TRANSDUCERS WITH CONTROLLED DIRECTIVITY AND THEIR USE IN REDUCING NOISE IN ARRAYS

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1. INTRODUCTION

In order to utilise as large an aperture as possible, passive sonar arrays are increasingly being placed over larger areas of the ship's hull. In addition, low frequencies are becoming more important as longer range detection is demanded. These factors inevitably mean that the array cannot be "stood off" from the hull by a sufficient distance to avoid being influenced by the near field of structureborne vibration.

This field is created by acoustically slow waves in the structure and the associated sound pressure decays exponentially with distance into the fluid. Because the mechanism is acoustically slow (i.e. of high wavenumber compared to acoustic values) one might expect that large area transducers would help to alleviate the problem. Traditionally, large transducers have been regarded as a viable solution to high wavenumber platform noise such as flow noise. The averaging of pressure over the surface of the transducer produces a noise reduction which depends on the wavenumber distribution of the noise. In the case of flow noise, the dominant wavenumbers are so far above acoustic values that very effective processing gains are achieved. However, the same philosophy does not work quite so well with the near field of structureborne sound. The major components of this self noise are at wavenumbers which are only just above acoustic values (i.e. the structureborne sound propagates at near sonic velocity whereas flow noise mechanisms are closely associated with the convection speed of the turbulence, which is almost the same as vessel speed). Recent developments in transducers have however led us to re-examine the possibilities of using large transducers to reduce near field self noise.

The problem of structureborne noise has already been discussed in another paper [1]. A simplified overview of the problem is presented here in section 2. A description of a new transducer concept is given in section 3, and the application of the idea to near field self noise is considered in section 4.

2. THE PROBLEM DEFINED

Since beamforming selects a region of wavenumber/frequency space which contains only acoustically fast mechanisms, one might be tempted to think that near field noise would be

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rejected by the beamformer. However, as shown in [1], the coherent components of this type of self noise, largely due to the periodic nature of the hull, can be processed up by a beamformer and enhanced by the same gain as a real target. Incidentally, towed arrays are usually periodic structures and may suffer similar problems. The hydrophones discussed in section 3 may also be useful there.

We are dealing with spatially sampled (array) data, so the beams are subjected to aliasing in the same way that all sampled data are. This is best illustrated on a simple wavenumber/frequency diagram as shown in Figure 1. The vertical scale is frequency, and wavenumber is plotted horizontally.

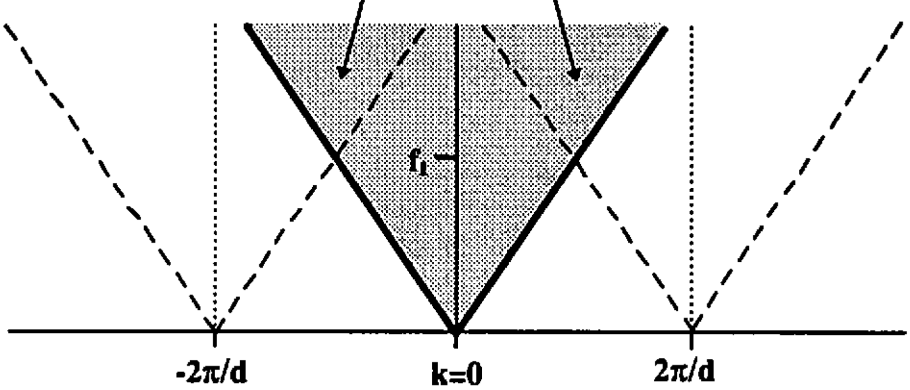

Figure 1.

The area of wavenumber/frequency space swept out by the beams from -90^0 to +90^0 is shown in thick solid lines. The slope of these lines is determined by the velocity of sound in the fluid, and the broadside beam is represented by the vertical line at k = 0. There are aliases of this beam at $k = \pm 2n\pi/d$, where d is the element spacing of the array (dotted lines). All other beams are aliased in the same way, and the areas occupied by these aliases are delineated by the dashed lines in the figure. Where the aliased regions overlap the area swept out by the beamformer, the well known "diffraction secondaries" occur in the beam patterns. These regions correspond to frequencies above f_1, which is where the array spacing becomes greater than $\lambda/2$. Their effect is to produce beam patterns with response lobes as large as the main beam, but pointing in unwanted directions.

In the above discussion about diffraction secondaries, we have assumed that all the signals received by the array are due to mechanisms which propagate with a phase velocity equal to the sound velocity in the fluid. When lower phase velocities are appropriate, then "diffraction secondaries" will occur at lower frequencies, and unexpected spoking effects may be displayed

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(i.e. false targets may appear on particular bearings). This is equivalent to saying that the beamformer cannot distinguish between noise which occurs in the aliased beams and real targets, even at frequencies below f_1.

Now let us consider the processing gain that a large transducer can bring to bear on this problem. Point transducers, of course, are totally non-selective as far as their wavenumber response is concerned (i.e. their response characteristic is "white" in wavenumber terms). Large transducers respond over a narrower range, as the averaging effect reduces their response at high wavenumbers (i.e. a spatial low-pass filter). Using large transducers is therefore the spatial equivalent of using an "anti-aliasing" filter in the time domain.

Usually, the largest transducer we can consider is one which fills the inter-element space in the array completely. The wavenumber response of this transducer is shown in Figure 2, with Figure 1 repeated immediately below it for ease of reference.

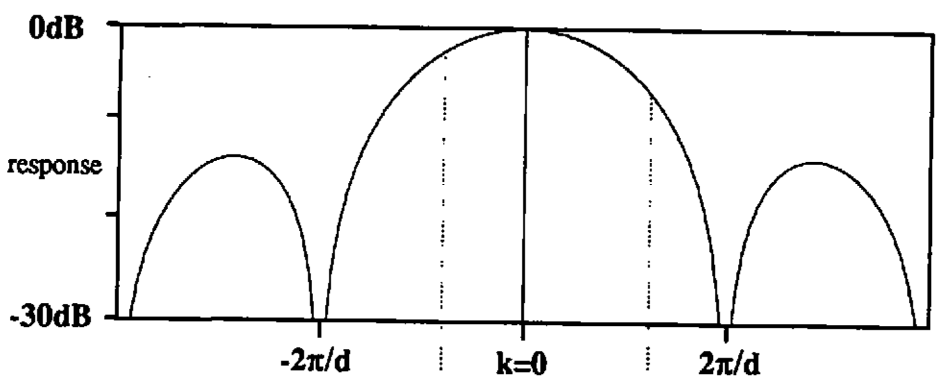
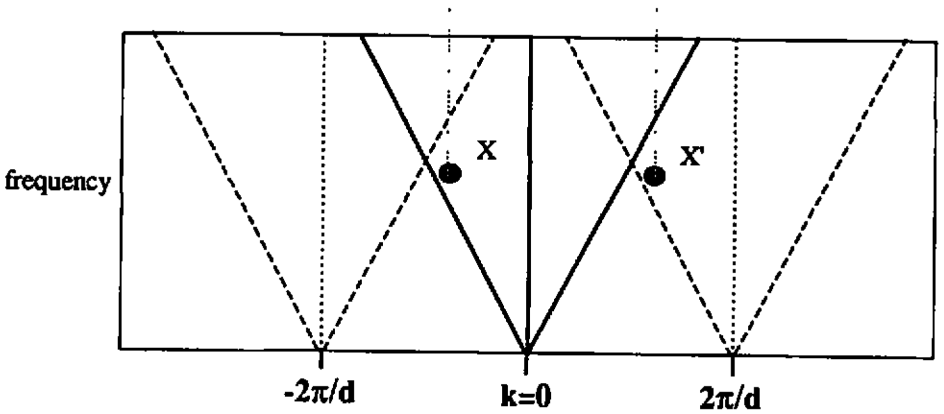


Figure 2.



It is plain to see that the first null in the response occurs at $k = 2\pi/d$, which corresponds exactly to the wavenumber for the alias of the broadside beam in Figure 1. Thus, high

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wavenumber near field noise will not affect the broadside beam using these transducers, no matter what frequency it occurs at. The same is not true of the other beams however, since nearfield noise can be present anywhere in the aliased regions. For example, noise occurring at point X' in Figure 1 (the version presented immediately below Figure 2) will produce a false target at X in the beamformer. We can see, therefore, that even with transducers which fill the array completely, the rejection of such near field noise by the transducer may only be marginal - a few dB at most (Figure 2 implies that the response of this transducer at the wavenumber corresponding point X' is only 3 or 4dB lower than that due a real target at point X).

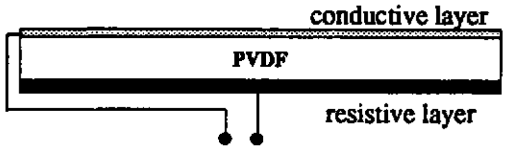
It would be dangerous to assess the performance of the array on the noise in the broadside beam alone. Serious noise problems can arise when the array is steered off broadside, and even transducers which fill the array completely may not reduce the problem by much more than a few decibels. This "anti-aliasing filter" has far too wide a passband - and has sidelobe levels which are too high. Could we do better?

3. THE NEW TRANSDUCERS.

The new transducer concept is based on a particularly simple method of producing transducers with controlled directivity. It is possible to produce transducers with constant (frequency independent) width of main beam, having any desired beamwidth so long as the required aperture is available. The concept is currently being applied to ultrasonic transducers as well as loudspeakers (both electrostatic and electrodynamic types) and microphones. In many of these cases the requirement is that the transducer retains omnidirectionality at higher frequencies. This is our requirement here too, if we wish the array sensitivity to remain unaffected when the array is steered all the way round to endfire.

The fundamental principle applied to, for example, a PVDF transducer is to shade the response of the transducer over its active face in a frequency dependent manner, such that the effective size of the transducer changes as frequency changes. The device producing this shading consists of a dielectric layer coated on one side with a conductive layer (e.g. silver) and on the other side with an electrically resistive material, as illustrated below.

Figure 3.



One electrical connection is made to the conductive layer and the other connection is made at a point in the electrically resistive layer (e.g. in the centre of the resistive layer). In this particular case the PVDF itself constitutes the dielectric layer. The electrical resistance between this second connection and the more remote parts of the resistive layer is a function of position. It is this resistance, in combination with the local capacitance associated with the dielectric layer, which is utilised to vary the effective size of the transducer as a function of frequency. The signals are integrated by the CR circuit created by the composite, leading to a reduced response at higher frequencies. Since the resistance to the more remote parts of the device is higher, the response of these parts is more affected by the integration effect. This means that the response of the more remote parts of the transducer reduces more rapidly as frequency is increased, and consequentially the effective size of the transducer reduces as frequency increases. A simple analysis of the principle is presented as an appendix at the end of this paper.

A further benefit of this type of construction is that an array can be produced simply by making multiple connections to an extensive composite. Each connection creates a new transducer, with its area of highest sensitivity located around the point connection to the resistive electrode. By designing the resistive electrode correctly, the "effective" size of the transducer can be made to be larger or smaller than the array spacing, as desired. This implies that we can use the same technology to shape the wavenumber response of the transducers as a function of frequency.

Since we do not wish to receive signals from mechanisms with wavenumbers higher than π/d it would seem to be desirable that the transducers should have a wavenumber response which is no wider than this (and preferably narrower still at lower frequencies). This requires transducers which are even larger than the array spacing. Simply doubling the size of conventional transducers (and overlapping them!) would halve the width of their response in wavenumber terms, and put the first null at π/d. This would produce a worthwhile benefit - aliases could then only be received through side-lobes of the transducer response. Appropriate shading of the transducer sensitivity would be of further benefit in that respect. However, this transducer would also be starting to become directional itself at frequencies approaching f_1.

Indeed, the most effective transducer which could be used to address this problem would be one which was as large as possible, without being so large that it became directional itself (it could therefore be larger at lower frequencies) and which had low sidelobe levels. This would require a transducer with tapered shading which also changed its size as a function of frequency, and *that* is the development which has renewed the interest in large area transducers.

4. CURRENT POSITION

It would, of course, be difficult to overlap conventional transducers in an array, but the solution being proposed involves a single layer of a sensitive material composite. The array design would involve the determination of those material parameters required to produce transducers with sufficient noise rejection at wavenumbers outside the sonic region delineated by solid lines in Figure 1.

One idea being considered is to make each "transducer" by making multiple connections and summing their outputs (and possibly weighting them) in groups equal in extent to the array spacing. The resulting transducer sensitivity would approximate to that of a conventional transducer with exponentially decaying, frequency dependent "tails" extending from its edges into the rest of the array. Preliminary calculations show that this configuration can be made to have the right width of (frequency dependent) wavenumber response with very little sidelobe response (>40dB down on the main lobe) This means that the array would reject near-field self noise very effectively, because the wavenumber response of such transducers would be 40dB or more down in the region of the aliased beams.

So far, the discussion has all been of a qualitative nature. Using the knowledge gained in recent research, it would now be possible to quantify the available benefits. We have done a similar exercise before, comparing the self noise performance of various size transducers in flank array positions (Refs. [2,3,4]) using theoretical models which predict the near field platform noise, both in level and spatial properties. The relative benefits of this new transducer concept could be determined using the same procedure.

5. APPENDIX

Consider a one-dimensional transducer of the type shown in Figure 3, having an a.c. voltage applied to its connections. Current will flow in the electrically resistive layer, outward from the connection point. Displacement currents will also flow through the capacitive layer.

The rate of loss of current from the resistive layer to the capacitive layer is:-

$$\frac{di(x)}{dx} = -j\omega C' V(x) \qquad (1)$$

and the voltage at any point x in the resistive layer is given by

$$\frac{dV(x)}{dx} = -R' i(x) \qquad (2)$$

where R' = resistance/unit length of the resistive layer
C' = capacitance/unit length of the dielectric layer

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(1) and (2) have solutions of the form

$$i = ae^{-\alpha x} \qquad (3)$$

$$V = be^{-\alpha x} \qquad (4)$$

Note that both the current and the voltage in the resistive layer are shaded in the same way.

Substituting (3) and (4) back in (1) and (2) we get

$$-a\alpha = -bj\omega C'$$

$$-b\alpha = -R'a$$

$$\text{i.e.} \qquad \alpha = \pm\sqrt{j\omega C'R'} \qquad (5)$$

In the case of a two dimensional transducer, the equations equivalent to (1) and (2) involve:

- i ≡ current density in the layer (amps / unit width)
- C' ≡ capacitance / unit area
- R' ≡ surface resistivity (= volume resistivity / thickness)

Their solution is similar, except that it involves Bessel functions instead of complex exponentials. The argument of these Bessel functions is the same, however, and so the length scale of the "shading" function corresponding to equations (3) and (4) is approximately the same as the simpler case we analyse here.

Equation (5) implies that the shading function created by simple layers of spatially uniform dielectric and resistive materials varies on a length scale proportional to $1/\sqrt{\omega}$. To maintain constant directional characteristics we would require this length scale to be proportional to $1/\omega$, so that the effective size of the transducer would halve for each doubling of frequency. To achieve this it is necessary to add some shading by altering the properties of one (or both) of the dielectric/resistive layers. A convenient method is to vary the resistivity of the resistive layer. It turns out that for this special case the resistance/unit length (R') needs to vary inversely with position.

$$\text{i.e. } R'(x) = \frac{R'_0}{x} \qquad (6)$$

This can be achieved either by thickening the resistive layer toward the outer extremities, or modifying the electrical properties of the material.

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To prove this, we must solve the simultaneous differential equations (1) and (2) and show that a linear form for R'(x) as in (6) makes the functions V and i depend only on xω.

Substituting (2) in (1) we have

$$\frac{d}{dx}\left\{\frac{1}{R'}\frac{dV}{dx}\right\} = j\omega C'V \tag{7}$$

To make the shading function V(x) depend only on xω we can write

$$\omega\frac{d}{d(x\omega)}\left\{\frac{\omega}{R'}\frac{dV(x\omega)}{d(x\omega)}\right\} = j\omega C'V(x\omega) \tag{8}$$

and thus, writing $x\omega = X$ and $R' = \frac{R'_0}{x}$,

$$\frac{d}{dX}\left\{\frac{X}{R'_0}\frac{dV}{dX}\right\} = j\omega C'V \tag{9}$$

or

$$\frac{X}{R'_0}\frac{d^2V}{dX^2} + \frac{1}{R'_0}\frac{dV}{dX} - j\omega C'V = 0 \tag{10}$$

the solution to this equation is

$$V = AI_0(2\sqrt{jC'R'_0X}) + BK_0(2\sqrt{jC'R'_0X}) \tag{11}$$

where A and B are constants and I_0 and K_0 are modified Bessel functions.

Note that this functional form has a singularity at the origin. Here, the resistance gradient would be infinite and the central connector would be insulated from the transducer! This is, of course, due to the fact that the mathematics is modelling a transducer which maintains constant beamwidth to arbitrarily high frequencies, requiring arbitrarily small effective size. Provided an upper frequency is specified, such a physically unrealisable singularity will not be encountered.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] D. J. W. HARDIE, M. BLAKEMORE, J. POWER, 'The Influence of Hull Vibration on Array Performance', (in I.O.A proceedings of this conference)

[2] J POWER, M. BLAKEMORE, P. R. BRAZIER-SMITH, 'An Overview of Issues Affecting Self-Noise in Flank Arrays', Topexpress Report No TOP0078/EXT2/93/1 (1993)

[3] P. R. BRAZIER-SMITH, M. BLAKEMORE, J. POWER, J. WOODHOUSE, 'Sonar Array Sensitivity to Propagating Structural Vibration', Topexpress Report No TOP0078/EXT1/92/1 (1992)

[4] M. BLAKEMORE, P. R. BRAZIER-SMITH, J. POWER, J. WOODHOUSE, 'Flank Array Sensitivity to Fluid/Structure-Borne Self Noise', Topexpress Report No. TOP0078/EXT2/93/2 (1993)