

APPLICATIONS OF BLUMLEIN SHUFFLING TO LEFT/RIGHT DISCRIMINATION IN TOWED ARRAYS

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ABSTRACT

In 1931 Blumlein proposed using a pair of identical ear-spaced microphones pointing in the same direction with a "shuffling" network to create stereo. Although Blumlein shuffled stereo techniques have not to date been used commercially, one of their advantages that makes them potentially attractive in towed array applications is the ability to form cardioid-like directivity patterns from a pair of closely spaced sensors that are frequency-independent. This makes it possible to achieve left/right discrimination with two hydrophones within the width of a conventional towed array hose, but without the disadvantages of loss of sensitivity and low frequency roll-off normally associated with classical cardioid-forming methods. This paper explains the straightforward theory behind the technique and presents experimental results confirming that the theory can be realised in practice.

1. INTRODUCTION

The advantages of towed arrays are well known, and with the low operating frequencies currently envisaged for both active and passive sonars they constitute almost the only option for the receiving array. Towed arrays, however, suffer from one major drawback: a simple line array is one dimensional and it cannot distinguish between targets on either side of the towing direction. There are a number of potential solutions, but the most promising use a pair of transversally separated hydrophones per receiving element to obtain left/right directivity. These hydrophone pairs may be enclosed in a single array hose, or may be in the form of a number of arrays towed in parallel.

The outputs the sensor pairs can be combined to provide various directivity patterns, and such techniques are common in radio antenna and stereo microphone technologies. In the present case it is required to produce two outputs, one of which rejects signals arriving from the left, and the other from the right. The classical approach to achieving this [1] is to delay one sensor output and subtract it from the other to obtain cancellation in a direction determined by the delay. The disadvantage of this method is that the response is frequency dependent and, in particular, falls at 6dB/octave as frequency is reduced below the point where the sensor separation is a quarter wavelength.

2. BLUMLEIN SHUFFLING

The loss in sensitivity intrinsic in this process may be overcome by borrowing an alternative technique from the field of audio engineering [2], based on Blumlein's original stereo patent [3].

The basic concept, called shuffling in the audio literature, is shown in Figure 1. Two signals, V_1 and V_2 , are converted by a $\Sigma\Delta$ or sum-and-difference matrix into the form of a sum or Σ signal and a difference or Δ signal. The two signals Σ and Δ are passed through non-identical filters to give Σ' and

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Δ' and then converted back into left-right form by a second $\Sigma\Delta$ matrix, producing modified signals L_0 and R_0 at the output.

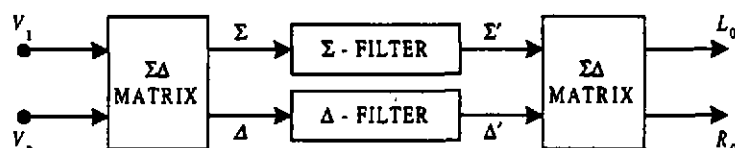


Figure 1: General Blumlein shuffler.

The $\Sigma\Delta$ matrix is defined in a way that both forms its own inverse, and also preserves the total energy in the signals, as follows:

$$\Sigma = \frac{1}{\sqrt{2}}(V_1 + V_2) \quad \Delta = \frac{1}{\sqrt{2}}(V_1 - V_2) \quad (1)$$

3. A BLUMLEIN SHUFFLER CARDIOID PROCESSOR.

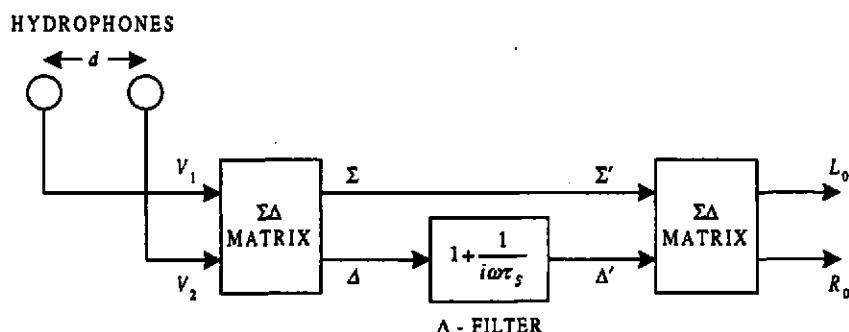


Figure 2: Blumlein shuffler configured as a cardioid processor.

The amplitude and phase responses of the filters in the shuffler both affect the outputs. In general phase shifts in the Δ channel have the effect of converting phase differences in the input signals to amplitude differences at the output, and vice versa, and this phenomenon can be exploited for the present application using the configuration shown in Figure 2. In this arrangement the Σ channel is unfiltered, but the Δ channel is modified by a filter with time constant τ_s and transfer function

$$h(\omega) = 1 + \frac{1}{i\omega\tau_s} \quad (2)$$

where $\omega = 2\pi f$, and f is frequency. This particular filter was chosen for the original stereo configuration because it is easily implemented as a simple passive RC network. Better transfer functions may be found for the present application.

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3.1 Signal response and low frequency approximation.

Consider sinusoidal signals arriving at the two hydrophones with a time of arrival difference of T . The complex amplitudes of these two signals may be written as

$$V_1 = \exp(\tfrac{1}{2}i\omega T) \quad V_2 = \exp(-\tfrac{1}{2}i\omega T) \quad (3)$$

and, noting that $\exp(ix) = \cos x + i\sin x$, the Σ and Δ signals are then

$$\Sigma = \sqrt{2}\cos(\tfrac{1}{2}\omega T) \quad \Delta = \sqrt{2}i\sin(\tfrac{1}{2}\omega T) \quad (4)$$

These expressions may be expanded as power series to give

$$\Sigma = \sqrt{2} \left[1 - \tfrac{1}{2}(\tfrac{1}{2}\omega T)^2 + \dots \right] \quad \Delta = \sqrt{2}i \left[(\tfrac{1}{2}\omega T) - \tfrac{1}{6}(\tfrac{1}{2}\omega T)^3 + \dots \right] \quad (5)$$

For low frequencies, if $\omega T \ll 1$, second order terms and higher may be neglected and, multiplying the Δ signal by the filter transfer function $h(\omega)$, Σ' and Δ' become

$$\Sigma' = \sqrt{2} \quad \Delta' = \sqrt{2} \left(\frac{T}{2\tau} + \tfrac{1}{2}i\omega T \right) \quad (6)$$

The output signals are then simply

$$L_0 = 1 + \frac{T}{2\tau_s} \quad R_0 = 1 - \frac{T}{2\tau_s} \quad (7)$$

Finally, assume a standard array configuration with the two hydrophones nominally horizontal and normal to the line of the array, and let θ represent bearing measured from the tow ship direction, then the delay between the hydrophones is just $T = (d/c)\sin\theta$, and the low frequency outputs become

$$L_0 = 1 + \frac{d}{2c\tau_s}\sin\theta \quad R_0 = 1 - \frac{d}{2c\tau_s}\sin\theta \quad (8)$$

These expressions will be recognised as cardioid-like directivity patterns. They are exact cardioids if $\tau_s = d/2c$, or else the nulls in the pattern can be steered to an angle ϕ relative to the line of the two sensors by setting $\tau_s = d \cos\phi / 2c$. It is also noted that these expressions are frequency independent.

3.2 Conventional cardioid process response

For comparison, it may be shown that if the same low frequency approximations are used, the outputs of a conventional delay and subtract cardioid processor, with a delay τ_c , can be written as

$$L_c = \omega\tau_c \left(1 + \frac{d}{c\tau_c}\sin\theta \right) \quad R_c = \omega\tau_c \left(1 - \frac{d}{c\tau_c}\sin\theta \right) \quad (9)$$

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Two points are immediately apparent:

- If the time constants are chosen so that $\tau_c = 2\tau_s$, then the directivity patterns of the existing cardioid and the shuffler implementation are identical in shape, with nulls steerable by varying τ_s (or τ_c) and an exact cardioid when $\tau_s = d/2c$.
- The signal output of the conventional cardioid is proportional to frequency (ie rises at 6dB/octave), whereas the output of the shuffler circuit is constant and at broadside equal to twice the output from one hydrophone.

The approximate and exact responses in the direction of maximum sensitivity of both the shuffler network and the conventional cardioid are plotted in Figure 3 against frequency normalised relative to quarter wave spacing ($f_0 = c/4d$). It is immediately apparent that both approximations agree well with the exact calculations up to a frequency of about $f_0/2$. Secondly, below this frequency the shuffler response is constant at 6dB above the output from a single hydrophone, whereas the conventional cardioid falls rapidly as frequency reduces.

This loss of sensitivity at low frequencies may well cause problems with maintaining dynamic range and an adequate signal to noise ratio throughout the system. With this in mind, the effect of these networks on noise at the input terminals must be considered.

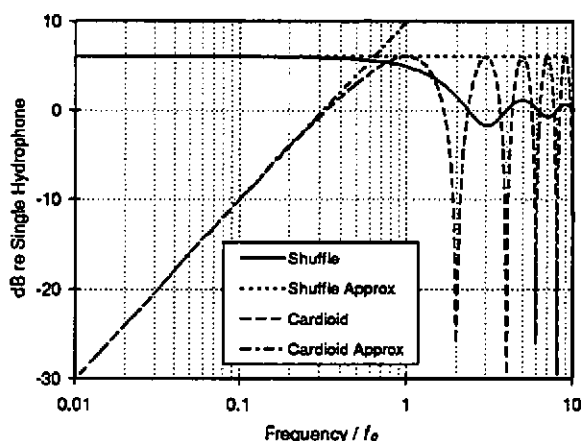


Figure 3: Shuffler response compared with conventional cardioid, plotted against frequency normalised relative to quarter wave spacing.

3.3 Noise response

Noise response may be modelled following the approach used by Urick [4] to calculate array gain. The array output depends upon the crosscorrelation coefficients of signal or noise between each of the elements of the array. For an architecture where the output can be represented as the weighted sum of the delayed element outputs this can be expressed as:

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$$V_o = V_I \sqrt{\sum_{m=1}^N \sum_{n=1}^N A_m A_n \rho_{mn}} \quad (10)$$

where V_o is the rms output, V_I is the rms voltage at the hydrophone terminals (assuming it is the same for both hydrophones), A_m is the (amplitude) weighting coefficient of the m th element and ρ_{mn} is the crosscorrelation coefficient between element m and element n . The correlation coefficient ρ must include any time delays or phase shifts in the network, and generally $\rho_{mn} = 1$ if $m = n$.

By inspection of the shuffler network diagram, Figure 2, the (left) output may be written in a suitable form as

$$V_o = V_1 - \frac{i}{2\omega\tau_s} V_1 + \frac{i}{2\omega\tau_s} V_2 \quad (11)$$

The expression $i/2\omega\tau$ has a magnitude $1/2\omega\tau$ and a constant phase shift of $\pi/2$. Thus, representing the three terms in Eq(11) as three virtual elements gives $A_1 = 1$, $A_2 = -1/2\omega\tau$ and $A_3 = 1/2\omega\tau$ so, from Eq(10) and with some manipulation, the noise response becomes

$$V_o = V_I \sqrt{1 + \frac{1}{\omega\tau_s} (\rho_{13} - \rho_{12}) + \frac{1}{2(\omega\tau_s)^2} (1 - \rho_{23})} \quad (12)$$

3.3.1 Uncorrelated noise

Electrical noise from the hydrophones or associated electronics is uncorrelated between channels. Furthermore, there is no correlation between the noise and a delayed version of itself. Thus the correlation coefficients are given by

$$\rho_{mn} = \begin{cases} 1 & m = n \\ 0 & m \neq n \end{cases} \quad (13)$$

and the noise response is

$$V_{Uncor} = V_I \sqrt{1 + \frac{1}{2(\omega\tau_s)^2}} \quad (14)$$

3.3.2 Correlated noise

Ambient noise in the ocean is spatially and temporally correlated and the correlation coefficient may be approximated by [4]

$$\rho_{mn} = \frac{\sin(\omega \delta x_{mn}/c)}{\omega \delta x_{mn}/c} \cos \omega \delta \tau_{mn} \quad (15)$$

where δx_{mn} is the spatial separation between elements m and n and $\delta \tau_{mn}$ is the associated time delay. For the present application $\delta x_{mn} = 0$ where m and n relate to the same physical hydrophone, or d

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otherwise, and $\omega\delta\tau_{mn} = \pi/2$ where there is a phase shift. It may then be shown that the response to ambient noise is

$$V_{Cor} = V_I \sqrt{1 + \frac{1}{2(\omega_s\tau)^2} \left(1 - \frac{\sin kd}{kd}\right)} \quad (16)$$

where $k = \omega/c$ is the acoustic wavenumber.

3.3.3 Conventional cardioid

For comparison, the equivalent expressions for the conventional cardioid network are

$$V_{Uncor} = V_I \sqrt{2} \quad V_{Cor} = V_I \sqrt{1 + \cos\omega\tau_c \left(1 - \frac{\sin kd}{kd}\right)} \quad (17)$$

Signal to noise ratios at the network output for correlated and uncorrelated noise, with a 0dB SNR at the hydrophone terminals, for both the shuffler network and the conventional cardioid are plotted against normalised frequency in Figure 4. Here it can be seen that the noise response is similar for both networks up to just below f_0 . For correlated ambient noise the SNR below f_0 is constant at 4.8dB, which is the DI expected for a cardioid directivity pattern. For uncorrelated noise, the SNR falls at 6dB/octave with reducing frequency, and this implies that at low frequencies system and electrical noise that is insignificant at the network input is boosted relative to the signal. This boost is about 30dB two decades below f_0 .

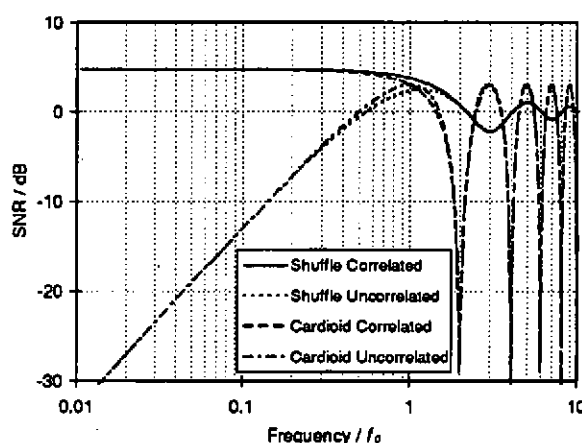


Figure 4: Output SNR of shuffler and conventional cardioid networks, with correlated and uncorrelated noise at 0dB SNR at the hydrophone terminals, plotted against normalised frequency.

4. EXPERIMENTAL CONFIRMATION

A simple experiment was conducted in a 6m wide \times 10m long \times 7m deep test tank, using a pair of hydrophones as the sensors. These were mounted with a small horizontal separation, and short pulses transmitted from a flextensional transducer were recorded as the hydrophone pair was rotated in the

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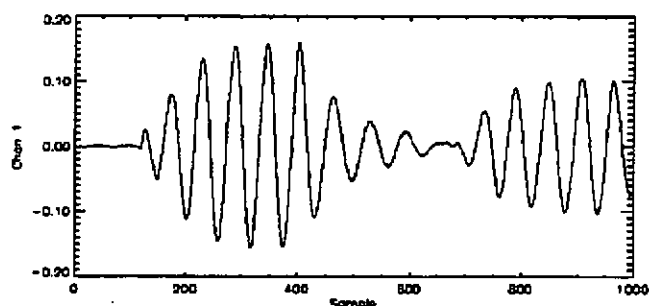


Figure 5: Typical tank experiment received signal.

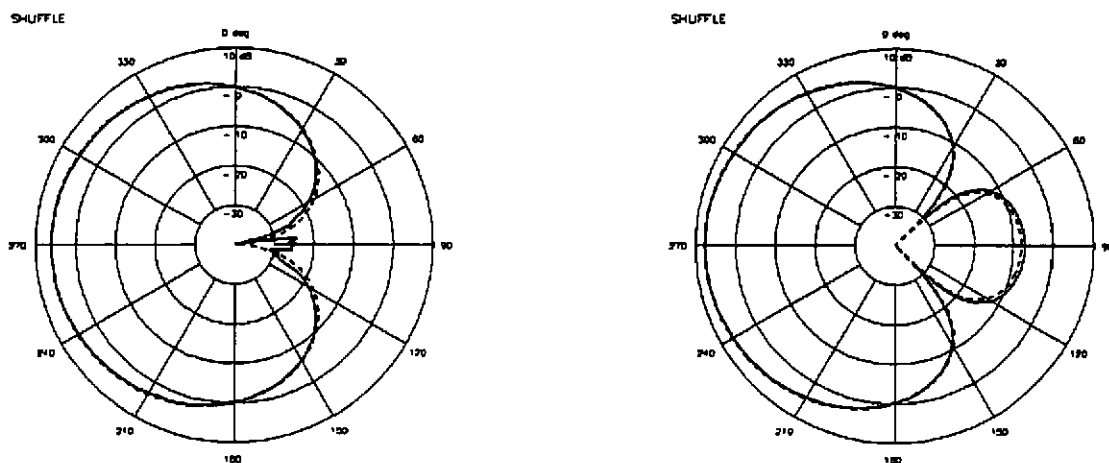


Figure 6: Shuffler directivity patterns at $f = 0.44f_0$ for exact cardioid (left) and nulls steered 45° (right). Solid line is measured result and dashed line is theoretical pattern.

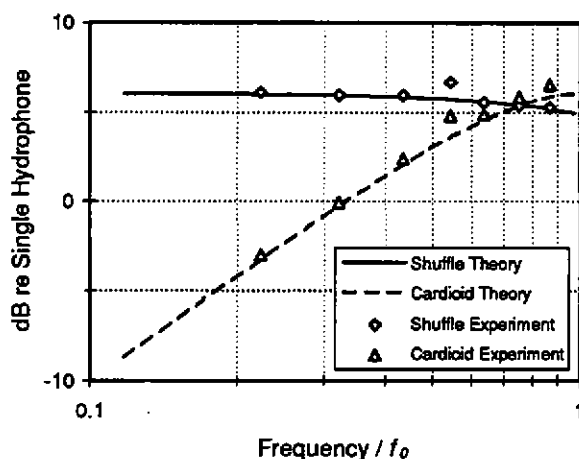


Figure 7: Shuffler measured response (diamonds) compared with prediction (solid line) and cardioid response (triangles) compared with prediction (dashes), plotted against normalised frequency.

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horizontal plane. A typical received signal is shown in Figure 5, where it is seen that the first echo from the tank boundaries arrives very soon after the direct signal, and this severely limits the length of signal pulse that can be used. The signals were sampled directly from the hydrophones and stored on a PC. All processing and calculations were carried out in software.

Typical directivity patterns obtained are shown in Figure 6. The measured response with τ_s set for an exact cardioid is shown on the left as the solid line, with the predicted pattern plotted as a dashed line. The measured and predicted patterns with τ_s set for nulls steered to 45° are shown on the right. Frequency responses are shown in Figure 7 with the measured shuffler response plotted as diamonds compared with the theoretical response plotted as a solid line and the measured cardioid network response plotted as triangles with the theoretical equivalent plotted as dashes.

Good agreement between measurement and theory is observed in both the directivity patterns and the frequency responses. Total cancellation is not achieved in the polar plot for the exact cardioid, and this may be due either to problems associated with the very short signal pulse or an error in setting the spacing between the sensors. However, discrimination between left and right is still about 30dB. One measurement in the frequency response at $f = 0.54f_0$ is about 1dB above the prediction, but the transmitting transducer was found to have an underdamped resonance at this frequency, which may have influenced the result.

5. DISCUSSION AND CONCLUSION

The Blumlein Shuffler, a technique from the field of audio engineering, has been suggested as an alternative to conventional cardioid-forming networks for achieving left/right discrimination in towed arrays. It has been demonstrated, both theoretically and experimentally, that the directivity patterns obtained are the same as those of the conventional process but with the advantage that the signal response is constant with frequency up to the cut-off at f_0 .

Disappointingly, it has been found that the noise response, expressed in terms of the output SNR, is the same as that of the conventional process. However, only the form of Δ channel filter originally specified by Blumlein has been considered here. A variety of filter formats for both Σ and Δ channels have been proposed for different audio applications [2], and it is possible that further investigation might lead to a filter that gives equivalent left/right discrimination performance, but with improved noise response.

6. REFERENCES

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