 3dB better signal-to-noise ratio than the arrangement of figure 3). The other diagonal entries indicate that the perpendicular arrangement "sees" only the S, T and V second order components, while the parallel arrangement concentrates the same total amount of second degree energy sensitivity (180 units) into the R and U components.

Energy sensitivity can be distributed evenly between the second degree components by twisting the capsules by an angle $\tan^{-1}(\sqrt{(2/3)}) = 39.2°$, as shown in figure 5.

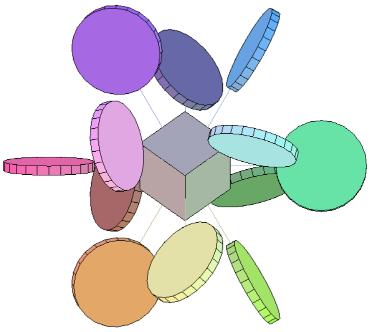

Figure 5: Sensors on the edges of a cube, with 'twist'

On recalculating matrix $A^T A$ we now obtain:

$$A^T A = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 12 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 12 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 12 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 36 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 36 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 36 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 36 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 36 \end{bmatrix}$$

confirming that an elegant compromise between the two previous situations has indeed been found, the first and second degree harmonics being resolved unambiguously, i.e. without contamination in either direction.

Analysis to third degree reveals some contamination of the retrieved second degree harmonics from third degree harmonics. However, the first degree harmonics X, Y and Z are retrieved without third degree contamination, unlike with the arrangements previously discussed. (Such third degree contamination is typically manifest as 'beaming', i.e. sharpening of nominal figure-of-eight polar patterns at high frequencies.) We would thus expect that the arrangement of figure 5 could provide the basis for a first-order microphone with a performance very substantially better than current tetrahedral designs (which suffer from second-degree as well as third-degree contamination).

7 RETRIEVING 'W'

As noted, the arrays described so far do not provide a degree zero or 'W' output. We propose therefore to augment these arrays with one or more pressure sensors. Ideally, symmetry should be preserved, and accordingly we advocate that a symmetrical arrangement of pressure sensors should be incorporated into the surface of the solid sphere. This is shown in figure 6, which is like figure 5 but with the reference cube enveloped by a sphere, on the surface of which the black dots represent pressure sensors, each sensor being placed centrally with respect to a face of the (hidden) reference cube, so there are six pressure sensors altogether.

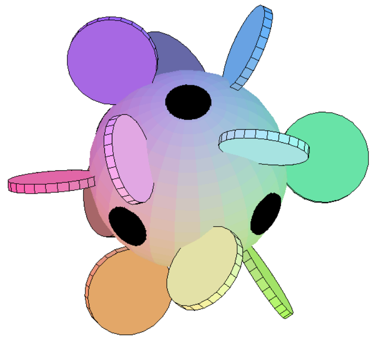

Figure 6: Velocity and pressure sensors on a sphere.

A zeroth degree output ('W') can be obtained by adding together the outputs of all six pressure sensors. This output will be uncontaminated by harmonic components of degrees one, two and three.

8 DODECAHEDRAL SENSOR ARRANGEMENT

Arrays with larger numbers of capsules can of course be used, for example as shown in figure 7.

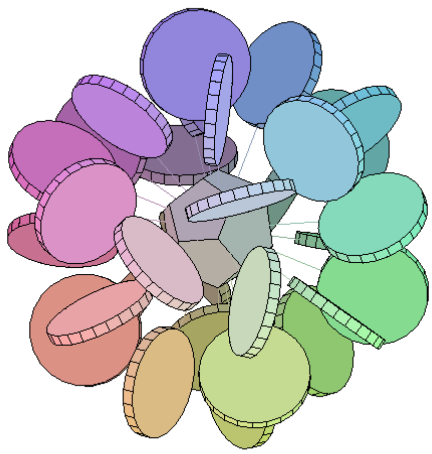

Figure 7: Dodecahedral arrangement, with "twist".

Such a dodecahedral arrangement of 30 sensors provides correct recovery of second degree harmonics, irrespective of whether a parallel or a perpendicular orientation of the sensors is used. A twist is preferred however, the optimal twist being 35.69° relative to the perpendicular orientation. Using the simple and completely stable numerical method (of taking scalar products of sensor directions with computed pressure gradients) outlined in section 6, this arrangement then provides:

- correct recovery of all 15 harmonics of degrees 1, 2 and 3
- if restricted to degrees 1 and 2, recovery of the eight harmonics of these degrees with zero contamination from degrees 3 and 4

Further, a slightly different numerical inversion method, still numerically stable (inverting a matrix having eigenvalues within a factor 2.2 of each other) can recover all 24 harmonics of degrees 1, 2, 3 and 4, thus making highly 'efficient' use of the information from the 30 capsules.

9 COMPLETE STUDIO MICROPHONE

Combining the 'W' retrieval method with one of the velocity sensor arrays described above, a complete studio-quality microphone of first, second or higher order can be assembled, the processing being as shown in figure 8.

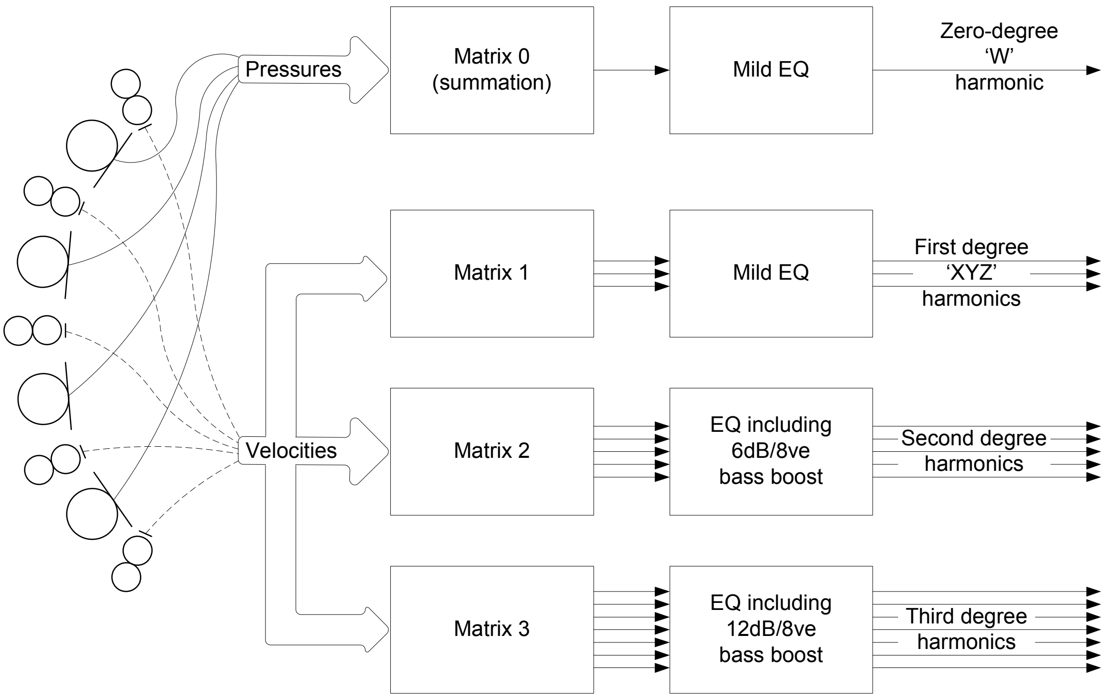

Figure 8: Microphone array processing

Although this is not the only possibility, figure 8 shows the simplest case where the pressure sensors within the array are used exclusively to provide the "W" output of degree zero, while the velocity sensors are used exclusively to provide the outputs of degree one and higher. In the case that the pressure sensors are arranged in a symmetrical array, the "Matrix 0" processing to provide the zero-degree harmonic will generally be simple summation.

As noted, there is one equalization characteristic required for each degree of harmonic. This equalization may be determined empirically or, if the sensors are considered not to present significant acoustic obstruction and are mounted on the surface of a solid sphere, calculated analytically as detailed earlier.

10 CONCLUSION

We have proposed the use of dipole (= "velocity", "pressure gradient" or "figure-of-eight") sensors as a means to reduce the bass boost required in providing second-order or higher-order capture of a sound field at a point.

We have displayed several suitable symmetrical arrangements of dipole sensors, based on alignment relative to the edges of a regular reference polyhedron. We have advocated that these sensors be mounted on or close to the surface of a solid sphere.

We have shown an arrangement of twelve velocity sensors and six pressure sensors having hexahedral/octahedral[7] symmetry that can provide a first-order microphone of extremely high quality, with no bass boost required and complete freedom from 'beaming' at high frequencies caused by contamination from third degree components of the sound field.

This arrangement of twelve sensors can also be used to provide a second-order microphone, with only 6dB/8ve bass boost required.

[7] Or, acknowledging the twist, chiral octahedral symmetry.

We have also shown a dodecahedral arrangement of thirty velocity sensors that can be used as the basis of an extremely high quality second-order microphone that is free from contamination from harmonics of degrees three and four. The same arrangement can also be used as the basis of a third-order or a fourth-order microphone.

Practical details that are needed in order to build such a microphone, such as the size of the sphere and the specifications of the individual sensors, have not been addressed in this paper and are under consideration by the authors.

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