Detection of time of arrival of ultrasonic pulses

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Abstract: Applications exist that employ transit-time measurements to determine distances to scattering objects. These include blood-flow measurements, fluid-level detection, non-destructive testing of materials, image processing of geometrical bodies etc. Many of these require extreme accuracy in measuring transit time through a medium. The system typically consists of a transmitter, a medium and a receiver. The signal sent must operate within the limitations imposed by this overall system. Under ideal conditions a finite duration pulse consisting of a sinusoidal signal is sent and received. If the transmitted signal contains an integer number of complete cycles of a single frequency, performing a correlation between transmitted and received signals can accurately recover the transit time information. The method has difficulties especially in the presence of noise. The problem is compounded if the desired accuracy is a small fraction of a single sinusoid period. Noise could cause the correlation results to be off by a complete cycle. For a one MHz signal, one cycle error corresponds to a one microsecond error. For applications requiring nanosecond accuracy, this is not acceptable. Varying the frequency content of the signal reduces the error but requires that the transmitter, receiver and medium all have a broader band spectrum. The improvements we propose here work within a narrow band while enhancing the chance of recovering the signal accurately.

Keywords: time of arrival, ultrasonic pulse, correlation, frequency sweep, Piezoelectrics, Signal Coding, Arrival Time Detection, Vibroseis.

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1. Introduction
When transmitting a pulse through a medium, the received signal is attenuated, time shifted and distorted. We define a pulse to be any signal of finite amplitude and temporal duration, composed of one or a combination of frequencies. Even if the pulse is designed to be of a single frequency, the mere act of turning a signal on and then off, introduces many unwanted frequencies. These frequencies make the problem of receiving the signal more complex but not intractable. Maximizing the energy transmitted in the form of higher amplitude or longer pulse duration improves the signal to noise ratio making signal reception more manageable. However, the system parameters and time constraints limit the pulse duration and maximum energy possible. Receiving a signal imbedded in noise is a task that can be handled effectively by correlation. Correlation is a commonly used mathematical operation where two signals are multiplied together and the result integrated over all time. If the signals are time shifted relative to each other the integration results in a function of time shift. The function has a maximum point corresponding to the time shift of "best alignment". For a given amount of energy, performing a correlation between transmitted and received pulse (cross correlation) gives an accurate measure of the delay time between the signals. The correlation plot of the transmitted and received pulses generally has multiple peaks, but the maximum absolute value occurs when the pulses align perfectly. For correlation we used \( C = \text{XCORR}(A,B) \), which is one of the many Matlab® functions. This function takes two vectors \( A \) and \( B \), each of length \( N \) and returns a vector, \( C \) of length \( 2^N - 1 \). Where \( C \) is a cross correlation sequence. In the case of \( A = B \) then the result is called the autocorrelation. This is the function we used to get many of our plots.

If the signal is transmitted without distortion, doing a cross correlation between the transmitted and received signals gives an accurate means of measuring time delay. This is accomplished by locating the absolute highest point of the cross correlation function. The time shift required to accomplish this maximum represents the transit time. Unfortunately, in the presence of noise and with bandwidth limitations of the system, the highest peak in the cross correlation may be difficult to distinguish from its nearest neighbors. It is desirable to increase the difference between the maximum peak and the secondary peaks in order to more reliably determine the true maximum peak and thus the true time delay. Working within the fixed limitations of the system, we propose a method, of improving the discrimination between the correlation peaks to improve the chance of identifying the true maximum.

An application requiring very accurate measurement is the measure of speed of sound through a liquid. Typical velocities are in the order of Mach 1. This method may be used to study the effects of pressure and other parameters on the speed of sound through the liquid in question. It may also be used to measure flow rates of the liquid. The restrictions imposed by the system are critical when it is necessary to measure transit times accurate in the nanosecond range. For example, if the driving frequency of the sinusoidal signal is 1 MHz, one period corresponds to one microsecond. If the speed in question is of the order of 300 meters per second, a nanosecond represents about 3 millimeters. If the desired accuracy is in the nanosecond range it must be possible to measure accurately within a small portion of a single cycle of the 1 MHz signal. This is approximately three orders of magnitude smaller time than a single period of the transmitted frequency. By appropriate selection of frequency and pulse duration, a cross correlation of the transmitted and received signals can very accurately recover the transit time. In practical applications the medium introduces not only a time delay, but also a distortion. The transmitter and receiver also have characteristics, which operate
as filters, further introducing noise. The transmitter and receiver also often resonate at these frequencies. All these conditions complicate the problem and limit the effectiveness of the cross correlation.

2. System Limitations
Assuming the system is fixed and cannot be modified, improvement of the correlation can be accomplished by carefully crafting the transmitted pulse. A coded pulse technique of this type has been used by the oil exploration industry since the 1960’s and is called Vibroseis [1]. Vibroseis uses large trucks to shake the ground with swept frequency signals and detect the reflected signals with seismometers. The choice of frequency sweep was dependent on many factors. A typical sweep duration was in the order of five to twenty seconds with frequencies from 5 to 100 Hz. Their application was therefore less restrictive than the one we are addressing. Unlike the Vibroseis[1] application, the system we are addressing uses low energy and narrow band transducers, which actually resonate at their natural frequency. If the application refers to measuring velocity through a medium, this velocity is affected by various parameters including flow direction and rate. For example, in flow measuring applications, the transducer is used for both receiving and transmitting the signal. This means that the pulse must travel with and against the flow and have a relatively short duration. A short pulse limits the amount of energy injected in the system and thus making it more susceptible to noise. Working within these constraints, we propose some solutions.

![Figure 1. “1 MHz, 10 Cycle Pulse”](image)
3. Limitations of Single Frequency Pulses

A single frequency sinusoid of finite duration has an autocorrelation whose value is a function of the number of complete cycles, N. We used Matlab® to do all our models and simulations for this paper. A single frequency example is illustrated in Figure 1. This figure illustrates a 1 MHz pulse of 10 microsecond duration. The value of the signal outside this range is zero. This particular 10 microsecond pulse was modeled using 200 sample points. The Autocorrelation is shown in Figure 2. The x axis corresponds to shift in sample points. Each sample point therefore corresponds to 50 nanoseconds. Thus, the 600 point on the x axis corresponds to a zero time shift, and maximum overlap, whereas 400 or less, or 800 or more are the points where the transmitted and received pulses have no overlap. The larger we make N, the larger the maximum correlation value. Making N too large, however, introduces the unwanted result that the secondary peaks of the autocorrelation are close in magnitude to the maximum. For example, if the maximum peak of the autocorrelation is K*N, the next peak has a magnitude K*(N-1). For large values of N, the two adjacent peaks are close in magnitude relatively measured and it is difficult to tell which one is the true maximum. Another problem with large N is that for a given frequency, it makes for a long pulse. The applications often limit the pulse duration. If N is too small, however, there may be insufficient energy that makes it to the receiver. Selecting N in the range of 10 to 20 and the frequency of about 1 MHz may be a good compromise. We will work under this assumption and use these numbers in our paper. Actual numbers selected must conform to the actual system parameters. With these numbers in mind there are other practical problems to be addressed. If the transducers used in the system are very narrow band they may resonate and oscillate even when no longer energized. To reduce the introduction of unwanted frequencies the pulse should be amplitude modulated with a suitable envelope. Although the envelope reduces the amount of total...
energy, it is advantageous because it reduces the amount of unwanted frequency components being transmitted. Quantitative analysis of the effects of envelopes, or "windows" on the signal can be found in fundamental textbooks on signal analysis such as [5], [6], [7], and are beyond the scope of this paper.

4. Proposed Pulse Designs
An improvement to the single frequency method is the use of a swept frequency pulse that operates within the bandwidth of the transducers in question. A swept frequency has a very unique shape and is easier to recognize at the receiver than a fixed frequency. Figure 3 illustrates such a pulse. The sudden start and stop of a frequency pulse, due to a rectangular envelope, has the additional disadvantage of generating unwanted frequencies. To reduce these unwanted frequencies the pulse must not only consist of the desired frequencies but also be combined with an appropriate envelope in order to transmit a more suitably shaped pulse. The envelope causes the overall pulse amplitude to smoothly grow from zero to peak value and descend smoothly at the end of the pulse. An unwanted result of the inclusion of the amplitude modulating envelope is that the total amount of energy transmitted is reduced.

Figure 3. “Linear Sweep (0.9 MHz to 1.1 MHz)”
Figure 4. “Swept Sine RectEnv AutoCorr”

Figure 5. “Two Frequency” Pulse
Another possible improvement is to generate a pulse consisting of two distinct frequencies, close to the resonant frequencies of the transducers, and added together. The two frequencies are carefully selected such that they consist of integer number of cycles each and correspond to the resonance points of the transducers. For example, if the pulse duration is 10 microseconds and the two frequencies are to have nine and eleven complete cycles each, the calculation is as follows:

\[
T = N_1 \times T_1 = N_2 \times T_2 \]

where \( T \) is the 10 microseconds, \( T_1 = 1/f_1 \) and \( T_2 = 1/f_2 \) are the periods of the two frequencies in question and \( N_1 \) and \( N_2 \) are the number of cycles that are to occur in the given time \( T \). Arbitrarily choosing \( N_1 \) to be 9 and \( N_2 \) to be 11, it can be found that the corresponding frequencies are \( f_1 = 0.9 \text{ MHz} \) and \( f_2 = 1.1111\ldots \text{ MHz} \). The frequencies selected will depend on the actual application. Figure 5 illustrates this pulse and Figure 6 the autocorrelation. By combining the frequencies this way, the correlation has a “beating” effect, which improves the results by accentuating the difference in the amplitudes of the primary and secondary peaks in the cross correlation.

**5. System Models**

To evaluate the effectiveness of our proposed improvements and to compare with the single frequency methods used, we modeled the system and the pulses using Matlab®. The system we modeled consisted of two narrow band transducers that could each operate as both a receiver or a transmitter, and a medium, such as water, to transmit the signal. The transducers were modeled after units actually in use [2]. These transducers had a tendency to oscillate at their resonant frequency even after they were no longer energized. The model for the transducer created in Matlab® is an approximation of the real system and may not fully incorporate all of the complexities associated with an actual transducer [3]. Although the transducers are not modeled in their full complexity, they clearly illustrate the advantages of the multi frequency pulses over the single
frequency ones. Our intent here is to show that by carefully designing the pulse, tangible improvement, over the single frequency method, can be realized. A block diagram of the Matlab® model used (which includes the pulse generator, the transmitter, the medium, and the receiver) is illustrated in Figure 7.

Figure 7. “System Block Diagram”

6. Testing the Pulses
In order to evaluate the efficacy of our proposed solution we generated a series of pulses with different frequency contents, envelopes and durations. We will illustrate only a small sampling of these in this paper. To obtain a baseline, we generated pulses of 10 cycles of a 1 MHz frequency of amplitude 1. This frequency was selected to match the narrow frequency bandwidth of the transducers. To illustrate a comparison of the results we did an autocorrelation of each of three types of pulses. Each was investigated both with a rectangular (no amplitude modulation) envelope and with a sinusoidal envelope. The latter envelope $e(t)$, which we will call Sinusoidal, has the form of Equation (1).

$$e(t) = 1 - \cos(xt). \text{ For } 0 < t < 2^\pi/x. \quad (1)$$

This envelope rises and descends smoothly from a zero amplitude to a maximum value of two and returns to zero. We arbitrarily selected this envelope to match the duration of the pulse. Other envelope shapes are also possible (such as Gaussian) but the main objective here is to demonstrate the advantages of certain pulse designs based on their frequency content. We used Matlab® [4] to do the modeling and mathematical operations. To get a baseline we started with a pulse consisting of 10 cycles of a pure 1 MHz sinusoidal signal with a rectangular envelope (that is to say, the signal abruptly
starts and abruptly stops) as shown in Figure 1. The time function $CP(t)$ is depicted in Equation (2).

$$CP(t) = A\sin((2\pi \times 10^6) \times t) \quad \text{for} \quad 0 < t < 10 \times 10^{-6}$$

Doing an autocorrelation on this 10 microsecond, 1 MHz pulse reveals a “diamond” shaped waveform as shown in Figure 2. This waveform exhibits secondary peaks that have an amplitude approximately 93% of the main peak. Multiplying the pulse with the Sinusoidal envelope and repeating the autocorrelation gave similar results. That is the secondary peaks were also around 93%, however the tertiary and other peaks were considerably lower than the corresponding peaks with the rectangular envelope. In the presence of noise it becomes more difficult to identify the maximum peak of the correlation.

The second pulse design that we are considering here is also 10 microseconds in duration but consists of a linearly swept frequency ranging from 0.9 MHz to 1.1 MHz. Equation (3) and Figure 3 illustrate the waveform.

$$SP(t) = A\sin(2\pi \times (0.9 \times 10^6 + (0.2 \times 10^6) \times t/(10 \times 10^{-6})) \times t), \quad 0 < t < 10 \times 10^{-6}$$

The autocorrelation of this pulse, with the rectangular envelope shown in Figure 4, illustrated a dramatic improvement over the single frequency pulse $CP(t)$. The secondary peaks of the autocorrelation of the swept pulse were less than 77% of the primary peak. This greatly improves the ability to discriminate the primary from secondary peaks. The swept pulse was then multiplied by the envelope and again autocorrelated. As expected the main peak was lowered and a small degradation in performance was noticed. This resulted in secondary peaks approximately 81% of the main peak. This, however, is still a great improvement over the single frequency case.

The third pulse design we considered, $TF(t)$, given by Equation (4) and shown in Figure 5, was also 10 microseconds in duration and consisted of the sum of the two distinct frequencies, 0.9 MHz and 1.1 MHz.

$$TF(t) = A \times (\sin((2\pi \times 0.9 \times 10^6) \times t) + \sin((2\pi \times 1.1 \times 10^6) \times t)), \quad 0 < t < 10 \times 10^{-6}$$

With a rectangular envelope this pulse exhibited the best results with secondary peaks 64% of the primary peak. When the Sinusoidal envelope was incorporated, the secondary peaks increased to 78% as depicted in Figure 6. This proved to be the best performing of the three pulses considered.

It was then a question to see how well these pulses performed in the simulated “real” system. The three pulses, with Sinusoidal envelopes and injected noise were each applied to the input of the system and correlated with the output. The particular characteristics of the system and the noise may further degrade the performance of the pulses, but the overall performance of the multi-frequency pulses was far superior to that of the single frequency pulse. Figure 8, Figure 9 and Figure 10 illustrate these results. Figure 11 illustrates the relatively small effect that 25% noise had on the correlation.
Figure 8. “1 MHz RectEnv, System Output and Cross Correlation”

Figure 9. “1 MHz SinEnv, System Output and Cross Correlation”
7. Conclusions
Accurately measuring the arrival time of an ultrasonic pulse in a “real” system with nanosecond accuracy is a difficult problem. This necessitates the use of carefully
crafted signals and sophisticated signal processing techniques. To maximize the accuracy of time of arrival measurement, the pulse should be customized to best operate within the system parameters. To make the transit from transmitter and be accurately recognized at the receiver, the pulse should be made as unique as possible. This is necessary because the pulse will be distorted in transit and also by the transducer characteristics. In this paper we briefly discussed the advantages of multiple frequency pulses over the currently used single frequency versions. The swept frequency pulse is fashioned after a technique used in the seismic exploration field. The application considered here, however, had the additional limitations of short time duration and high frequencies, making the pulse design even more critical. One advantage of a narrow band system is that the injection of white noise in the system has little effect on the received signal as evidenced by Figure 11. In this paper we compared the performance of the single frequency pulse with our proposed swept frequency and two-frequency pulses. Table 1. below summarizes the findings. The pulses were all 10 microsecond duration and the two envelopes used were Rectangular and Sinusoidal. An autocorrelation of each pulse was performed and a measure taken of the relative amplitudes of the primary and secondary peaks. The primary peak was considered 100%.

| 10 Microsecond Pulse | Autocorr. Peak | Secondary Peak Amp. | Envelope |
|----------------------|---------------|---------------------|----------|
| 1 MHz.               | 100%          | 93% Rectangular     |          |
| 0.9 MHz to 1.1 MHz Linear Sweep | 100% | 77% Rectangular |          |
| 0.9 MHz to 1.1 MHz Linear Sweep | 100% | 81% Sinusoidal     |          |
| 0.9 MHz and 1.1 MHz Frequencies | 100% | 64% Rectangular |          |
| 0.9 MHz and 1.1 MHz Frequencies | 100% | 78% Sinusoidal     |          |

If system parameters could be modified, i.e. if the transmitter and receiver can be made to have slightly different frequencies or if the transducer bandwidth broadened the pulse frequencies should be selected to take advantage of these facts. Methods to take advantage of different transducer designs, such as broadening the bandwidth or using different resonant frequencies in the transmitter and receiver, are being studied. It should be noted that white noise had relatively little effect on a system with such tight frequency constraints. This is so because most of the noise energy is filtered out. In summary, and based on our findings, multi frequency pulses outperformed their single frequency counterpart operating under similar conditions. Of the two pulse designs we proposed, the swept frequency pulse showed great improvement over the single frequency pulse, but the two frequency pulse was the one that performed the best.
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