Fourier transform of high frequency ultrasonic waves propagated with a transmission mode

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Abstract. When ultrasonic propagates as a wave, the frequencies contained in the propagated waves may carry information regarding to the medium. The transformation of time-domain propagated signals into those of frequency domain is a common digital signal processing (DSP) technic to extract such important information. This requires quite a high resolution of the detection device which relates to the high frequency ultrasonic waves. The advancement of microprocessor technologies enables the complex and fast digital signal processing in the frequency domain. This allows measurement and evaluation using a broadband frequency domain analysis which is effective in the extraction of information contained in the ultrasonic signals. This work presents the implementation of Fourier transform of propagated ultrasonic signals through air medium. The generation of ultrasonic waves employs two pairs of transmitter-receiver ultrasonic transducers which have the center frequencies of 200 kHz and 1 MHz, respectively. The transmitter transducer was excited by a 107.1-ns negative spike to generate ultrasonic waves propagating through the air and converted into an electrical signal by a receiver transducer. This was amplified and recorded as a digital signal for subsequent off-line digital signal processing.

1. Introduction

Ultrasonic based measurements and evaluations have become one of the versatile methods because of its features of relatively inexpensive, no electromagnetic radiation and high precision. When an ultrasonic wave propagates into a medium, it experiences energy absorption resulting in the reduction of a portion of energy indicated by a reduction of the amplitude of the received signal. More reduction occurs when it propagates at higher frequencies [1]. For the purposes of non-destructive evaluations, frequency content of propagated signals become the importance of interest. They indicate the information of the propagating medium [2, 3]. In addition, ultrasonic waves are useful for the generation of aerosol droplets for material syntheses, such as zinc oxide and barium titanate, using aerosol processes [3, 4].

The extraction of frequency content of time domain signals commonly applies a DSP technic which is so called a discrete Fourier Transform (FT) [5, 6]. This technic requires fast digital processors to perform FT calculation of a recorded digital signal. This analysis frequently applies specific window functions to obtain the desired frequency response related to the applications. The application of window functions improves amplitude and frequency response resolution, such as reduction of noises due to signal discontinuity and sampling process [7].

Many works report the application of frequency domain analysis of ultrasonic signals for non-destructive evaluations and measurements. They include bone density measurements, irregular surface
shape thickness measurements [8, 9]. Xu et al. (2007) reports the implementation of the spectrum of ultrasonic signals with a frequency center of 0.5 MHz for the measurement of bone density for clinical assessment. Ultrasonic-based thickness measurement of irregular surface reports that the thickness can be calculated accurately by resonant algorithm based on spectral analysis with accuracy up to ±15 μm [10, 11].

This work briefly presents the implementation of FT technic to represent a received digital ultrasonic signal in a transmission-mode in a frequency domain for further signal analysis and interpretation of ultrasonic-based measurements and evaluations. A negative spike high voltage excited a 200-KHz transmitter transducer to generate ultrasonic waves which propagated through air received by the receiver transmitter. The received signals subsequently amplified, displayed and recorded as a digital signal.

2. Method
2.1 Experimental setup
Figure 1 describes the experimental setup of a typical ultrasonic-based non-destructive evaluation system. The excitation negative spike pulse activates a transmitter transducer which converts the electrical signal into ultrasonic waves. The generated ultrasonic waves propagate through the medium and applied for ultrasonic-based application purposes. The ultrasonic propagates as longitudinal wave with a speed determined by the density of propagation medium. It propagates faster in a denser medium. The applications of ultrasonic-based evaluations frequently involve under-test object with the density is higher than that of air. This causes a large propagation speed discrepancy between object and medium, which subsequently causes significant wave impedance mismatch. When it occurs, most portion of ultrasonic energy is reflected at the boundary between media and the under-test object. Underwater ultrasonic evaluation is commonly applied in order to attain the higher impedance matching because of the larger density of water compared to air as medium. Thus, two types of ultrasonic transducers were evaluated, a pair of air-coupled transducer and a pair of water-coupled transducer, respectively.

In the pulse-echo mode, only one transducer is employed as both transmitter and receiver transducer. The ultrasonic wave is transmitted and received from the same transducer. It alternately transmits and received the ultrasonic wave and hence there is only one access to the transducer when it is in operation. In comparison, the transmission mode includes a pair of identical transducers, transmitter and receiver transducers, placed in-sight position of the active surface. This mode allows the operation of continuous ultrasonic wave to the under-test object and analysing frequencies at which resonance frequencies are the importance of interest and determine the properties of the object [12].

The evaluation uses air- and water- coupled medium on transmission mode propagation, in which the transmitter and receiver transducers were in sight at a fixed distance of 3 cm. This test employed two pair transducers with each pair frequency of 200 kHz and 1 MHz, respectively. Table 1 shows the specifications of each transducer employed. A pair of transducer 1 is air coupled medium with 18 mm in diameter with the center frequency of 200 ± 8 kHz, maximum pulsed voltage 200 Vpp and 400 pF capacitance. This transducer is air medium-dedicated usage. As comparison, transducer 2 is a water-flow sensor type, 21 mm in diameter with the center frequency of 1.0 ± 5% MHz, maximum pulsed voltage 500 Vpp and 1200 pF capacitance.

The generated ultrasonic waves propagate through air from the transmitter to the receiver transducer. The receiver converts the mechanical ultrasonic waves into an electrical signal. It is very weak with a very low signal-to-noise ratio (SNR) value. A high frequency and broadband amplifier (OPA365 based operational amplifier) amplifies this signal prior to displaying and recording. The amplified signal is subsequently displayed and recorded as a digital signal by a high speed digital oscilloscope storage (GW-Instek GDS2014). The spike pulse is connected to the oscilloscope for signal triggering. It is displayed and recorded as well with number of samples of 5000, recording with frequency sampling of 50 MHz, 250 MHz, and 2 GHz. All wiring connections use high frequency coaxial cables to suppress noises may interfere the measurement.
Figure 1. Schematic system for testing the fabricated pulse generator using the transmission mode propagation.

Table 1. Specifications of transducers employed for the testing.

| Parameters                  | Transducer 1       | Transducer 2       |
|-----------------------------|--------------------|--------------------|
| Brand                       | ZHIPU              | XIN NUO QI         |
| Diameter                    | 18 mm              | 21 mm              |
| Center Frequency            | 200 ± 8.0 kHz      | 1.0 MHz ± 5%       |
| Bandwidth                   | 16 kHz             | 0.2 MHz            |
| Oscillation Excitation 0 dB | 200 Vpp, 50 Bursts, 20 cm | 500 Vpp, 8 Bursts, 8 cm |
| Min. Parallel Resistance    | 600 Ω ± 30%        | 130 Ω ± 30%        |
| Capacitance                 | 400 pF ± 20%       | 1200 pF ± 20%      |
| Input Voltage Max. (Pulse)  | 500 Vpp            | 500 Vpp            |
| Directivity at -3dB         | 7° ± 2°            | 7° ± 2°            |
| Detection Distance          | 0.1 - 2 m          | 0.1 - 5 m          |

2.2 Frequency Domain Transformation

The received ultrasonic signal may contain a direct current (DC) which does not carry any information. This appears as the mean of recorded signal. The elimination of DC content is performed as described in equation (1) [5].

\[ \alpha x_i = x_i - \frac{1}{N} \sum_{i=0}^{N-1} x_i \]  

with \( x_i \) is the signal of current in the recorded digital signal, \( N \) is number of samples, and \( \alpha x_i \) is the DC-eliminated signal.

Stromer and Ladani applied rectangular, Tukey, Hann, Hamming and Blackman-Harris window functions to a transmission-mode received digital ultrasonic waves for the detection of inclusion in an object. This reported that the resulting power spectra of received signal were smooth and computational efficiency improved. Hence, for suppressing noises due to signal discontinuity, it applies a Hanning Window prior to the Fourier Transform and Power Spectrum calculations. Power spectrum of signal is calculated using equation (2) and (3) [5].

\[ \hat{P}(f) = \frac{1}{N} \left| \sum_{n=1}^{N} x_n \exp(-jfn) \right|^2 \]  

\[ \hat{P}(f) = \frac{1}{\Delta^2} \hat{P}(f) \]
with $\hat{P}$ is the power spectrum of signal. The normalized power spectrum, $\bar{P}$ by a factor $A$.

3. Results and Discussions

Figure 2(a) shows the excitation pulse of transducer. The pulse is negative spike -740 V with 107.1 ns at half width. This signal has data length of 5000 and sampling frequency of 50 MHz. Spike excitation pulse optimizes broadband response and near surface resolution. The fast rise times of pulse proportionally contains broadband frequency spectral excitation resulting in wideband transducer response. The optimization of transducer response can be done by selecting pulse energy and damping values, which adjust pulse rise time, width, and voltage. The pulse must have a width at which the pulse frequency content covers the bandwidth of transmitter transducer.

Frequency domain transformation of the excitation pulse is shown in figure 2(b). The frequency content spreads up to 10 MHz. The maximum peak is at a frequency of about 1 MHz. In the range of 0-5 MHz, the power spectrum exhibits higher magnitude. These results identify that the pulse contains frequency bandwidth of 5 MHz enabling transmitter excitation with frequencies up to 5 MHz. This indicated that the excitation pulse adequately drives the transmitter transducer with a center frequency up to 5 MHz. This pulse is subsequently applied to excite transmitter transducers with frequencies of 200 kHz and 1 MHz as described in the following discussions.

![Figure 2](image_url)

**Figure 2.** The excitation pulse of transmitter transducer: (a) time-domain negative spike pulse and (b) frequency domain.

The typical pulse-excited ultrasonic signal is an underdamped oscillation with a certain damping ratio as shown. A spike negative voltage -740 V with a half-width of 107.1 ns excites the transmitter transducer with frequency of 200 kHz. This ultrasonic wave propagates through the medium in which a portion of ultrasonic energy absorbed by the medium resulting in the reduction of signal amplitude of received signal [13]. Figure 3(a) shows the time-domain digital signal received at the receiver transducer, with data length of 5000 and sampled at a frequency of 250 MHz. The signal is underdamped oscillation with a frequency of 200 kHz. The oscillation amplitude diminished in accordance with damping ratio of transducer.

It is difficult to visually extract the information contains in the time-domain signal, particularly, frequency and amplitude components [14]. Prior to Fourier Transformation, a Hanning window with length of 5000 is applied to the signal (figure 3(a) and 3(b)). As a result, the points at begin and end of the windowed signal has zero values, suppressing high frequency noises due to signal discontinuities and enhances the signal-to-noise ratio (SNR) of the signal (figure 3(b)) [15].

Using equation (1-3), the windowed signal is calculated as a frequency domain signal as shown in figure 3(d) It is seen that a dominant peak appears at 0.2 MHz. No other peaks appear. This results strongly indicated that the received ultrasonic signal contains dominantly frequency of 200 kHz, in accordance with the center frequency of transducer used.
Figure 3. Ultrasonic signal received at the 200-kHz receiver transducer, (a) as-received time domain signal, (b) Hanning windowed signal, (c) Hanning-windowed signal and (d) frequency domain signal.

In addition to air coupled transducer, a pair of 1-MHz water-coupled transducer (Transducer 2) was applied using this method as well. The similar spike signal excites a water-coupled transducer transmitter having a center frequency of 1 MHz. The time domain of one packet received signal is shown in figure 4(a). The measurement shows that it is containing a frequency 961.5 kHz lower than its specified center frequency value (table 1). However, this value is acceptable because it is in the range of 5% tolerance of center frequency (range of 950-1050 Hz). At one spike pulse excitation, the amplitude diminished, decaying from maximum peak-to-peak 2.5 V to zero, exhibiting under-damped oscillation characteristic. These results demonstrate that the frequency content of pulse is adequately capable to excite ultrasonic transducer in the order of 1 MHz of frequency.

The recorded signal is initially windowed to cut out zero values at the beginning, resulting signal with length of 3801 (figure 4(b)). Figure 4(c) shows the application of a 3801-data-length Hann window, resulting in zero values on begin and end points. The power spectrum of windowed signal is apparent in figure 4(d). Two adjacent peaks of 0.965 and 1.0 MHz appear, indicating that the received signal contains two dominant frequencies which they are indistinguishable in time domain.
Figure 4. Ultrasonic signal received at the 1-MHz receiver transducer, (a) time domain signal and (b) Hann window function, (c) Hann windowed signal and (d) frequency domain signal.

4. Conclusion
Ultrasonic data acquisition in transmission mode has been demonstrated. Digital signal processing using Fourier Transform of received signals has been demonstrated to evaluate its frequencies content. The results concluded that calculated frequencies of Fourier Transformed signals strongly in accordance with that of measurement in the time domain. In conclusion, this technic is prospective applicable to ultrasonic signal analysis.

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