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Measurement of radiated noise using a vessel's own towed array – a progress report

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Abstract

This paper describes progress to date on a project to investigate the feasibility of using a vessel's own towed array to measure the underwater noise radiated by the vessel.

Aspects of the problem discussed include the determination of array shape, the development of a forward simulation to provide data for algorithm development, the effects of ocean boundaries, the requirements for dynamic near-field beam forming / imaging, and the prediction of far-field signatures from the array data.

1. Introduction

All vessels radiate sound into the water to a greater or lesser extent as an inevitable by-product of the mechanical energy required to drive them through the fluid. To operators of most pleasure and commercial craft this is of little or no importance but to submariners and the crews of military surface vessels radiated underwater sound can be a critical factor in determining the vulnerability of their vessel to detection by a threat.

Fixed and portable acoustic ranges (see for example Mathews et al. 2000) have been developed to measure the acoustic radiation from vessels and, when coupled with acoustic propagation and ambient noise models, these measurements can provide reasonable estimates of the vulnerability of a particular vessel to detection in a given situation, *providing the acoustic signature of the vessel has not altered since it was measured*.

This last proviso can be of critical importance where a vessel is to be deployed into a theatre of operations at short notice, and it has been some considerable time since its acoustic signature was measured. Wear of machinery, minor propeller damage, and differences between the operational state of the vessel and its state when measured can all make significant differences to the acoustic signature of the vessel. Such differences in operational state could include a different fuel load, a requirement to operate at a different speed, or the use of some combination of auxiliary equipment that was not used when ranging took place.

It is thus extremely attractive for a vessel to have a means of measuring its own acoustic signature, or at least detecting changes in its signature, without recourse to a normal fixed or portable range and without relying on the presence of any other vessel or aircraft. Submarines are commonly fitted with hull mounted self-noise hydrophones for this purpose but it is highly problematic to accurately relate the far-field signature of the vessel to these near-field measurements.

Military surface vessels and submarines commonly carry towed arrays for the detection and tracking of other vessels. These arrays are streamed behind the vessel, may have a total length of more than 800 m and are typically populated with around 100 hydrophones. A diagram of a generic towed array is shown in Figure 1. The array shown has a total of 97 hydrophones arranged in three sub-arrays, each comprising 49 hydrophones. The total number of hydrophones and associated processing channels is minimized by designing the acoustic section so that some hydrophones are common to two or three sub-arrays.

By carrying out an appropriate manoeuvre it is possible

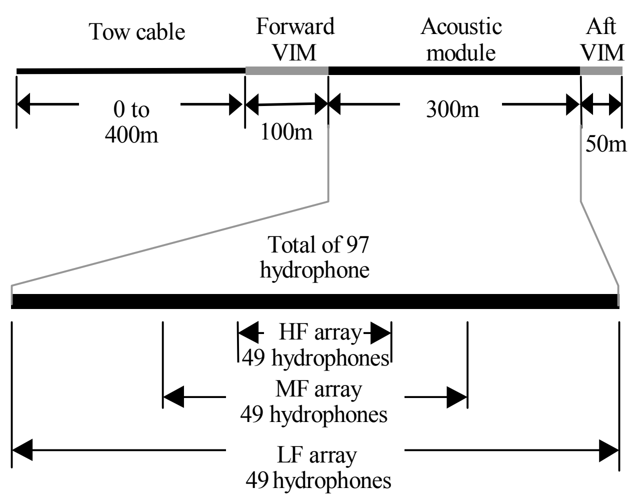

Figure 1 Schematic representation of a generic towed array. VIM = vibration isolation module. HF = high frequency, MF = medium frequency, LF = low frequency.

for a vessel towing such an array to bring the acoustic section of the array into a position that is favorable for imaging noise sources on the vessel. As will be seen below, while not necessarily in the true acoustic far-field of the vessel, the acoustic sub-arrays are at sufficient range that they are in the far-field of individual vessel noise sources and consequently the corrections required to estimate the far-field signature of the entire vessel are expected to be relatively minor (Anderson & McMahon 2000).

The research described in this paper forms the principal author's Ph.D. research topic which aims to explore the practical issues associated with using a vessel's own towed array for radiated acoustic noise measurement. There are many components to the task of predicting the performance of such a measurement method and the following sections detail the most significant of these and outline the progress that has been made on each so far.

2. Towed array hydrodynamic simulation

An initial requirement for this research was a method of determining realistic shapes for a towed array during a manoeuvre and the resultant hydrophone positions relative to the vessel. To this end a two-dimensional (horizontal plane) lumped-mass hydrodynamic simulation of a towed array was written in Matlab. The simulation uses reasonable estimates of the hydrodynamic and mechanical parameters of a typical towed array rather than measured values for a particular array and is intended to provide realistic results for simulation purposes and algorithm development rather than an accurate prediction for operational purposes.

The simulation output for one manoeuvre is shown in figures 2 and 3. Figure 2 shows the vessel and array positions in global coordinates whereas Figure 3 shows the position of the acoustic module of the array relative to the vessel during the manoeuvre. The latter figure is particularly revealing and leads to a number of important observations:

1. The acoustic module is in a reasonably good position and orientation to image the vessel from the 200 second mark to the 300 second mark. During this period the array is at a range of approximately 500 m from the vessel.
2. The motion of the hydrophones relative to the vessel is rapid (about 8 m/s) and the array shape and orientation also change quite rapidly. Note however that this simulation is for the relatively high tow speed of 5 m/s (10 knots) and that the relative speeds are proportionately slower at lower vessel speeds. To a first approximation the path the array takes is independent of tow speed so that array shapes at lower speeds can be estimated simply by changing the time labels on the plots appropriately.
3. Acoustic sources on the vessel are in the near-field of the acoustic sub-arrays, with l^2/λ being 7200 m, 3600 m and 1800 m at the design frequencies of the LF, MF and HF sub-arrays respectively. (l is the length of the sub-array, and λ is the acoustic wavelength. The design frequency is the frequency at which the hydrophone spacing is half a wavelength.)

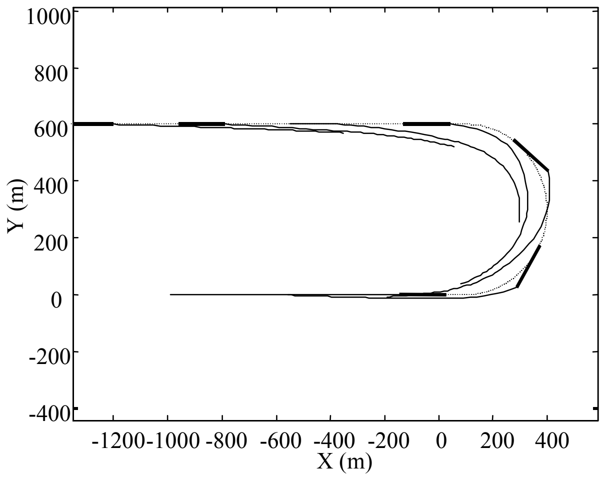

Figure 2 Six snap-shots of the simulated towed array shape during a U-turn manoeuvre. Thick line is vessel, dotted line is vessel track, thin line is towed array. Simulation starts with vessel at (0, 0) and moving to the right. Vessel speed = 5 m/s, turn radius = 300 m, tow cable length = 400 m.

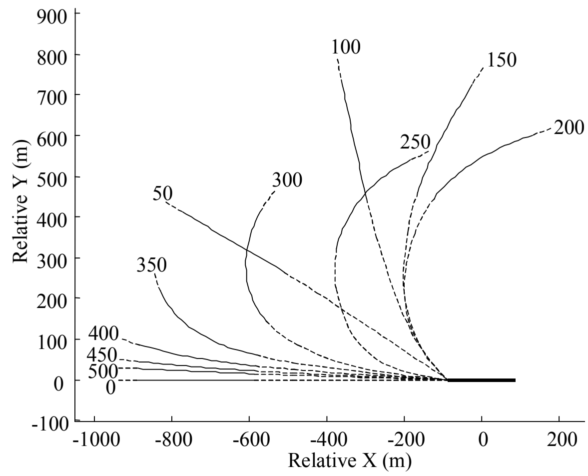

Figure 3 Simulated towed array shape relative to the tow vessel for the same manoeuvre as in Figure 2. Thick line is tow vessel, thin line is acoustic module, broken line is remainder of array. Numbers are time in seconds from start of simulation.

4. The hydrophones sample radiation emitted in a range of directions from slightly forward of the beam to directly aft of the vessel.
5. The time at which the array extends the most in a forward direction corresponds to the time at which the vessel straightens up after the turn.
6. During the first half of the manoeuvre there is a significant angle between the vessel and the tow cable where it leaves the aft end of the vessel. Avoiding violating the tow cable's minimum bend radius requirement at this point is likely to determine the minimum vessel turn radius that can be used.

3. Development of a forward simulation

A major component of the work on this project so far has been the development of a numerical simulation (in Matlab) of typical vessel noise sources and the propagation of these sounds to the moving hydrophones.

3.1 Simulation of typical vessel noise sources

The simulation has been configured to allow a variety of different noise sources to be specified and placed at arbitrary positions on the vessel. Far-field interfering sources and uncorrelated noise with a spectrum typical of noise in oceans and seas around Australia have also be included.

For reasons of computational efficiency each source has been approximated as a point source with a beam pattern that may be frequency dependent or frequency independent. This is a good approximation as can be seen by using the far-field criterion for a circular piston given in Medwin & Clay 1998, $R > \dfrac{\pi a^2}{\lambda}$ where R is the distance from the piston to the hydrophone and a is the radius of the piston, to solve for the piston radius for a hydrophone range of 500 m. The far-field criterion is met for all sources smaller than the calculated values shown in Table 1.

Table 1 Maximum radius of circular piston source that meets far-field criterion at a range of 500 m

Frequency (Hz)	**Maximum source radius (m)**
10	155
50	69
100	49
500	22

Surface vessel noise is usually dominated by propeller cavitation noise, although at low speed other noise sources may dominate. Cavitation noise has a broadband component due to the collapse of individual cavitation bubbles and a narrowband component due to fluctuations in the overall cavitation volume attached to each blade as the blade encounters different flow velocities and hydrostatic pressures through a revolution. Narrowband cavitation is at the blade passage frequency and its harmonics, whereas broadband cavitation has a wide frequency spectrum, usually peaking at around 100 Hz.

Broadband cavitation noise has been simulated by generating a sequence of gaussian random numbers of the required length, Fourier transforming this sequence to the frequency domain, applying a frequency domain filter of the required spectral shape, and then inverse Fourier transforming back to the time domain. The resultant time series can optionally be amplitude modulated at the shaft and blade rates.

Narrowband cavitation noise has been simulated by summing a deterministic and random component. The deterministic component was generated by summing sine waves with frequencies equal to the blade rate and its harmonics. The random component was generated in a manner similar to broadband cavitation noise but in this case band-pass filters were used centered on the blade-rate frequency and its harmonics. The filter bandwidths and relative amplitudes of the deterministic and random components were chosen to give time series with similar modulation characteristics to measurements reported in Gray 1981.

Due to a lack of consistency in the reported measurements cavitation noise has been simulated as having an omni-directional beam pattern even though there is some evidence in the literature for dips in the sound levels in the fore and aft directions (see for example Urick 1983).

Figure 4 shows the spectrum of the simulated propeller

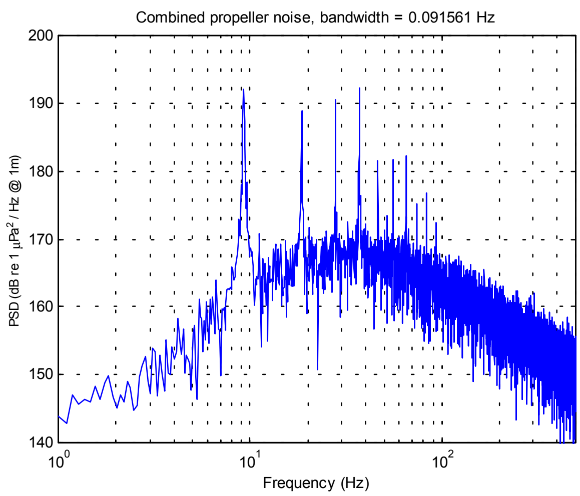

Figure 4. Simulated propeller cavitation noise for a bulk carrier

noise for a bulk carrier operating at 16 knots. The narrowband cavitation noise peaks can be clearly seen superimposed on the background of broadband cavitation noise .

Non-cavitating propellers also radiate sound, but generally at much lower levels than cavitating propellers and with a dipole (cosine) beam pattern which has a null at right angles to the propeller shaft. The primary mechanism is fluctuations in the force exerted on the fluid by the propeller as each propeller blade encounters different inflow velocities during a revolution. This mechanism directly radiates sound but can also excite resonances of the propeller blade and the hull which can greatly enhance the radiation (see Ross 1987).

Only direct radiation of non-cavitating propellers has been simulated so far. The characteristics of this mechanism are very similar to narrowband cavitation and it has been simulated by the same method apart from making due allowance for the lower source levels and different beam pattern.

The vibrations of rotating and reciprocating machinery can be coupled to the hull of the vessel by various structural elements and then radiate into the water as sound. All of these sources can be modeled as a well defined sequence of harmonics, possibly with some additional amplitude modulation, and this led to a simple implementation in the simulation as a sum of sinusoids. The beam pattern of the radiation depends on the detail of the excited hull vibrations and so a number of options have been provided for, including omni-directional, circular pistons and rectangular pistons. More can be easily added as the need arises.

Several generic sources have also been included in the simulation for test purposes. These include a tone-burst source and a general broad-band source. In both cases a variety of beam patterns can be specified.

3.2 Acoustic propagation modeling

The simulation will include three levels of complexity in modeling acoustic propagation from the sources to the hydrophones: boundless ocean, deep ocean, and shallow ocean. At the time of writing the boundless ocean case has been fully implemented, implementation of the deep ocean case is close to complete, and some preliminary work has been done on investigating algorithms appropriate to the shallow ocean case.

The boundless ocean case ignores the water surface and seabed reflections and deals only with the direct acoustic path between the source and hydrophone. This is quite straightforward in the case of a frequency independent beam pattern as the only requirement is the appropriate scaling and time shifting of the signal. For a frequency dependent beam pattern and a rapidly moving hydrophone, however, there is a significant complication because the beam pattern acts as a filter with a time varying frequency response. Although this situation can be dealt with exactly the computational cost is large and consequently an approximate method was devised which makes use of the relatively slow change in frequency response with time for realistic beam patterns and hydrophone motions.

The deep ocean case adds the complications of reflection and scattering at the water-air interface. Reflection is most conveniently dealt with by introducing a mirror image source corresponding to each real source on the vessel. Scattering has two effects - it reduces the amplitude of the coherently reflected signal and introduces an incoherently scattered signal with random phase. The reduction in amplitude of the coherent signal can be simply modeled in terms of the surface roughness, the acoustic wavelength and the angle of incidence (see, for example, Medwin & Clay 1998) whereas the calculation of the amplitude of the incoherent signal is significantly more complex and, for all but the simplest geometry, requires numerical integration over the region of sea surface contributing to the scattering. An efficient method of carrying out these calculations is currently being developed and will shortly be incorporated in the simulation.

Modeling propagation in the shallow ocean introduces another boundary - the sea floor - the acoustic properties of which are often not well known. A great deal of effort has been expended by many people on trying to accurately predict acoustic propagation in shallow water and a number of different techniques have emerged and been implemented in what have become standard numerical models. These include normal mode models (eg KRAKEN), parabolic equation models (eg RAM) and fast-field models (eg OASIS). Useful summaries of these methods are given in Etter 1991. Normal mode and parabolic equation models are intended for the prediction of propagation over ranges that are long compared to the water depth and are unlikely to give good results at the short ranges required for this simulation. Fast Field models are applicable to both short and long range propagation where the water depth and medium properties are independent of range (Kuperman et al. 1985). The Fast Field approach is being considered for this simulation although the rapid relative motions of the hydrophones and sources will require the development of special techniques. .

An alternative approach is outlined in Tolstoy & Clay 1987, and is an extension of the image method described above for the deep ocean case. In principle the presence of both an upper and lower boundary results in an infinite number of image sources. However, providing the lower (seabed) interface is lossy only a relatively small number of these image sources are important contributors to the received signal at short range, making the calculation manageable. Using this approach the seabed would be defined in terms of its complex plane wave reflection coefficient as a function of incidence angle and frequency, and a correction given in Brekovskikh 1960 would be used to correct the reflection coefficient for the spherical divergence of the sound waves. (This correction is not required for reflection at the sea surface because at that interface the plane wave reflection coefficient is independent of the angle of incidence.) This approach is valid providing the angle of incidence is less than the critical angle and $kr >> 1$ where k is the acoustic wavenumber and r is the slant distance between the image source and receiver, which for r =500 m translates to $f >> 0.5$ Hz where f is frequency. Difficulties with this approach occur for incidence angles at and above the critical angle where beam displacement effects and the existence of interface waves make the simple image method less accurate and more complex to apply.

The image method has the advantage of being easily implemented with minor modifications to the code already developed for the deep ocean case. Sea surface scattering can also be handled in the same manner as for the deep ocean case.

4. Beamforming

Algorithms

From the discussion in Section 2 it is apparent that the algorithm used to perform the beamforming operation has to perform near-field beamforming in a situation in which both the array shape and the relative location of the source being tracked are changing rapidly with time.

There are many different beamforming algorithms of varying degrees of sophistication and efficiency described in the literature (see Krim & Veberg 1996, or Owsley 1985 for useful summaries), but none to the authors' knowledge that deal with the complexities of this particular requirement.

The saving grace is that the sources of interest are located on a relatively small, and known surface - the vessel hull. This should make it practical to apply a modification of delay and sum beamforming to dynamically focus the array at the required locations, with the delays being computed using the instantaneous locations of the hydrophones.

The dynamic nature of the beamforming problem may, in fact, turn out to be an advantage when it comes to suppressing interference from surface and seabed reflections and from far-field sources which will tend to be defocused as the array tracks the vessel.

Prediction of far-field signature

The results given in Table 1 show that in most cases the hydrophones will be in the far-field of the vessel noise sources, however it will be necessary to remove the effects of surface and seabed reflections in order to determine the source levels appropriate for computation of far-field signatures in different propagation conditions. There are a number of possible approaches to this:

- As mentioned above, dynamic near-field beamforming will tend to defocus the multipath arrivals relative to the direct path. The effectiveness of this mechanism is likely to be frequency dependent with it being least effective at low frequencies.
- Providing the depths of the sources and hydrophones and the sea state are known it should be possible to calculate and correct for the energy transmitted by the surface reflected path.
- If the seabed reflectivity is known then it would also be possible to compensate for the energy transmitted by bottom reflected paths. For this to be practical some in-situ method of determining the bottom reflectivity would have to be devised (see Kuperman et al. 1985 for one possible method).
- In the case of broadband sources it should be possible to detect significant multipath arrivals by autocorrelation techniques and then correct for them. This is complicated by the fact that in general the relative time delays of the multipaths will be changing quite rapidly, but given that the geometry is already reasonably well known it should be possible to compensate for this.

In the case of a high frequency source of large spatial extent or horizontally well separated sources that are coherent the far-field criterion may be violated and the computation of the vessel's far-field signature would become somewhat more complex. In this case, however, the shape of the source in the horizontal plane is likely to be resolvable by the beamformer which would allow the appropriate corrections to be calculated.

Hydrophone position errors

An important part of this project will be determining the required hydrophone position estimation accuracy for acceptable beamformer performance, and whether this degree of accuracy is likely to be achievable in practice.

A number of towed array shape estimation methods have been reported in the literature including those based on Kalman filters which use heading and depth sensors on the array as inputs (Gray, Anderson & Bitmead 1993, Riley & Gray 1993), and those that effectively use acoustic data from the array to find the shape that provides the sharpest focus (Quinn et al. 1993, Wahl 1993). If these methods are unable to provide the required accuracy then a third possibility would be to equip the vessel with one or two acoustic sources in known locations that emits short bursts of sound at the upper end of the array hydrophones' frequency range. Although obviously not covert, and therefore more limited in application, this would provide an accurate and straightforward way of determining the array shape.

Conclusions

This paper has summarised the work that has been carried out on an investigation of the practicalities of using a vessel's own towed array to measure its radiated acoustic noise signature, and has also scoped the issues that are still to be addressed and the approaches that are likely to be taken to tackling them.

Although there is still much work to be done, and there is no guarantee that the approaches outlined here will be the ones finally adopted, this technique appears to have the potential to be a very useful addition to existing signature measurement methods.

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