Advanced Sonar Technologies For 21st Century Torpedoes and UUVs

James G. Kelly and Gerald T. Stevens
Naval Undersea Warfare Center Division Newport
Newport, RI – Tel 401 832 4558
Kellyjg@npt.nuwc.navy.mil

Fred Nussbaum
Anteon Corporation
Middletown, RI
401 832 3188
nussbaumf@npt.nuwc.navy.mil

Abstract

The US Navy needs to develop advanced sonar technology for torpedoes and UUVs to conduct effective operations in littoral waters that are defended by increasingly sophisticated platforms, weapons and countermeasures. To deal with these challenges, torpedo sonars must provide more acoustic resolution than was formerly required for open ocean ASW. This will drive designs of advanced torpedo sonars to differ markedly from the torpedo sonars currently in use. For example, to double acoustic resolution, the number of sensors in a torpedo sonar will quadruple. To address the technical issues associated with higher sensor counts, consideration is given to separating acoustic transmit and receive hardware functions. Processing hundreds of sensor signals in real time poses technical (and cost) challenges. Ongoing development at NUWC of advanced sonar transducer and array technology and development of advanced signal conditioning and processing hardware technology is the subject of this paper

Introduction

Prior to the last decade the US Navy's ASW mission was to prosecute threat submarines in open ocean. Today and for the foreseeable future the most likely engagement sites are in the littoral, but current fleet torpedoes that were introduced in the 1970's and 1980's are optimized to detect and home on targets in deep water. Although current torpedoes can operate effectively in some benign shallow water environments they do not approach their (deep-water) performance effectiveness when operating in the harsh acoustic environments found at many potential littoral conflict sites. This, coupled with proliferation among our potential adversaries of quiet air independent powered submarines, advanced torpedoes and sophisticated weapon countermeasures provides impetus to the Navy to develop an advanced torpedo that can operate effectively in both open ocean and littoral environments.

Environmental conditions that make it difficult for an acoustic homing torpedo to operate effectively in shallow water include false targets, reverberation from surface and bottom boundaries, and sound velocity profiles that exhibit large unpredictable depth/horizontal gradients over short ranges. Echo returns from relatively nearby targets (and false targets) arrive via multiple paths with varying angles of arrival and a range of time delays. Under these conditions, range and bearing to a target are more difficult to estimate to an acceptable level of confidence. A straightforward way to improve range and bearing measurement is to increase acoustic resolution (narrow the beams) of a torpedo's homing sonar. That will enable receive angles of target echo returns to be measured more precisely.

Since diameters of US torpedoes are fixed and will remain so for the foreseeable future, the physical aperture of an advanced (nose mounted) sonar will not be much greater than apertures of current sonars. To increase acoustic resolution it will therefore be necessary for an advanced torpedo sonar to operate at higher frequencies. Increasing the operating frequency of a sonar will increase its acoustic aperture provided its physical aperture is unchanged. The downside is that absorption of acoustic energy increases at higher frequencies and that reduces target detection ranges. This penalty is outweighed by the reality that in certain littoral conditions only a high-resolution sonar can operate effectively albeit at shorter ranges.

The reason that current torpedo sonars don't provide the angular resolution needed to be effective in shallow water is that their (1970's – 80's) design was subject to a trade-off to maximize detection ranges in <u>deep water</u> while maintaining enough bearing resolution to home effectively. That tradeoff <u>minimized</u> operating frequencies, which reduced acoustic aperture, which reduced angular resolution. At the time, this was an effective sonar and homing system design since it was adopted before the advent of sophisticated weapon countermeasures. But given the serious challenge to open ocean ASW that is posed by modern countermeasures, the effectiveness of torpedoes operating in deep water can also be improved significantly if their "low frequency" sonars were supplemented with a high-resolution capability.

Ideally, a torpedo sonar and homing system should be able to operate effectively in both deep water and shallow water environments. Countermeasures will challenge torpedoes in both environments and to defeat them it is necessary for torpedo sonars to operate over a wide band of frequencies. For open ocean operation where "low frequencies" are advantageous (because they enable longer detection ranges), a torpedo sonar must be able to operate over a range of "low frequencies". Similarly in shallow water a torpedo sonar must be able to operate over a wide range of "high frequencies". Such "frequency agility" will provide effective capability to defeat modern countermeasures.

In addition to "frequency agility", the capability of a sonar to operate over wide bandwidths will confer significant benefits. Wide bandwidth is required to use advanced waveforms, and when operating in shallow water wide bandwidth is needed to avoid data starvation in situations where frequency dependent fading occurs. Small changes in relative positions of torpedo and target have been observed to cause echo returns to fade abruptly at one frequency and appear abruptly at a different frequency.

At this point it is helpful to highlight differences between torpedoes and UUVs, in particular the differences that influence the design and operation of their acoustic sensors. Torpedoes, because of the nature of their missions, operate at high speeds, 25 knots and generally much higher . . . UUVs typically operate at much lower speeds. A consequence of this difference is that conformal flank mounted sonars can be used on a UUV but not on a torpedo because the high level of flow noise generated at torpedo speeds will mask flank mounted acoustic sensors. This constrains torpedoes to use homing sonars that are mounted in the nose where flow noise can be controlled.

Although there is more latitude for UUVs in the choice of sensor suites, most UUVs will be fitted with a forward looking sonar in addition to the other acoustic sensors they may carry. A forward looking sonar is essential for obstacle avoidance and in many cases will be employed to select objects of interest, e.g., prior to conducting a high resolution scan with a side looking sonar. When used to select objects for closer examination or for destruction (as in mine clearing), a forward looking sonar that has "higher" resolution will be more effective at rejecting false targets that would otherwise waste time and assets. So for certain UUVs a forward-looking sonar similar to that needed for advanced torpedoes would prove of value.

Following is a discussion of the engineering and design challenges posed by a torpedo sonar that can transmit and receive acoustic signals over a range of frequencies spanning nearly two octaves.

Design of a Wide Band Torpedo Sonar

To discuss technologies that need to be developed and their associated engineering challenges, we postulate a notional torpedo sonar that can operate over a frequency range of 15kHz to 50kHz.

The upper limit of this sonar's operating frequency band dictates its sensor spacing and sensor count. To function effectively acoustic sensors will be spaced a bit more than 1/2 inch apart (half wavelength at 50 kHz). If the sensor spacing was appreciably more than half wavelength the sonar would generate aliasing (grating) side lobes and spatial discrimination would be degraded. This is a fundamental constraint on any sonar array and cannot be disregarded. With sensors spaced ~1/2 inch apart that criterion is satisfied at all frequencies lower than 50 kHz. At lower frequencies the array will oversample the acoustic field but that will not degrade performance.

With a center-to-center spacing of ~1/2 inch, the fully populated array will contain approximately 500 sensors. While it is possible to maintain proper spacing with fewer sensors (by randomly deleting sensors from the array) that would degrade sidelobe control. The more sensors deleted, the higher the resulting sidelobe levels. For example, if a beamwidth of 6° is required at 50 kHz and if the count were reduced by half to 250 sensors, analysis indicates that sidelobe levels could not be brought below -25 dB. Actual sidelobe levels would likely be higher. Since low sidelobes are essential to reduce reverberation returns (which are particularly problematical in shallow water environments), this sonar will have a fully populated array.

How to configure the sonar? First we summarize what we want the notional sonar to do. It should be able to project acoustic signals over a band of frequencies ranging from 15 kHz to 50 kHz at high power levels. It should be able to receive acoustic signals, both echo returns and target generated noise, over that same frequency band broadened slightly by own and target doppler. The operating frequency band of this sonar will span nearly two octaves.

There are hydrophone technologies that can be configured to a sensor head size of ~1/2 inch and that are able to receive acoustic signals over the frequency range of 15-50 kHz. But there is no active transducer technology that (if limited to one sensor design) can project acoustic signals (at the power levels required for torpedo operation) over that band of frequencies. To do that will require a number of different active transducers with a range of head sizes. Therefore, to configure this sonar, the acoustic transducer hardware functions will be separate and independent.

A two-layer arrangement of transducers is proposed for this nose-mounted sonar. An array of active acoustic projectors is the bottom layer and a hydrophone array is the top layer. The hydrophone array will consist of ~500 sensors that function to receive acoustic signals over the full (15-50 kHz) frequency range of the sonar. Outputs of the hydrophones will be <u>individually</u> processed to provide optimum resolution over the operating band. The bottom array of acoustic projectors (perhaps numbering as many as 100, probably fewer) will be employed exclusively to transmit high power acoustic signals.

The hydrophone array is thin and relatively transparent to acoustic energy; it is mounted directly over the active transducer array. This configuration enables both arrays to use the entire available physical aperture.

Design of the Active Transducer Array

The output of the receive array will usually be processed to provide maximum resolution, that is to produce the narrowest possible <u>steered</u> beams commensurate with required side lobe control. But when transmitting signals into the medium it is not always desirable to use narrow beams. At the low end of the operating band, where beamwidths are relatively wide, transmitting a small number of sequentially steered beams can be useful. But at the high end of the band, where beamwidths are much narrower, the time required to illuminate the environment with sequentially transmitted beams will reduce volume search rates to an unacceptable degree. So at high frequencies transmit beams will be shaped and broadened to cover as much of the search volume as possible while minimizing illumination of boundaries.

To transmit acoustic signals over this sonar's full frequency range (15-50 kHz), a number of transducers of differing design that operate in contiguous frequency regimes will be used in the active transmit array. These variously sized transducers must all fit into the same area that is occupied by the narrow band sonar currently used on a conventional torpedo, so some compromise is unavoidable. Since it is desirable to provide narrow transmit beamwidths when operating at the <u>lower end</u> of the frequency band, the low frequency transducers will predominate on the periphery of the array. Other low frequency transducers will also be distributed (more or less sparsely) over the inner regions of the array to enable sidelobe control and beam steering. Active transducers that operate at somewhat higher frequencies will be similarly arranged but will tend to be more centrally located. That trend continues for the transducers that operate at the top end of the frequency band.

The compromise entailed by interleaving various sized active transducers (that operate in different frequency regimes) is that sidelobe control of the transmitted beams is somewhat degraded. That drawback is to a large extent compensated for by the ability of the receive array to collect and process high-resolution data.

Engineering the active transducer array described above, while not trivial, is definitely within the current state-of-the-art.

Design of the Wideband Hydrophone Array

The hydrophone array for this notional torpedo sonar consists of ~500 identical sensors that are able to receive acoustic signals over a range of frequencies spanning 15-50 kHz. This array is mounted directly over the face of a high power acoustic transmit array and is the outermost structure on the nose of the torpedo, the rubber window excepted. Following are the engineering challenges that need to be addressed to make this work:

a) Select/develop a hydrophone technology that

- Provides adequate acoustic sensitivity over the operating band
- Is acoustically transparent enough so as not to unduly attenuate acoustic energy transmitted by the underlying active array
- Is robust enough to survive the mechanical stresses and heating caused by transmission through it of high power acoustic signals

b) Develop technology to transmit 500 individual signals to the signal processor in the interior of the torpedo

c) Process 500 signals in real time

There are hydrophone technologies that are promising candidates to meet these requirements. Among them are two incarnations of 1-3 composite transduction materials. A preliminary test on one of these materials indicates that the acoustic transparency issue is resolvable. The question of mechanical and thermal survivability at high power levels remains to be answered, but it is expected that those issues, if they arise, can be addressed and solved.

The transmission of hundreds of signals from a hydrophone array into the interior of a torpedo poses a number of serious challenges. The most important is how to maintain signal integrity. The electrical signal outputs of hydrophones are low level and would be susceptible to noise contamination and cross talk if transmitted unconditioned into the interior of the torpedo. And if that were not a consideration, the transmission by wire of four hundred analog signals would pose a penetration and connection nightmare. A development program at NUWC is addressing both these issues. The aim of this program is to embed within each sensor die sized analog and digital circuitry that will condition the sensor's output signal, digitize and filter it. Additional miniature circuitry will be embedded in the array and on its periphery to multiplex the digital signals and transmit them into the interior of the torpedo via a small number of wire penetrations. This effort has progressed to successful testing of the analog and first stage digital die. Development efforts are continuing.

Technology to process hundreds of individual signals in real time is currently within the state-of-the-art. Although the notional sonar design discussed above refers to a 500 sensor array, our research has and will continue to address as many as 1000 channels. That is particularly challenging when working at higher frequencies because while the number of sensors (spatial samples) increases as the square of frequency, the (spatial and temporal) signal processing load increases as the cube of the frequency. The engineering challenge is to package existing signal processing technology into a torpedo and to do it in a way that is cost effective.

The oral presentation will include details of ongoing development programs that address these topics.