THE ‘THINARRAY’; A LIGHTWEIGHT, ULTRA-THIN (8 mm OD) TOWED ARRAY FOR USE FROM SMALL VESSELS OF OPPORTUNITY.

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Abstract.

Conventional towed arrays are typically 40-80 mm in diameter and weigh >1 kg/m, requiring facilities unavailable on small vessels and inconvenient for submarines. The large diameter is needed to suppress turbulence noise. As the diameter of the array hose increases, so does the weight as the square of this dimension, so that the associated strain relief, bending radius, storage and other operational considerations escalate. There is growing demand for a quality lightweight compact towed array. To achieve this, sensor element, amplifier and overall size must be minimised without compromising turbulence noise performance. This work presents a design that uses miniature cylindrical ceramic sensors and surface mount electronics on an integrated multi-layer PCB only 6 mm wide. A novel turbulence suppression technique is proposed, based on an assumption of near-isotropic turbulence structure scaling with the dimension of the towed body below a critical diameter. By making long and narrow sensors, turbulence noise is averaged incoherently while desired signals in the bandwidth up to 20 kHz are summed coherently, providing signal to turbulence noise gain. An 8mm diameter prototype array has been constructed that can easily be handled by one person. Preliminary acoustic results are given and potential applications explored.

Introduction.

Towed arrays have been in use for many decades, but designers have typically found that an incremental reduction in the overall diameter of the towing tube below some critical value (in the region of 40 mm) results in a concomitant substantial increase in turbulence noise. Towed arrays are usually turbulence noise limited [1] (although often tow-vessel noise limited in the forward endfire beamforming direction) so that this restriction effectively limits the minimum practical diameter of towed arrays. Since towed arrays must be nearly neutrally buoyant to avoid unacceptable array curvature in the water, the density usually exceeds 1 kg/m length. To date, the smallest diameter commercial towed arrays known to these authors are the TB-29 & TB-23 thin-line under development by the US Navy and the Namara and Kariwara developed in Australia. These arrays are still of 30-40 mm in diameter. The result is a large, heavy array that requires substantial dedicated deck handling equipment to deploy and recover it, an expensive and inconvenient arrangement for submarines and impossible for small vessels.

The critical issue is that turbulence noise increases intolerably if the sensors are not large enough to exceed turbulence coherence scales and are not sufficiently separated from the turbulent boundary layer flow adjacent to the external surface of the towing tube. If only these restrictions could be circumvented, towed arrays could be made much smaller, lighter, and suitable for many more vessels, in addition to providing a means to achieve the submariners’ holy grail of towed arrays; internal pressure hull deployment.

Principles of turbulence noise averaging

The primary difficulty in reducing towed array size is turbulence noise. Leading and trailing edge turbulence sources can be suppressed or removed far from acoustic elements by vibration isolation modules (VIMs) and non-acoustic sections. The predominant source of turbulence noise at the sensors is then the surface turbulent boundary layer immediately adjacent to the towed array outer skin. Turbulent boundary layers formed by fluid flow past a surface are characterised by high Reynolds numbers (at speeds and dimensions of interest for towed arrays) and are therefore fully turbulent. Such turbulence has been investigated for fluid-filled elastic cylinders [2] (the case for liquid-filled towed arrays) and is usually considered either dipole (arising from tangential viscous drag at the surface) or quadrupole (arising from fluctuating Reynolds’ stresses).

The detailed modelling is rather complicated but, to first order, the resulting acoustic pressure sensed by an array element appears isotropic in coherence structure, apart from a minor asymmetry incurred due to the non-zero Mach number. For tow speeds of typically 5-10 m/s, this bias is negligible. That is, the spatial auto-correlation function of the turbulence pressure field is independent of spatial orientation, tangential to the towed surface.

If a body is towed through the sea, the boundary layer turbulence coherence scale peaks near $U_c/2\pi f$, where U_c is the turbulent convective speed (about 80% of the tow speed) and f is the frequency [3]. For a tow speed of 12.5 knots, this scale ranges from 1-16 mm at frequencies of 50-800 Hz. This explains why physically large sensor groups and array tubes of 40 mm or more experience a degradation in performance if their diameter is incrementally reduced, since they benefit from incoherent averaging over several coherence scales, suppressing the turbulent flow noise contribution.

Now suppose we are able to make a towed array of overall diameter 8 mm, much smaller than typical array diameters of 40-80 mm. The approximate turbulent coherence scale at typical frequencies of interest is now comparable to the array scale, and so the theoretical results for turbulent boundary layer flow over extended surfaces no longer applies. Once the limits of the dimensions of the towed body are felt by the turbulent boundary layer, coherence begins to scale with towed body size, becoming smaller.

If the towed array sensors are also made of the order 80 mm in length then the sensor will coherently average the turbulence acoustic signal longitudinally over at least 5, and more probably 10 characteristic coherence scales even at the lowest frequencies of interest. This spatial averaging is expected to reduce the coherent turbulence pressure signal by a factor of $\sqrt{10}$, or 10 dB. Thus, longitudinal spatial turbulence averaging could be a very useful turbulence noise suppression technique providing the diameter of the array is reduced significantly below 16 mm. It is proposed that this turbulence noise improvement may sufficiently offset the loss of boundary separation obtained in larger arrays, so providing an acceptable turbulence noise level despite the miniature size.

Thinarray prototype design

We have established that we need to reduce the overall diameter significantly below 16 mm, and we wish to make the acoustic sensors at least 80 mm long. Such a long, narrow sensor can be constructed from connecting many smaller sensors in series, to make a ‘super-element’.

The spatial averaging will only be effective if the desired signal is coherently added without destructive interference loss. For this to be true, the length of the spatial aperture should be small compared to the wavelength of sound of interest. For 20 kHz sound in water, the wavelength is some 76 mm. For lower frequencies, the wavelength is correspondingly longer. An 80 mm sensor would thus not pose a problem except at the highest frequencies of interest and at angles nearing end-fire, i.e. angularly close to the orientation of the long super-element, when an appreciable coherent phase error would be encountered.

In fact, near end-fire sensitivity reduction would not be necessarily undesirable. Near end-fire sensitivity reduction is often arranged using adaptive beamforming techniques in the digital domain to suppress tow vessel source noise. In any event, below 10 kHz or so, the effect is minimal.

A second requirement is to miniaturise the electronics to fit into the same package. Using very small piezoelectric sensors implies that their capacitance will be low, and the weak raw signal must be pre-amplified very close to the sensor to avoid degradation by electrical noise pickup. We selected also to include pre-whitening, low-frequency cutoff and anti-aliasing filters in the same package. The result is a 6-layer printed circuit board (PCB) 6mm across, using only surface mount devices (SMD), with a series of small cylindrical air-backed ceramic sensors mounted on one side, and all electronic components on the other. Signals from other sensors in the array are conducted from one end of the PCB to the other via a separate layer, as are the power bus and ground plane. This avoids the need for separate wires to

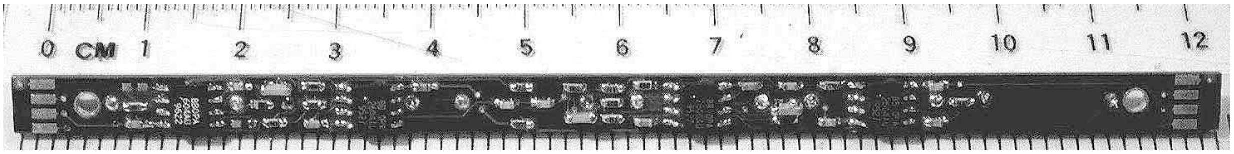

Figure 1. Photograph of a ‘super-element’ PCB showing electronics SMD side. Overall dimensions 6 x 120 mm.

pass the PCB, keeping the cross section to a minimum and reducing diffraction problems. Super-elements are linked by copper wires and a wire or monofilament nylon strain relief. Longer prototypes would probably require carbon fibre or kevlar stranded strain relief. A picture of an assembled super-element PCB is shown in Fig. 1.

Once the super-element design was established, it remained to draw up the overall assembly and related components. For the initial testing prototype, VIMs were not employed, and only a 6m long non-acoustic section was built to distance the first sensor from leading edge turbulence noise caused by the tow cable connector. A conventional multi-fibre streaming tail was provided to suppress fishtailing at the end of the array tube.

The 160m-long tow cable was selected to be significantly more dense than seawater to provide a depressor function without recourse to separate weights or hydrodynamic depressors, which can add turbulence noise. The tow depth was simulated as a function of tow speed with and without a feathering on the cable to suppress strumming. The results are summarised in Fig. 2.

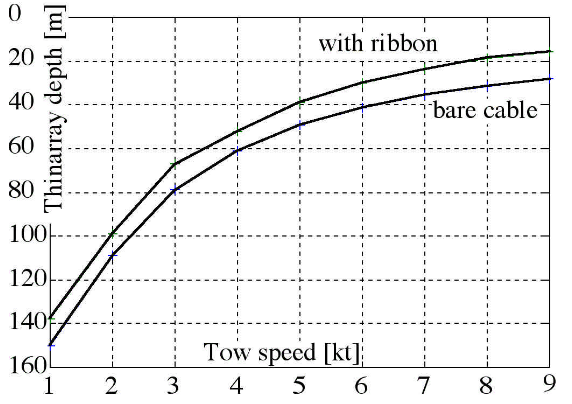

Figure 2. Predicted tow depth vs. tow speed.

With such a small and neutrally-buoyant thinarray, the predicted tow depth was easily sufficient to escape low sea-state surface wave action for tow speeds up to 9 knots. Actual tow depth was confirmed by a pressure sensor fitted to the end of the tow cable.

A SONY DAT recorder on board the towing vessel acquired the data. The thinarray preamplifier and pressure sensor were powered by separate batteries housed in a surface control box to minimise electronic pickup noise.

The prototype thinarray was inserted into a silicone tube with internal diameter 6mm and external diameter 8mm. The silicone provides a 1 mm visco-elastic layer, within which the super-elements were elastically supported by mild interference contact with the inside of the tube. The internal void spaces of the tube were filled with castor oil; a nearly-neutrally-dense and almost chemically inert viscous fluid acoustic coupling medium. The use of a visco-elastic shield and viscous fluid interior has been shown to be particularly effective in reducing low-wavenumber turbulent noise [4].

Results of preliminary prototype testing

The prototype thinarray was deployed on several occasions in Singapore coastal waters. The ambient noise in these waters is dominated below a few kHz by very heavy shipping and at higher frequencies by snapping shrimp (to over 300 kHz) [5]. The prototype analogue filters and post-processing was configured to suppress acoustic energy below 200 Hz as the usual low-frequency noise suppression techniques (VIM's, etc.) were not being employed for ease of construction. If our turbulence noise scaling and incoherent averaging were not to work, we would expect considerable turbulence noise at frequencies extending far above this 200 Hz cutoff. Future prototypes will be configured to operate down to 50 Hz. The upper frequency cutoff was 24 kHz, corresponding to the Nyquist frequency of our DAT recording system. Recorded data were digitally corrected for the analogue pre-whitening on playback.

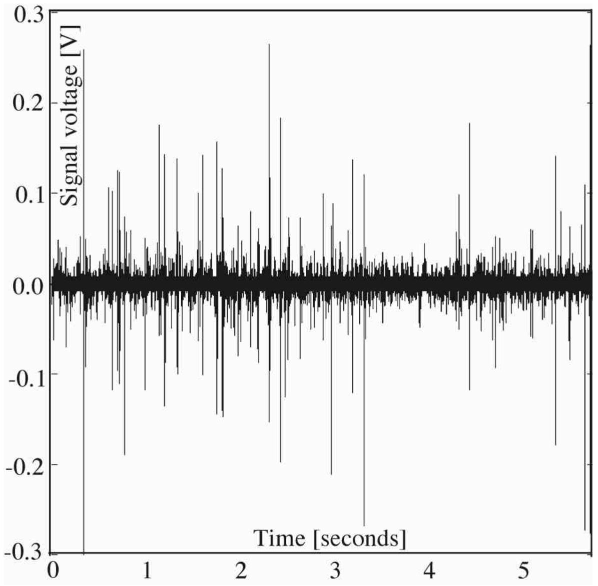

Figure 3. Sample time series of thinarray data.

A representative sample of just over 5 seconds of time series obtained from the thinarray is shown in Fig. 3. The data were taken near Raffles Lighthouse in Singapore, out of the way of major shipping channels and anchorages, over the shallow continental shelf where snapping shrimp are common. The tow speed was 8 knots. The characteristic sharp transients of snapping shrimp are clearly evident. The background noise level from shipping, surface wave action and turbulence is obviously of much lesser amplitude and appears as a solid block of perhaps 10% of the snapping shrimp transient amplitude. To visualise the non-shrimp contribution in greater detail requires a time-frequency analysis.

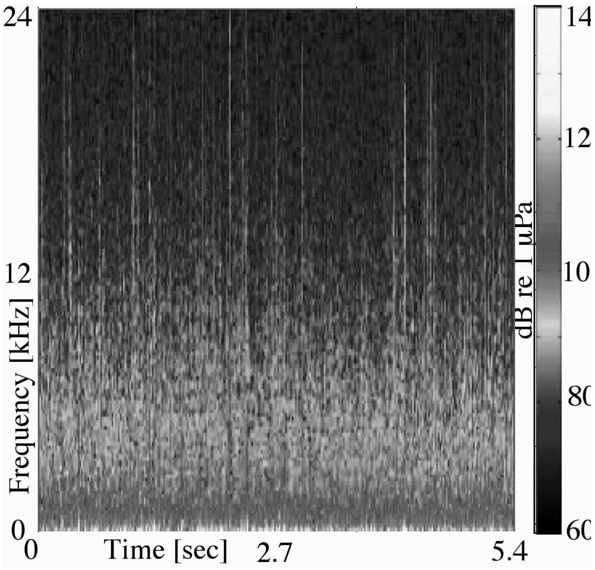

Figure 4. Spectrogram of sample dataset.

Fig. 4 shows a spectrogram of the same sample dataset. The spectrogram was calculated by the Walsh overlapping discrete windowed Fourier Transform algorithm with Hanning window shading. The snapping shrimp appear once again as sharp, broadband transients. The signal to self-noise dynamic range exceeds 80 dB at higher frequencies, indicating that electronic self-noise is negligible. Fig. 4 also clearly shows the temporally-smooth coloured background noise spectrum characteristic of open-sea ambient noise and heavy shipping. It is not clear form either Fig. 3 or 4 how significant turbulence noise might be, but it is clearly not so large as to preclude useful ambient noise observations. Listening to the time series used to construct these figures, no turbulence noise is evident.

Discussion

Although it would be premature to claim that the miniaturisation and turbulence averaging technique proposed here ‘solves’ the turbulent noise problem, the data quality is clearly sufficient to permit ambient noise measurements with a quality that would not be expected from conventional wisdom for a small towed array. The potential benefits in being able to produce a miniature towed array of perhaps 5% of the weight of a conventional array are so substantial that it seems unquestionable that the idea is worth pursuing. If it were possible to obtain quality data from such a small array, small ships of opportunity could collect valuable acoustic data in support of many types of marine research without dedicated deck gear. This is perhaps of particular interest for marine mammal and anthropogenic noise impact and mitigation research. At the same time, the drastically reduced size may pave the way forward to realising the submariner’s dream; a towed array that can be housed and reeled in and out from within the pressure hull.

Conclusion

By breaking away from conventional towed array diameter limitations, it seems plausible that the turbulent flow regime can be changed and scaled with the diameter of the towed body. Whereas an incremental reduction in towed array size below 40 mm increases turbulence noise, a drastic reduction in overall diameter to below 16 mm may produce acceptable results. Coupled with longitudinal turbulence averaging, enhanced by the reduced characteristic turbulence pressure field correlation length, comparable quality ambient noise results might be obtainable from an array with only 5% of the cross-section and associated wieght of conventional arrays. Preliminary testing indicates there is reasonable hope that this may be made to work in practice. Further research and development is now planned to build a longer prototype with 8 nested elements, operating down to 50 Hz and at tow speeds up to 14 knots.

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References

[1] A. Knight, *Flow noise calculations for extended hydrophones in fluid and solid-filled towed arrays.*

Journal of the Acoustical Society of America, 1996. **100**(1): p. 245.

[2] S.H. Francis, M. Slazak, and J.G. Berryman, *Response of elastic cylinders to convective flow noise. I. Homogeneous, layered cylinders.* Journal of the Acoustical Society of America, 1984. **75**(1): p. 166.

[3] W. Blake, *Fundamental underwater noise sources*, in *Encyclopedia of Acoustics*, M.J. Crocker, Editor. 1997, John Wiley & Sons: New York. p. 501-520.

[4] A.P. Dowling, *Underwater flow noise*. in *Theoretical and Computational Fluid Dynamics*. 1998: Springer-Verlag. p. 135-

[5] L. Hong, T. B. Koay, J. R. Potter & S. H. Ong, *Estimating snapping shrimp noise in warm shallow water*. in *Oceanology International ‘99.* 1999. Singapore: Spearhead Exhibitions. P. 441-451.