Optimizations for Fourier Synthesized Time Domain Pulse Propagation Calculations

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Abstract- **Fourier transform methods are the standard way for determining time-domain pulse structure and arrival time from a set of continuous wave (discrete frequency) underwater acoustic model calculations. This technique requires a large number of computer model runs at closely spaced frequencies, often making it computationally expensive. It has the advantages of including the correct attenuation at each frequency component, and of correctly treating continuity requirements at the water/sediment interface. Direct time-domain computer models are not as accurate for ocean bottoms with strong attenuation over a large bandwidth of frequencies. In this work the frequency-domain/Fourier approach is optimized for maximum efficiency at a given level of acceptable imprecision. Techniques are presented to improve the efficiency of the individual frequency component calculations, and to avoid running many of the frequencies. Efficiencies at individual frequencies are gained through intelligent selection of grid parameters in the ocean acoustic model (a parabolic equation model). Further improvements are achieved through intelligent zero padding schemes, and by interpolating envelope functions at the receiver location in order to estimate (and hence avoid running) up to 90% of the calculations required by the Nyquist sampling theorem. The effects of the various approximations are shown in the examples.**

I. INTRODUCTION

Fourier synthesis of time domain (TD) results from continuous wave (CW) model calculations is the standard[1] way of accurately modeling pulse propagation in underwater acoustics. Direct TD modeling is possible[2], however an accurate treatment of frequency-dependent bottom attenuation over large bandwidths remains a challenge. For accurate TD results the procedure involves making many CW runs over the relevant frequency band, each correctly treating the frequency-dependent bottom attenuation, followed by Fourier synthesis.

The practical limitations of synthesizing TD results from many CW model results are largely imposed by the total time window of the result (T_l), which is governed by the frequency spacing of the CW runs (Δf): $T_l = 1/\Delta f$

While it is desirable to include the entire time for propagating a signal pulse from the source to receiver point, in practice this may necessitate a very small value for Δf, which will consequently require a large transform size with a correspondingly large number of CW model runs.

A simple optimization to somewhat alleviate this frequency sampling problem is to zero-pad the frequency band outside of the source's significant bandwidth, thus eliminating many of the otherwise required model runs. While certainly better than running all frequencies and subsequently multiplying results outside the source's bandwidth by zero, even this optimization seldom improves runtimes by more than a factor of two.

Another commonly used optimization is to choose a time window long enough to contain the pulse at the receiver location, but not necessarily long enough to contain the entire propagation time. The total propagation time can later be estimated from range and a reference sound speed in the water column, and the total propagation time obtained by adding on subsequent time window values until the estimated time is approximately reached. There are two potential problems associated with this method: (1) the estimated propagation time may not be accurate in complicated underwater environments, thus making the stacking of time window lengths imprecise; and, (2) the time window chosen may not be long enough to contain all multipath arrivals of the pulse, thus, leading to wrap around in the final TD result.

The optimization method developed here is to make a limited number of model runs at regular spacings across the bandwidth of interest, and to then interpolate the pressure, as amplitudes and phases, to a sufficiently high sampling rate. This results in significantly reduced runtimes for the underlying CW model, with little degradation in the final TD result. In subsequent sections of this work, this method is detailed in the context of a developmental example, and directions for further research are described.

II. METHOD AND DEVELOPMENTAL EXAMPLE

The method described here and the physical motivation behind it are best illustrated with the aid of a elementary example. For simplicity and manageable computational times,

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a Gaussian pulse centered at 100 Hz. with a width of 5 Hz. was used as the source. The test environment, including source and receiver locations, is shown in Fig. 1. The long propagation range (141 km) and seamount near 90 km were chosen to give a variety of very difficult challenges to the methods tried. The parabolic equation underwater acoustic propagation model, RAM[3], was used to simulate the acoustic propagation. A transmission loss (TL) field plot at the center frequency was generated and is shown in Fig. 2. A TL level of roughly -95 dB for the center frequency at the receiver point shows that there will be significant acoustic energy present in the water column, even at this relatively distant range.

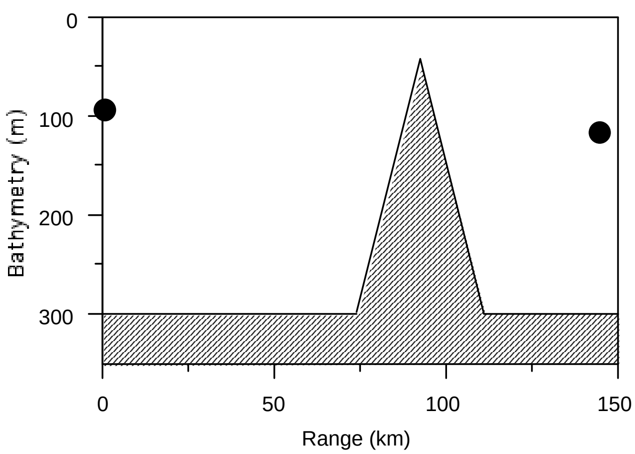

FIGURE 1. TEST ENVIRONMENT FOR DEVELOPMENTAL EXAMPLE. SOURCE POSITION IS SHOWN ON ORIGIN AXIS, RECEIVER POSITION IS SHOWN AT 141 KM RANGE.

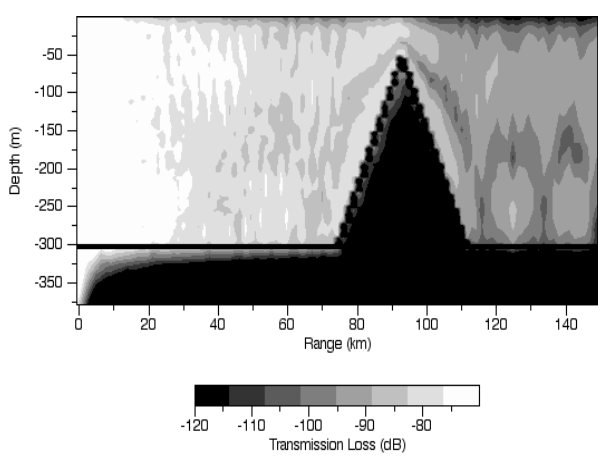

FIGURE 2. TRANSMISSION LOSS FIELD PLOT AT THE CENTER FREQUENCY OF 100 HZ.

A reference TD solution was generated using conventional Fourier synthesis. The RAM model was used to obtain the CW acoustic propagation; 512 individual frequency runs were made in a band 50 to 150 Hz. Zero padding, as discussed above, was applied to frequencies where the source weighting function was more than 100 dB down from the center frequency strength; this corresponded to 100±24 Hz. Out of the original 512 frequencies, only 246 actually required model runs, requiring 300 seconds on a desktop computer[1]. Because of the sparse frequency sampling rate, the propagation time to the 141 km receiver range was wrapped an estimated 18 times. The resulting output pulse is shown in Fig. 3.

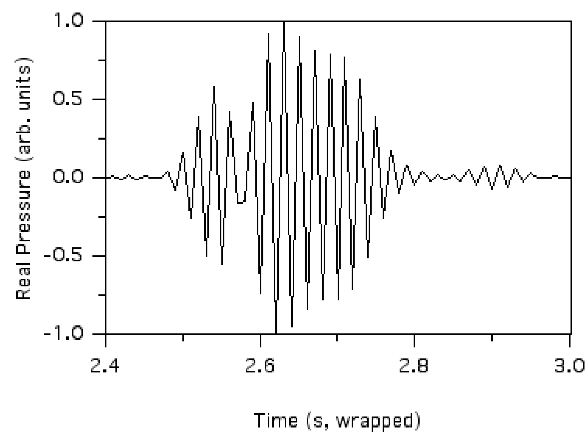

FIGURE 3. FOURIER SYNTHESIZED OUTPUT PULSE FROM TEST SOURCE AND ENVIRONMENT.

Examination of the complex pressure components of the pulse as a function of frequency (Fig. 4) shows a sinusoidal-like regularity. A simple way to reliably interpolate between the calculated frequencies is not evident. For clarity, this and subsequent figures will only show the band 100±5 Hz, however the relevant features are representative across the entire bandwidth.

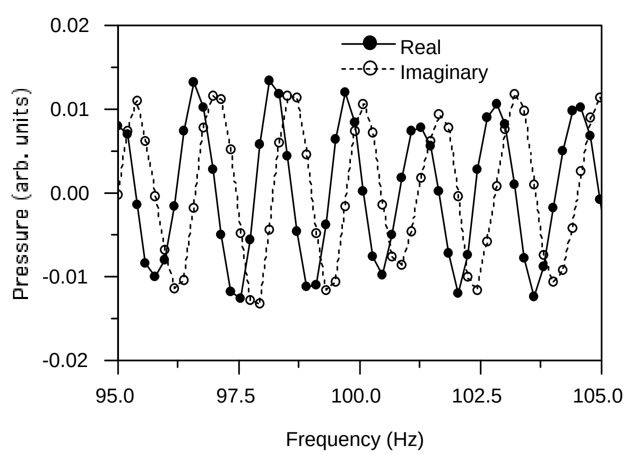

FIGURE 4. COMPLEX PRESSURE COMPONENTS NEAR THE CENTER FREQUENCY. SAMPLE POINTS ARE SHOWN.

[1] 2 GHz Macintosh G5 computer, using the OSX 10.4 operating system and Absoft Fortran 7.0 compiler.

Transforming the complex pressures into their phase and magnitude components greatly simplifies the structure, as is shown in Fig. 5. The magnitude varies slowly and regularly in a narrow band at roughly ±20% of its average value, while the phase appears to be an approximately linear function wrapped in the interval from –π to +π. This and several other trial cases have shown that the phase varies regularly in the manner seen here with a fairly consistent slope that may be positive or negative, depending on the underwater environment and receiver placement. Given the goal of eliminating the necessity of running many of the intermediate frequencies, the regularity shown in these figures makes it clear that at least some success may be had using interpolation if a way to reliably unwrap the phase can be found.

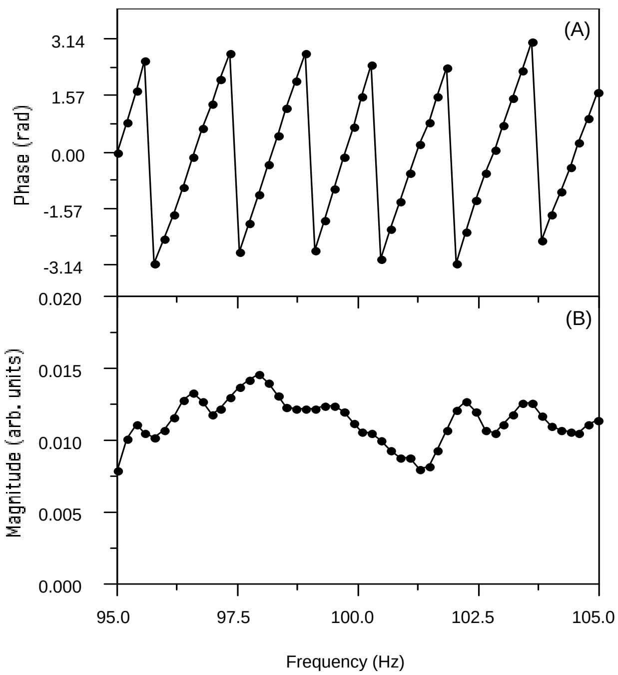

FIGURE 5. PHASE (A) AND MAGNITUDE (B) OF THE COMPLEX PRESSURE NEAR THE CENTER FREQUENCY. SAMPLED POINTS ARE SHOWN.

If it can be guaranteed that the phase wrap count can be accurately maintained between sample frequencies, the frequency domain may be sampled more coarsely than indicated in the Introduction. Note that this will not violate the Nyquist sampling requirement[4] for transforming between the frequency and time domains, because it only requires that the complex pressures be sampled at or above a certain level. There is no requirement on the model (or method) by which the pressure values are generated.

One very simple algorithm for unwrapping the phase reliably for large frequency strides is to thoroughly sample near the center frequency, and to obtain an average frequency slope in this region. Trial unwraps in more sparsely sampled frequency ranges can then be made by linearly extrapolating along this slope out to the next phase point, and counting the number of unwraps that will bring the extrapolated phase nearest to the target phase. By keeping track of the total unwrap at each calculated frequency, the phase relationship shown in Fig. 5a can be reduced to a nearly linear function. Subsequent interpolation to the desired sample rate can then be made, followed by transformation into the final TD result.

The results of this procedure applied to the example case are shown in Figs. 6 and 7. The frequency stride for the interpolated result is 1.8 Hz., or 10 times the original sampling rate. The section ±2 Hz around the 100 Hz center frequency has been fully sampled to obtain the average frequency slope for the above-described unwrapping procedure. The overall speed gain from this optimization is a factor of 7.3.

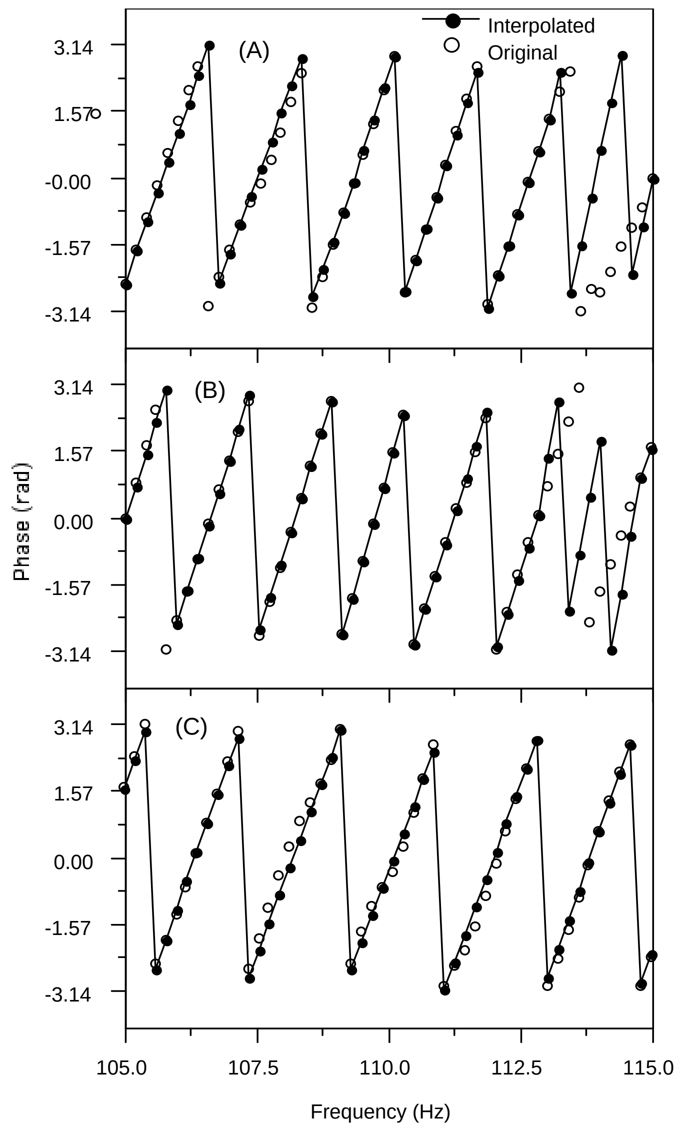

FIGURE 6. INTERPOLATED AND ORIGINAL PHASES IN THE (A) 85–95, (B) 95–105 (CORRESPONDING TO FIG. 5), AND (C) 105–115 HZ FREQUENCY BANDS. MIS-WRAPS ARE SEEN NEAR 94 AND 104 HZ.

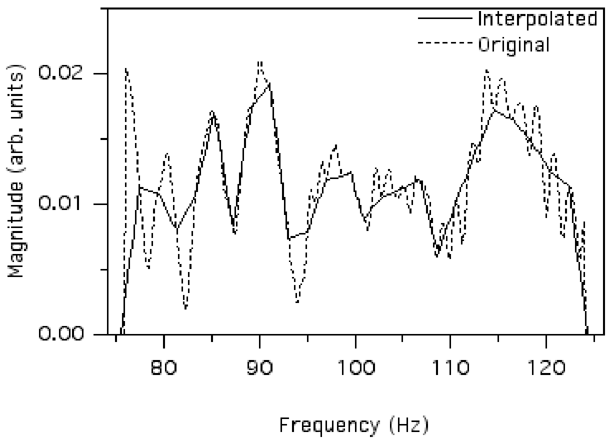

FIGURE 7. INTERPOLATED AND ORIGINAL MAGNITUDE OF THE PRESSURE, ACROSS THE ENTIRE FREQUENCY BAND.

A number of mis-wraps in the interpolated phase caused by the increased frequency stride are evident in Fig. 6, and several large deviations from the original pressure amplitude are seen in Fig. 7. However, when transformed into the time domain, the final result is in good agreement with the original solution, as shown in Fig. 8.

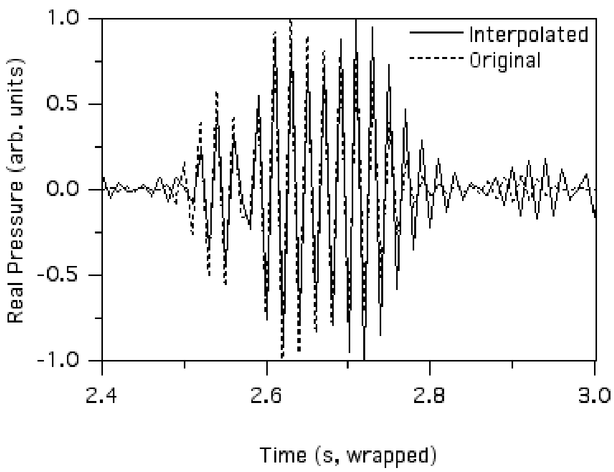

FIGURE 8. TIME DOMAIN RESULTS FROM THE PHASE AND MAGNITUDE INTERPOLATION OF THE CASE DESCRIBED IN THE TEXT, OVERLAYED ON THE ORIGINAL RESULTS FROM FIG. 3.

The RAM model was used to generate the examples presented in this paper. However, the technique presented, which converts multiple CW results into broad band pulse results, is applicable to any CW propagation model. A ten-fold decrease in overall computational time is typical. It is possible to achieve significantly greater reductions in overall computational time if the technique is mated to a particular propagation model and both technique and model are optimized for the ocean environment under consideration. As an example, consider that the arrival times and general pulse structure are desired for an acoustic pulse traveling in a shallow-water waveguide environment. The center frequency of the pulse is 1 kHz and the acoustic bandwidth is 1 kHz, extending from 500 Hz to 1,500 Hz. It is possible to choose different propagation parameters for the RAM model that are critically sensitive for each CW frequency component used in the Fourier synthesis; similarly, constraints can be lessen on less sensitive parameters. When combined with the technique discussed above, the result shown in Fig. 9 is obtained.

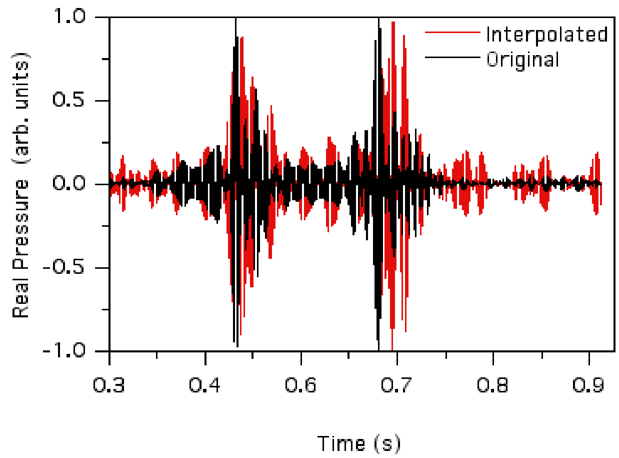

FIGURE 9. TIME DOMAIN RESULTS FOR A 1 KHZ BANDWIDTH WITH CENTER FREQUENCY AT 1 KHZ. THE FULLY SYNTHESIZED PULSE IS SHOWN IN BLACK AND REQUIRED 300 MINUTES TO GENERATE. THE PHASE-MAGNITUDE INTERPOLATION RESULT SHOWN IN RED TOOK 40 SECONDS.

The black curve is the result obtained by running the RAM model for each frequency over the entire 1 kHz bandwidth and performing a Fourier synthesis. The RAM model parameters were standard selections that ensure high-fidelity propagation predictions for each particular acoustic frequency. The red curve is the result obtained by applying the technique discussed in this paper together with RAM model parameters that were chosen to retain only the essential physics needed to generate a broad band result from sparsely selected CW results. The fully synthesized pulse (black curve) required 300 minutes on a desktop computer. The sparse synthesized pulse (red curve) was obtained in only 40 seconds on the same computer. While not a perfect replica, the red curve retains the correct first arrival time, very nearly the same second arrival time, and preserves the overall structure of the pulses. There is a 450 times reduction in run time. A future paper will discuss in detail how the phase-magnitude interpolation method can be combined with the RAM propagation model to produce rapid broad band simulations.

III. FUTURE DEVELOPMENT

In the work presented, a basic observation of the behavior of acoustic phase and amplitude with respect to frequency in an underwater waveguide environment has led to the development of a technique that can rapidly produce a TD result from a sparse number of CW calculations. The initial results are very encouraging and give insight as to where improvements could be made.

Further research is needed in the phase unwrapping part of the algorithm. Using variances in the slope of the phase in the sampled band, or sampling the average slope at several places in the source band, could produce a more reliable unwrapping. A more robust approach is to apply a series expansion to the total pressure field. Accurate phase estimates may be possible by using information obtained from the derivative of the magnitude function.

Another improvement under consideration is a more sophisticated interpolation scheme. In the work presented, a linear scheme was used. Higher-order interpolation algorithms could improve the magnitude interpolation.

Finally, because a TD pulse is being reconstituted from heavily decimated information, this method may be useful as a sound compression algorithm. The requirement of starting with complex pressures, and possibly the inability to encode a continuous signal as opposed to the isolated pulse in this example, may prove to be practical limitations on the method's usefulness in sound compression applications. This interesting ancillary application warrants further investigation.

IV. SUMMARY

A rapid method for computing and transforming underwater acoustic CW model results into TD signals has been presented. The method is based on the observed behavior of pressure phase and magnitude in an underwater waveguide environment. An example of pulse propagation using this method was presented with a net speedup of 7.3. When the method was combined with environmentally optimized propagation model parameters, and allowances for acceptable error were considered, a speedup of 450 was realized. Directions for possible future work were discussed.

ACKNOWLEDGMENT

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