Proceedings of The Institute of Acoustics

THE APPLICATION OF ARRAY SIGNAL PROCESSING TO THE LOCATION OF ACOUSTIC SOURCES IN FAST REACTORS - PRELIMINARY EXPERIMENTAL RESULTS

D. Firth and C. Waites

Risley Nuclear Power Development Laboratories, Warrington, England

1. INTRODUCTION

In the United Kingdom safety instrumentation is being developed to detect local faults in the liquid metal cooled fast breeder reactor, even though the probability of such events is extremely small. In this type of reactor the power is generated in fuel pin clusters known as sub-assemblies. In a large power reactor the core will contain over 500 sub-assemblies, each containing over 300 pins. The technique of monitoring the reactor core using an array of acoustic transducer is under investigation at Risley Nuclear Laboratories (RNL) [1]. Collaborative work with Topexpress Ltd, and measurements carried out by RNL during the commissioning of the UK Prototype Fast Reactor (PFR) [2], suggest that array processing techniques may be used for the detection and location of the noise produced by sodium boiling in an overheated sub-assembly.

In this paper we first describe the array processing techniques we have studied so far. The experimental equipment and data handling facilities are described next; some results using the two techniques are presented, and finally the continuation of the work is outlined.

2. PRINCIPLES OF LOCATION

Two of the simplest and most direct array processing methods, the delay and sum beamformer and the frequency domain beamformer have been used. The physical principles for the delay and sum beamformer are summarised first and the mathematical details follow.

The method depends upon the assumption of a known constant sound speed. The time taken for sound to travel between any two points can then be calculated precisely. When an acoustic source of interest is present, the output from each sensor consists of two components: a 'signal' component from the source of interest, and a 'noise' component which constitutes the remainder. Because of the different transit times from the source to the different sensors, the signal components will not be synchronised within the outputs. The array of sensors can be focussed at any point by calculating the transit time for sound to travel from that point to each of the sensors, and shifting the outputs in time by the relative transit times. Any signal coming from the focal point will then be synchronised in all the outputs. Averaging over the signals at each shifted time point will enhance the signal to noise ratio. By scanning over some region of interest and plotting the power of the average signal (the 'correlation value'), a representation of the source distribution is obtained. For the particular implementation considered here, an array of n sensors is assumed, with each sensor j at a position $\underline{r}_j$. The output from each sensor is sampled at discrete time points separated by a constant time interval δt. The signal from the jth sensor at the t th time point (t = 1 to N) is denoted by $\tilde{p}_j(t)$. Because of different amounts of attenuation and the different gains of the sensors, the signals are first normalised to $p_j(t)$:

$$p_j(t) = (\tilde{p}_j(t)-\bar{p}_j)/\sigma_j \tag{1}$$

where $$\bar{p}_j = \frac{1}{N}\sum_{t=1}^{N}\tilde{p}_j(t)$$

$$\sigma_j^2 = \frac{1}{N}\sum_{t=1}^{N}(\tilde{p}_j(t)-\bar{p}_j)^2 \tag{2}$$

For the focal point $\underline{r}$, the time shift quantity for sensor j is defined as:

$$\alpha_j(\underline{r}) = \mathrm{RND}\ (|\underline{r}_j-\underline{r}|/c\,\delta t) \tag{3}$$

where c is the sound speed and RND is the function that rounds a real number to the nearest integer. The delay and sum beamformer signal is then:

$$p(\underline{r},t) = \frac{1}{n}\sum_{j=1}^{n} p_j(t+\alpha_j) \tag{4}$$

The time series $p(\underline{r},t)$ is an estimate of the signal from a source at $\underline{r}$. The correlation value $\mu^2(r)$ is defined as the power over some interval:

$$\mu^2(\underline{r}) = \frac{1}{N}\sum_{t=1}^{N}[p(\underline{r},t)]^2 \tag{5}$$

The correlation value is plotted as described in section 5.1.1

The frequency domain beamformer is obtained by taking discrete fourier transforms of the signals $p_j(t)$. The array focussing is then performed using phase shifts rather than time shifts. Equation (5) can be written:

$$\mu^2(\underline{r}) = \sum_{m=1}^{N/2} p(m) \tag{6}$$

where p(m) is the correlation value for frequency component m (corresponding to $f = m/N\delta t$) and is given by

$$p(m) = \frac{2}{n^2}\sum_{j=1}^{n}\sum_{k=1}^{n} Q_{jk}(m)\exp 2\pi i m(\alpha_j-\alpha_k)/N \tag{7}$$

where Q_{jk} (m) is the cross power spectral density (CPSD) of channels j and k at frequency component m; p(m) is plotted as described in section 5.2.

3. THE HALF SCALE MODEL OF THE PFR CORE

A simplified model of the PFR core has been commissioned in a 10,000 gallon water tank. The model consists of 61 brass tubes 1.67 m long with hexagonal sections 70 mm across the flats. These simulate the sub-assembly wrapper tubes and are assembled on a stainless steel and rubber isolating sandwich, mounted on the rig supporting stool. The assembly is held together with two tensioned steel bands. Previous measurements showed that reverberation in the tank caused problems. Several layers of air filled 'bubble' plastic material have been wrapped around the model in order to reduce reverberation. Figure 1 shows a photograph of the completed assembly, with the acoustic array positioned above.

The acoustic array consists of 18 hydrophones mounted on 3 metre long 8 mm diameter stainless steel tubes. These are positioned in a two dimensional array above the model as illustrated in Figure 2. Two spherical hydrophones are used as sound sources. These are denoted A and B in Figure 2.

4. THE DATA ACQUISITION SYSTEM

A computer controlled data acquisition system has been developed to digitize and store data from up to 12 channels simultaneously. In the experiments samples of between 4096 and 24576 data points are stored for each channel with sample intervals of 10 or 40 μs.

The acoustic source is driven from a signal generator through a power amplifier designed for reactive loads. The output signals from the hydrophones pass through local preamplifiers, and are further conditioned by low noise amplifiers. The output signals from the amplifiers are fed to two analogue to digital converters, driven in tandem under computer control. The digitized signals are stored on a PDP 11-04 computer, and then transferred to a PDP 11-44 computer for analysis.

5. EXPERIMENTAL PROCEDURE AND RESULTS

The positions of the hydrophones were checked by pulsing individual transducers and measuring time delays. The maximum error in positioning was 11 mm which is less than the diameter of the hydrophone. Because of equipment failure, two channels could not be used. Thus a total of 10 channels of data were available for analysis. Two types of source signal were used, simple sinusoids and broadband noise.

5.1 Delay and Sum Beamforming

The data have been analysed by scanning over a one metre area below the array in the plane of the source. The resulting matrix of correlation values is then written to a file for subsequent display and plotting. The results given are based upon 100 data values for each of the 10 channels: this was found to be a suitable compromise between analysis time and result accuracy.

5.1.1 Location of Simple Sinusoid Sources. Initial measurements were made to locate short bursts of 3kHz sine wave generated inside the top of the simulated wrapper tubes. The results are shown in Figure 3a in terms of the correlation values calculated from equation 5 and shown as a series of contours. The contours are plotted at 0.95, 0.85, 0.75 etc times the maximum value of the correlation function. The noise source was positioned off-centre as shown in Figure 2 position B, and the location was determined correctly to within 40 mm of the source position. The ten channels are shown in Figure 3a, Figure 3b is an isometric plot of the correlation values, showing the source position and the overall variation.

5.1.2 Effect of Signal Fequency. Figures 4a to 4d show isometric plots of the correlation values obtained for short bursts of sinusoid at frequencies 1.5, 3, 5 and 10kHz. The source was positioned at the top and centre of the model shown in Figure 2 position A.

The maximum value of the correlation function is at the same position for all the frequencies shown. With increasing source frequency the sharpness of the peak increases giving a more precise location. There is an observable trading relationship here, because as the frequency is increased spatial aliasing occurs giving images of the source at incorrect focal positions. This is due to the wavelength of the signal becoming less than twice the separation between the array elements, giving increased correlation values at positions where the time shifts are an integer number of cycles away from the true time shifts.

5.1.3 Location of Broadband Noise. The ability of the technique to locate a continuous broadband noise source was investigated. The off centre source shown in Figure 2 position B was driven with continuous broadband noise, and low pass filtered at 8kHz to avoid spatial aliasing. The resulting contour plot is given in Figure 5a and associated isometric plot in Figure 5b. A clear indication of source location was obtained to within 40 mm of the source position.

5.2 Frequency Domain Beamformer

The frequency domain beamformer was applied to the location of broadband noise at position B, using 24576 data points stored per channel at a sample interval of 40 s. The data were subdivided into 96 blocks. For each block the cross power spectral density (CPSD) has been calculated using a 256 point FFT. The CPSD was then averaged over the 96 blocks. Scanning was then performed (using phase shifts as described in section 2), and the resulting matrix or correlation values displayed or plotted as above. Some results of the analysis are given in Figures 6a to 6d, which show isometric plots of the correlation values at four chosen frequencies 3, 4, 5 and 6 KHz. The location was determined to within 40 mm of the source position in each case. It is interesting to note that as the analysis frequency increases the location peak becomes sharper. This improvement in location is offset by the increase in background level observed, possibly due to the onset of spatial aliasing. Figure 7 shows a contour plot for 3KHz, for comparison with Figure 3a.

6. CONCLUSIONS

An acoustic array and associated data acquisition system has been developed and tested. The delay and sum beamformer and the frequency domain beamformer have been shown to provide suitable array processing methods for the types of acoustic signals considered. The predicted effects of spatial aliasing have been demonstrated. Problems involving tank reverberation have not been apparent, this is possible due to the acoustic absorber wrapped around the model. The ability to locate acoustic sources to within one scale sub-assembly has been clearly demonstrated, and suggests that such techniques may be applied to the reactor environment.

7. FURTHER WORK

It is intended to study quantitatively the array performance in the presence of background noise. More sophisticated array processing strategies using adaptive techniques are envisaged. Further experiments, involving the sources inserted into the simulated sub-assemblies, and using signals representative of the reactor condition are proposed.

8. ACKNOWLEDGEMENT

The authors gratefully acknowledge the help received from Dr M Blakemore of Topexpress Ltd, for his work in developing the array processing techniques.

9. REFERENCES

1 I.D. Macleod and M. Blakemore, 'Acoustic Techniques for the Detection of Boiling in Fast Breeder Reactors', 11th International Congress on Acoustics Paris, 301-304, (1983).

2 I.D. Macleod, E. Catling and C.G. Taylor, 'Acoustic Detection of Boiling in LMFBRs: An Estimate of Sensitivity Derived from Experiments during the Commissioning of PFR', Progress in Nuclear Energy Vol 1, 469-485, (1977).

THE LOCATION OF ACOUSTIC SOURCES IN FAST REACTORS

Figure 1.
Photograph of Model Core

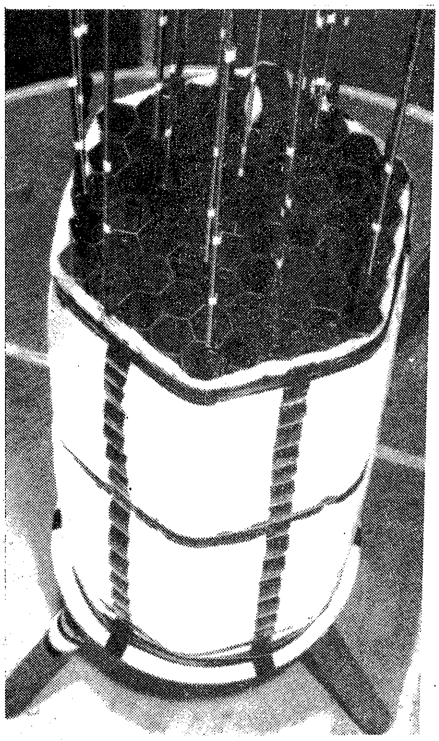
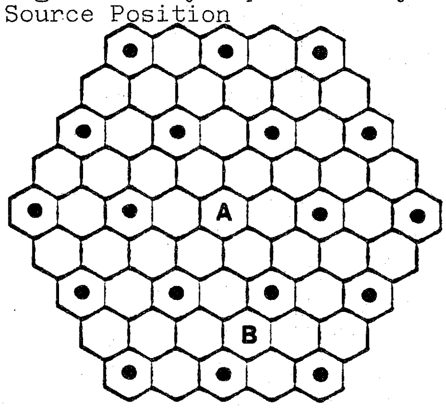


Figure 2. Hydrophone Array and Source Position



● HYDROPHONE POSITIONS
A,B SOURCE POSITIONS

Figure 3a
Contour
Plot

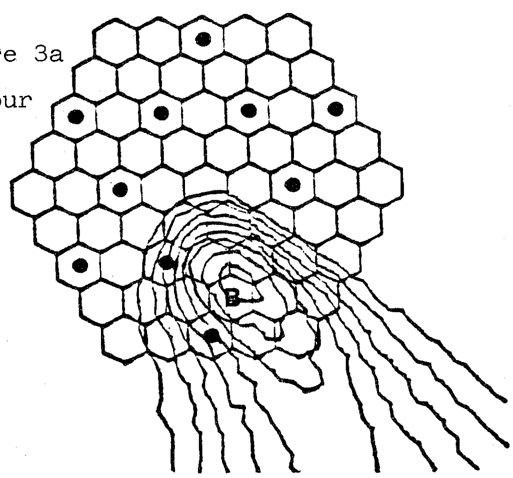
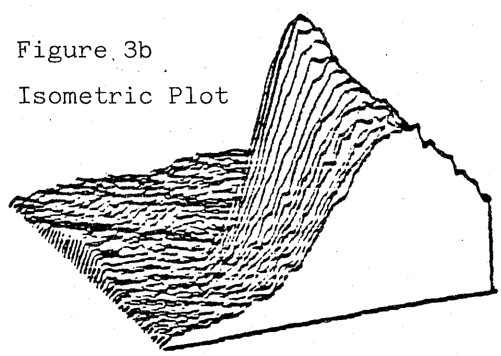


Figure 3b
Isometric Plot



Figures 3a and 3b

Location of 3 kHz Source Using Delay and Sum Beamforming

Fig 4a 1.5 kHz

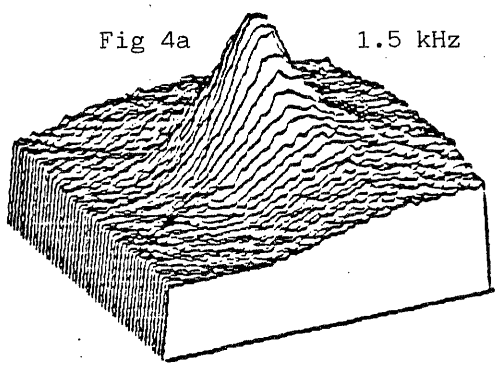


Fig 4b 3 kHz

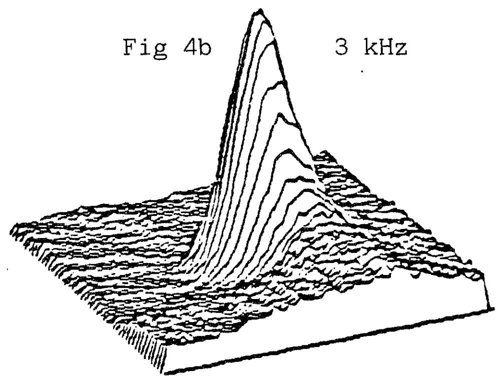


Fig 4c 5 kHz

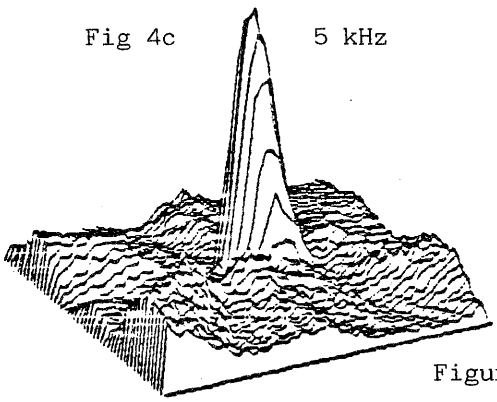
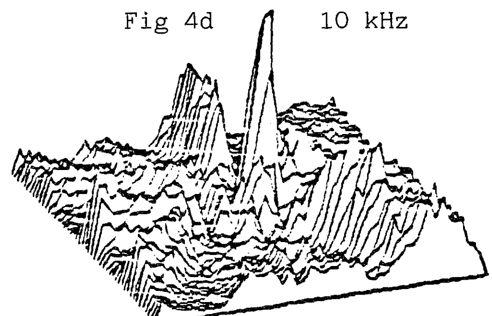


Fig 4d 10 kHz



Figures 4c-4d

The Effect of Source Frequency on Location Using the Delay and Sum Beamformer

Fig 5a Contour Plot

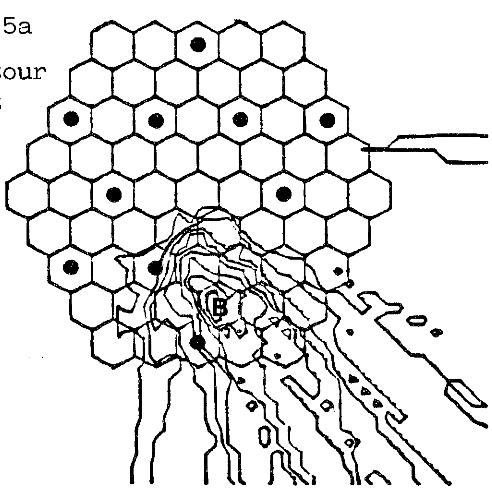
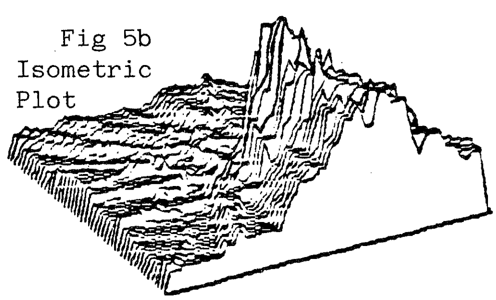
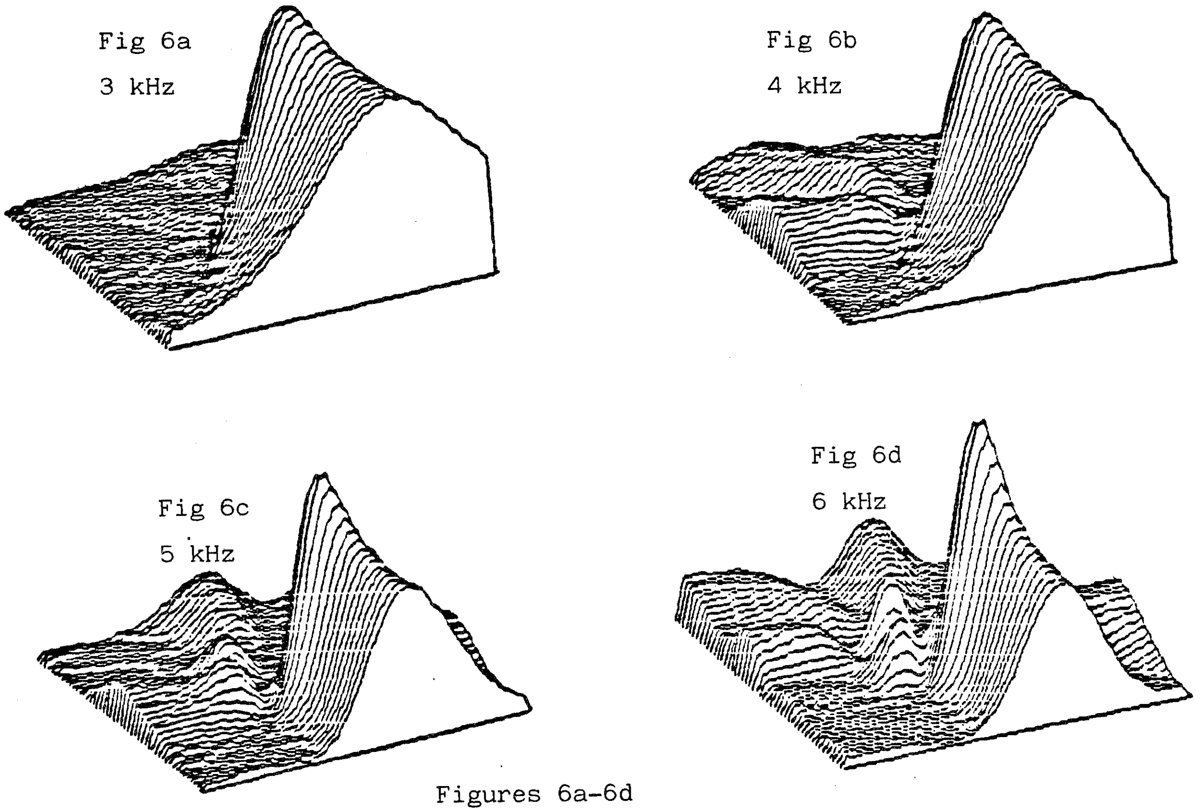


Fig 5b Isometric Plot



Figures 5a and 5b

Source Location of White Noise by Delay and Sum Beamforming



Figures 6a-6d

The Effect of Analysis Frequency on the Location of a Broadband Noise Source using the Frequency Domain Beamformer

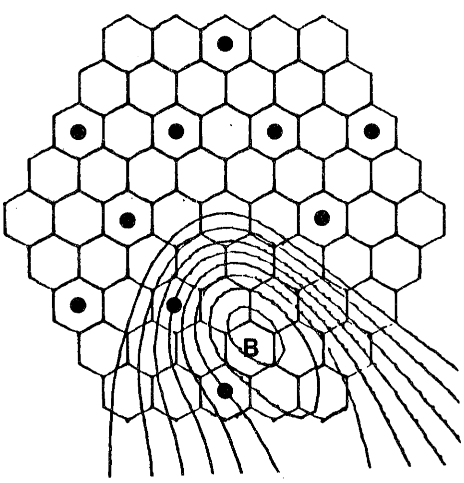


Fig 7

Contour Plot corresponding to Figure 6a