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Torpedo Detection using Multi-path Signals and Fast Orthogonal Search Techniques

Abstract—Detecting a high-speed torpedo by means of a passive acoustic detector is very challenging for most acoustic operators. Coupled with a very noisy environment, multiple sources in a multi-path scenario and varying environmental factors, a time-constrained assessment will prove difficult. In addition, a passive sensor cannot estimate the range of a torpedo approaching it at a constant bearing with conventional signal processing. The passive acoustic sensor will receive a direct path signal from the torpedo as well as a signal that has reflected off the surface. Due to the different angles of arrival, the direct-path and surface-reflected signals have different Doppler shifts. This paper introduces a torpedo detection algorithm, which is primarily developed in MATLAB. The Torpedo Detection Algorithm (TDA) employs the fast orthogonal search (FOS) algorithm for high-resolution spectral analysis to detect the closely spaced direct-path and surface-reflection signals. When a direct-path and surface-reflection are found, an automatic alert of a torpedo detection is initiated. In simulation, a torpedo is detected 20 times out of 20 as it travels from 5000 to 750 metres from the receiver. Simple trigonometric expressions are used to estimate the torpedo's range given the two frequencies estimated by FOS and apriori information about the torpedo speed and depth. The predicted range for a simulation in which a torpedo approaches from 5000 to 750 metres is shown.

I. INTRODUCTION

In a busy acoustic environment, torpedo detection from an operator perspective is very challenging, as the operator must manually search for visual cues to make a torpedo assessment. These cues are presented visually based on Fourier series analysis. Not only is the acoustic picture complicated by environmental factors and multiple sources from multiple platforms, a torpedo signal may initially be very weak and not identified at its earliest detection by an acoustic operator. Based on the short timeframe to impact of a high-speed torpedo, early detection by an operator is critical in order to allow sufficient time for a warship to effectively react. An automated system could alert operators at the earliest stage.

When a torpedo approaches a passive sensor at a constant bearing (zero bearing rate), the speed and range of the torpedo cannot be estimated using conventional techniques [1,2]. The precise source frequency of the torpedo may not be known, so the Doppler shift of the torpedo is also unknown and cannot be used to estimate the speed. Also the magnitude of the signal at the source as well as the acoustic path attenuation is unknown, so the range of the torpedo cannot be easily estimated.

For a submerged target, such as a torpedo, the acoustic detector will receive a direct-path signal, a signal reflected off the surface as well as other multi-path components [1]. The direct-path and surface-reflected signals will have slightly different Doppler shifts due to the different angles of arrival. The direct-path and surface-reflected signals will be very close in frequency even for a high-speed target such as a torpedo. For surface ships and slow submerged targets, the difference in frequency of the direct-path and surface-reflection signals is typically too small to detect outside 1000 m. Thus the presence of two closely spaced frequency components can be used to indicate the presence of a torpedo. The Torpedo Detection Algorithm (TDA) employs the fast orthogonal search (FOS) algorithm to detect the closely spaced direct-path and surface-reflection signals. The direct-path and surface-reflected signals are so close in frequency that they are difficult to resolve using an FFT. The FOS algorithm has been shown to have up to 10 times the frequency resolution of the FFT for the same length of data [3,4]. Thus, the FOS algorithm is used to perform a high-resolution spectral analysis of the passive acoustic data. If two closely-spaced frequencies are resolved by FOS, then TDA indicates the presence of a torpedo.

In addition to the FOS algorithm used in the TDA, a number of other techniques including multiple-signal classification (MUSIC), canonical variate analysis (CVA) and modified covariance auto-regression (MODCOVAR) have been shown to give a spectral estimate with higher resolution than the FFT. The FOS algorithm has been found to correctly identify closely spaced harmonics more frequently than the root-MUSIC algorithm [5, 6] and the MODCOVAR algorithm [7]. The FOS algorithm was also compared against CVA for modeling nonlinear auto regressive processes and the FOS method was found to generate a model using fewer model terms. [7]. Thus in the TDA the FOS algorithm was chosen for high-resolution spectral analysis.

The frequency separation of the direct-path and surface-reflected signals can be used to estimate a torpedo's range given the depth of the receiver and speed and depth of the torpedo.

The received time series from a torpedo approaching a detector was simulated using the WATTCH [9] model. Our detector indicated the presence of a torpedo 20 times out of 20 as the torpedo traveled from 5000 m to 750 m from the receiver. The range estimate achieved an average error of 450 m with a maximum range error of 950 m.

II. DOPPLER SHIFT

Consider a submerged target approaching an acoustic receiver as shown in Figures 1 and 2. There will be a direct-path signal between the target and receiver as shown in plan view (Figure 1).

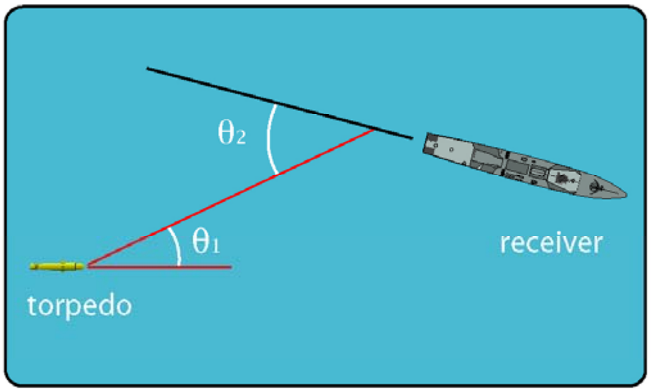

Figure 1 The top view as a target approaches a receiver.

The signal at the receiver will be Doppler shifted according to [1]

$$f_d = \frac{f_0 (c - v_s \cos\theta_2)}{(c - v_t \cos\theta_1)} \qquad (1)$$

where f_0 is the frequency at the target, v_s is the speed of the receiver, v_t is the speed of the target, θ_1 is the angle between the target direction and the receiver, θ_2 is the angle between the receiver and the incoming direct path signal, and c is the sound speed.

The signal arrival has the horizontal component (Figure 1) and a vertical component (Figure 2). When both dimensions are included, the Doppler shift associated with either the direct path (i=1) or surface-reflected path (i=2) is given by

$$f_d = \frac{f_0 (c - v_s \cos\theta_2 \cos\phi_i)}{(c - v_t \cos\theta_1 \cos\phi_i)} \qquad (2)$$

where ϕ_i is the angle between the receiver and the arriving ray. For the purposes of the remainder of this paper, the target is assumed to be directly approaching the receiver at constant (and equal) depth ($\theta_1 = 0$, $\phi_1 = 0$).

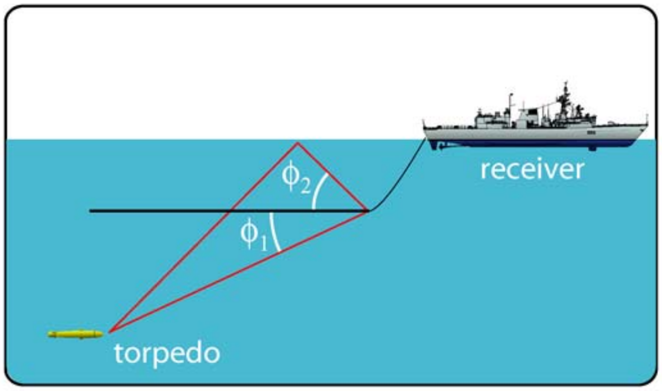

Figure 2 The direct-path and surface reflection as a target approaches a receiver.

Figure 3 shows the frequency separation between the direct-path and surface-reflected signals for a 500 Hz sinusoidal signal at the target. The frequency separation is calculated using equation (2). The earliest torpedo detection assessment that can be made by the FFT and the TDA based on empirical testing are also shown in Figure 3. The spectral resolution of FOS is signal dependent [3,4]. So although FOS has been shown to have up to 10 times the frequency resolution of the FFT (for sufficiently high signal-to-noise ratio, see e.g. [8]), 8 times the frequency resolution was used in this work, as indicated by the line marked TDA in Figure 3. At FOS resolutions above 8, the algorithm is unreliable and takes much longer to process. With the TDA resolution, torpedoes can be detected with confidence from approximately 2400 m from the detector based on the acoustic sensor receiving the initial torpedo signal at approximately 5000 m. If the FFT was employed in the algorithm to detect the direct-path and reflected path signals, a signal cannot be accurately assessed as a torpedo until approximately 1000 meters as seen in Figure 3. The FFT does not have the necessary resolution to separate the signals at longer range.

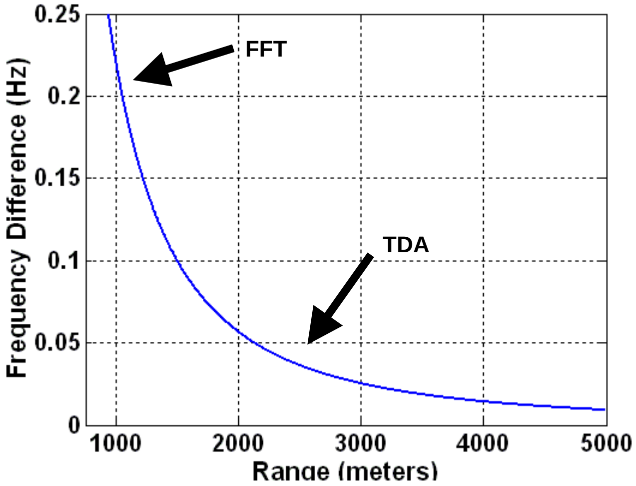

Figure 3 The frequency separation of the direct-path and surface reflection for a 500 Hz signal between a range of 5000 and 750 m. Based on the frequency resolution of the FFT and TDA, the earliest accurate torpedo detection assessments are indicated by the arrows.

III. DETECTION ALGORITHM

The TDA detects incoming torpedoes by using an iterative FOS algorithm call FOS-first-term-reselection (FOS-FTR [4]) to detect both the direct-path and surface-reflected signal from a torpedo. Since FOS is a relatively slow algorithm, the FFT is used on the raw signal to localize the energy in the signal. Then FOS is employed in a very narrow band around the peaks in the FFT to try to detect two closely space signals. If two closely spaced signals are detected, then a torpedo is considered present. Next, using trigonometric relations and the speed and depth of the target (assuming that it is known a priori) the range to the target can be estimated. The procedure can then be repeated using an overlapping sliding time window to decrease the time between executions of the detection algorithm.

IV. SIMULATION RESULTS

The time series resulting from a torpedo approaching a receiver was simulated using the WATTCH [9] model. WATTCH uses the US Naval Underwater Weapons Center (NUWC) Generic Sonar Model (GSM) [10] to provide frequency-dependant eigenrays as input. The GSM input environment was based on an August North Atlantic (42^{o}N 54^{o}W) sound speed profile [11]. Figure 4 shows the deep-water profile. In simulating the environment, the Thorp volume attenuation model and Bechmann-Spezzichino surface reflection model were assumed. Seabed effects were included by assuming a reflection loss coefficient and Rayleigh phase-shift model based on seabed with a 1650 m/s sound speed and 1.9 g/cm^3 density. Wenz shipping level 4 was also assumed. The wind speed and wave height were assumed to be 8 knots and 1.5 m, respectively.

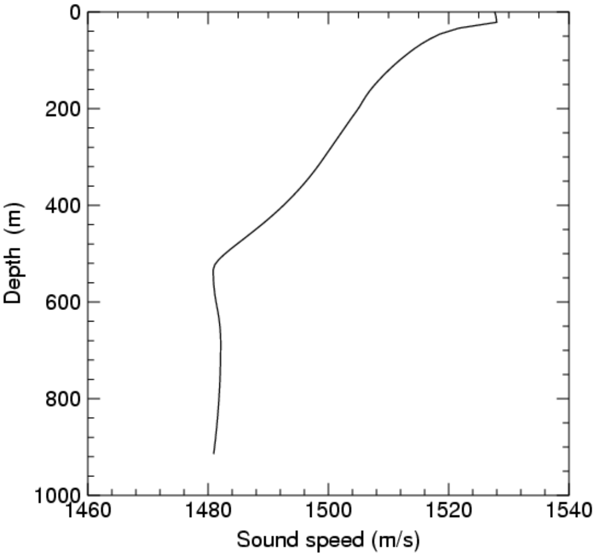

Figure 4 Podeszwa [7] North Atlantic Sound Speed Profile.

WATTCH simulated the received time series based on a torpedo with a 500 Hz tone with source level of 160 dB re 1 µPa at 1 m (about 20 dB SNR at 5000 m). Strong 60 Hz and 400 Hz (sound pressure levels of 100 and 80 dB re 1 µPa at the receiver, respectively) interfering CW signals were added. The WATTCH simulation was based on the torpedo closing on the receiver with a speed in excess of 25 m/s with both torpedo and receiver having a depth of 100 m.

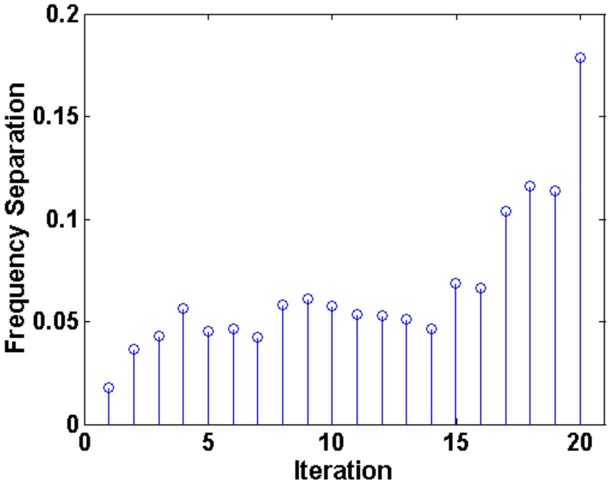

Figure 5 The frequency separation found by the FOS-FTR algorithm for 20 iterations (ranges) as the torpedo closed on the receiver from 5000 to 750 m.

Figure 5 shows the frequency separation of a torpedo detected by the FOS-FTR algorithm using 20 iterations (ranges) as the torpedo approached the receiver. The record length varied over the duration of the signal, starting at 80 s and was continually shorten as the torpedo approached the receiver so that the surface-reflected signal remained constant in the record length. The presence of a non-zero frequency separation, as illustrated in Figure 5, indicates the presence of a torpedo. Since two closely spaced frequencies were detected at each iteration, the TDA correctly assessed a torpedo in 20 of the 20 iterations shown.

Figure 6 shows the predicted range and the actual range of the torpedo as it approaches the receiver. Note that the predicted range has an average error of 450 m, or approximately 36%, and appears to over-range in nearly all of the 20 torpedo evaluations.

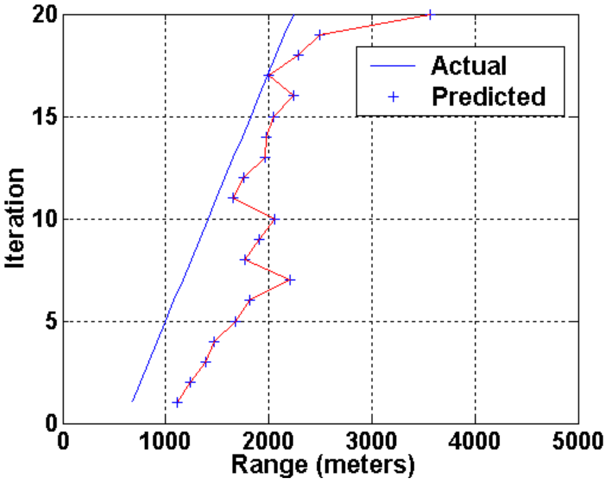

Figure 6 The predicted range (+) and actual range as a torpedo approaches a receiver.

V. CONCLUSION

Based on the simulation presented, a torpedo can be detected by detecting the direct-path and surface-reflection signal using the FOS-FTR algorithm. Given a priori information about the torpedo's speed and depth, the range can be calculated within 950 m, and an average error of 450 m. Further investigations to improve range estimation are ongoing.

VI. ACKNOWLEDGEMENT

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