INTERPOLATION BEAMFORMING WITH A BENT ARRAY

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Abstract

An interpolation beamformer (IBF) may be defined as a line-array beamformer where the output for a given beam is formed from the weighted sum of relatively few Fourier coefficients taken from the (spatial) Fast-Fourier transform of the narrowband data measured across the array. Such an implementation may be computationally efficient. It is the intent of this paper to discuss the application of the method to a bent line array where the weights are chosen to offer both array shading and bend compensation. It will be demonstrated that for reasonable amounts of array curvature the IBF has a beampattern close to the benchmark delay-and-sum beamformer and a rule-of-thumb is given for the number of weights necessary for Kaiser-Bessel shading of a uniform line-array bent into a circular arc of known radius.

I Introduction

This paper represents an investigation into efficient planewave beamforming using a bent line-array. The unbent array is a uniform line-array and, for simplicity, the curvature of the bent array takes the form of an arc of a circle of known radius.

Conventional, narrowband, delay-and-sum beamforming is easily applied to such a bent array but if there are N sensors, and N beams are to be computed, then the total computational load is of the order of N^2 operations per snapshot. A more efficient approach was suggested recently by Dalrymple [1], building on a concept of DeMuth *[2]*, wherein the Fast-Fourier transform is applied to narrowband (NB) sensor data, and relatively few, M, say, of the spatial-frequency Fourier coefficients are then used to produce each output beam sample. Hence, very roughly, the computational load is now on the order of $MN + N\log_2(N)$. Operating on M adjacent Fourier coefficients to provide an estimate of the output of a beam whose direction may not coincide exactly with any of the underlying M spatial frequencies is essentially an interpolation problem and for this reason the beamformer under study is known as an "interpolation beamformer"

The primary goal of this research is to provide a more thorough treatment of appropriate choice of M, the number of interpolator weights, than that given by Dalrymple [1]. The number should be small for efficiency reasons yet must be large enough to provide adequate beamforming performance, especially in the presence of significant array curvature. Among the parameters that influence M are the number of sensors, the size of the FFT, the extent of the curvature and the choice of array shading.

We shall demonstrate that it is useful to decompose M into the sum of two values, one dealing with the creation of the appropriate shading effect with an unbent array, the other dealing with the array curvature. Where the curvature is significant, the latter is the dominant effect. For Kaiser-Bessel shading we give a simple rule-of-thumb for the choice of M in any given scenario.

The results given here are extracted from a longer report by one of the authors [3].

II Development

A. Unbent line-array

Consider a uniform line-array with N sensors operating at a temporal frequency, f Hz. If the complex-valued (temporal-frequency) Fourier coefficient at this frequency obtained from the nth sensor time-series is written as $X(n)$ then the beam output at angle θ with respect to broadside may be written as the sum

$$B(\theta) = \sum_{n=0}^{N-1} X(n)\, W(n) \exp(-j\, k\, n\, d \sin(\theta)) \qquad (1)$$

where d is the element spacing, $k = 2\pi f / c$ and c is the acoustic propagation speed. $W(n)$ is the shading

As might be expected, we shall demonstrate that $M2$, and consequently $\tilde{M}$, increases as the amount of bow increases.

Finally it should be emphasized that bend correction is a function of the cosine of the steering direction, θ_0, and it is therefore necessary to explore the effects of bend correction over bearings in the full 0-360° range.

Rule-of-thumb:

By some simple mathematics and trial-and-error the following rule-of-thumb was established for $|D|>0$:

$$M2 = \left(8\frac{|D|}{\lambda}+7\right)\frac{M}{N} \qquad (12)$$

The utility of (12) will be demonstrated in the following simulations in which $M1$ and $M2$ are chosen, for convenience, to be odd.

III Simulation experiments over 0-360°

To fully understand the interpolation beamformer's action we need to plot beampatterns over the full 0-360^0 range.

We start by setting $D/\lambda=1$, $N=M=64$. *We* choose $M1=5$ from (6) and $M2=19$ from (12). N=64 is chosen so that the IBF beampattern is sufficiently wide to enable some detail to be visible in the polar plot of Fig. 2. The IBF is steered to $\theta_0 = 20°$, where we observe a relatively narrow beam with close-in sidelobes levels at -30dB with respect to the peak. [Note that the beampattern is normalised to the vicinity of 50dB maximum for plotting purposes; the annular rings represent 10dB increments.] The response in the vicinity of the complementary angle of 180-20=160° is clearly visible and while its peak is some 10dB below the steered output, the broadness of the complementary response is of concern.

Also on Fig. 2 we plot the benchmark CBF beampattern for the same bent array. The two curves are barely distinguishable by eye and so we plot the difference in the two beampatterns (difference = IBF-CBF where IBF and CBF represent beampatterns expressed in dB) and superimpose it on the 40dB contour for convenience. Both beampatterns are normalised by the maximum output of the CBF (itself set at 50dB) and beampowers less than 0dB are set to 0dB to avoid extraneous detail in the difference plot. The difference curve shows that there are negligible performance differences in the major lobe areas. Those larger differences that do exist occur where the sidelobe levels are sufficiently low for these to be of no concern.

Finally we note that the SNR loss associated with the IBF [loss = SNR(IBF)-SNR(CBF) where both are in dB], is about -0.01dB as indicated in the upper right of the figure.

In Fig. 3 we increase M and N to 128 and set the steering direction to $\theta_0=66°$. We have a significant bow value of D/λ =2.5 and (6), (12) suggest $M1=5$ and $M2=27$ as suitable filter lengths for the IBF. On the polar plot of Fig. 3 we again note a broad and relatively high complementary beam. There is also a response in the opposite endfire vicinity which exceeds the -30dB level. Again we note that there is little substantive difference in the performance of the IBF and CBF beampatterns.

In Fig. 4 we steer to 45° with a bow of $D/\lambda=0.5$. The number of sensors, N, is reduced to 65 with the FFT length, M, retained at 128. To compensate for the M/N ratio we set $M1$, $M2$ in accordance with (6), (12) to $M1=9$, $M2=21$. We note again in Fig. 4 that the IBF and CBF results are similar.

IV Summary

We have demonstrated that interpolation beamforming of a bent array is feasible and have established working guidelines for the choice of the two critical filter lengths, $M1$ and $M2$. The SNR performance of the interpolation beamformer has been shown to be within about 0.1dB of the benchmark conventional, delay-and-sum beamformer.

The interpolation beamformer and the conventional beamformer exhibit very similar problems associated with (i) the broadening of the complementary lobe and (ii) the loss of performance where the steering direction is close to endfire. The latter problem is common to any line-array beamformer operating near endfire.

References

[1] D.B. Dalrymple, "Mapping a 200 element, 300 beam curvature correcting line array beamformer into COTS octal TMS320C40 VME boards," in Proc. Int. Conf. on Signal Processing Applications and Technology (ICSPAT '97), held 14-17 Sept. 1997 in San Diego, CA, pp. 793-797.

[2] G.L. DeMuth, "Frequency domain beamforming techniques," in Proc. IEEE Int. Conf. on Acoustics, Speech, and Signal Processing (ICASSP '77), held 9-11 May 1977 in Hartford, CT, pp. 713-715.

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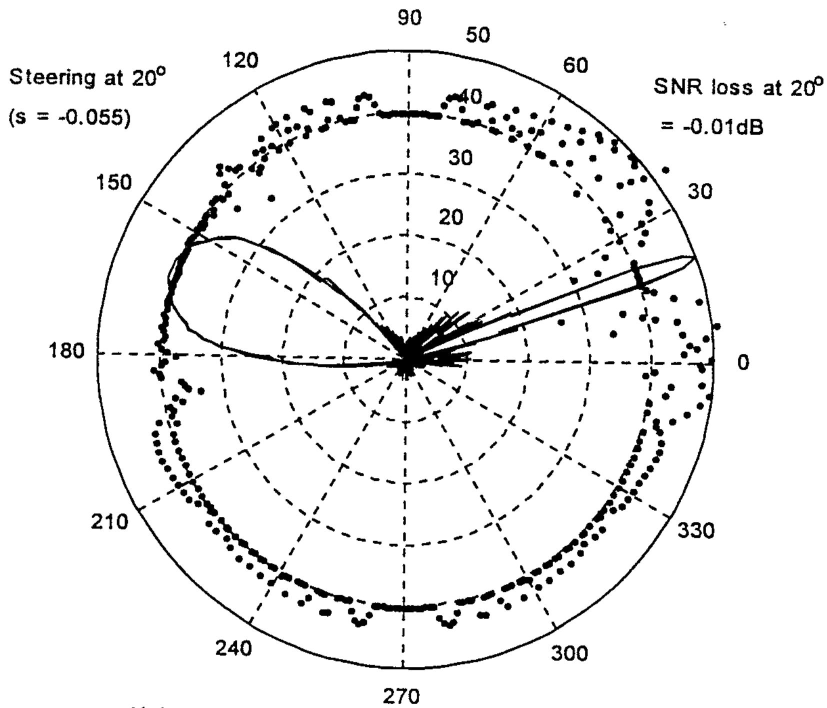
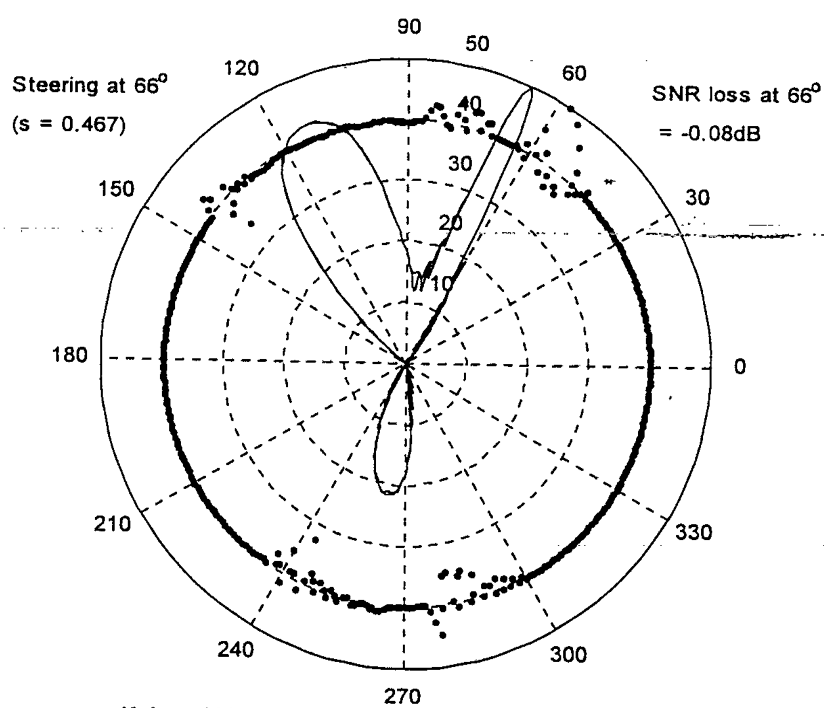


Kaiser, M1=5, M2=19, fr=1, D/λ=1.5, N=64, M=64,

Fig. 2. Beampatterns of IBF and CBF. Difference shown as •••.
θ_o, = 20°, D/λ, = 1.5, $M1$=5, $M2$=19, f_r = 1, N =64, M=64.



Kaiser, M1=5, M2=27, fr=1, D/λ=2.5, N=128, M=128,

Fig. 3. Beampatterns of IBF and CBF. Difference shown as •••.
θ_o, =66°, D/λ=2.5,$M1$=5,$M2$=27,f_r=1,N=128,M=128.

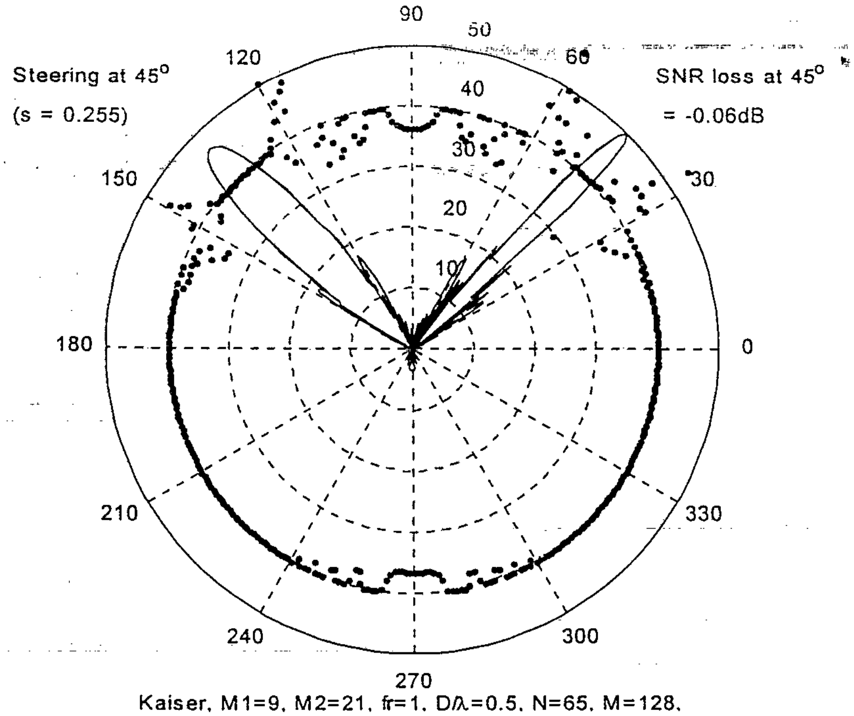


Fig. 4. Beampatterns of IBF and CBF. Difference shown as •••.
θ_0, =45°, D/λ=0.5, $M1$=9, $M2$=21, f_r=1, N=65, M=128.

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