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Air-coupled ultrasonic vertical reflection method using pulse compression and various window functions

パルス圧縮と窓関数を用いた空中超音波垂直探傷法の検討

Kento Suzuki[1‡], Masashi Ishikawa[1], and Hideo Nishino[1]([1]Tokushima Univ.)
鈴木健斗 [1‡]，石川真志 [1]，西野秀郎 [1]([1] 徳大院)

1. Introduction

Air-coupled ultrasonic non-destructive inspection has been reported in many papers. In previous studies, air-coupled ultrasonic inspection was frequently performed using the transmission method, in which two ultrasonic sensors are placed on the test object, one at each side [1, 2]. This is because, in air-coupled ultrasonic testing, most of the excited wave is reflected at the boundary between the air and object, and only a faint wave transmits into the object; the detection of signals received after propagation in objects is difficult because the signal can easily be submerged in a large surface reflection signal. However, the transmission method cannot always be applied under practical inspection conditions; hence, the vertical reflection method is easier and more desirable. Therefore, in this study, we aim to develop an air-coupled ultrasonic vertical reflection method. To achieve, we examine the use of chirp signals with various window functions and the pulse compression technique. In this report, we verify the effectiveness of using the pulse compression technique and investigate suitable window functions for the air-coupled ultrasonic vertical reflection method through experiments.

2. Excited waves and signal processing using pulse compression technique

Pulse compression is a signal processing method for extracting characteristic signals submerged in noise and unnecessary signals. When using this technique in ultrasonic inspections, waves detected by the receiver are correlated with a reference signal. A waveform excited from a transmitter is frequently used for the reference signal. In this study, a chirp wave with a frequency that changes linearly with time is used as the excited wave. With the initial frequency, bandwidth, and time duration of the excited signals are denoted as F_i, B_w, and T, respectively, the chirp wave $W_{\mathrm{chirp}}(t)$ is obtained as [3]:

$$W_{\mathrm{chirp}}(t) = \sin\left(2\pi F_i t + \frac{\pi B}{T} t^2\right), \qquad (1)$$

where t is the time in the range $0 \leq t \leq T$. The excited chirp wave is windowed by window functions in order to reduce the unnecessary side lobes observed after applying the pulse compression. Four window functions are used in this study: Hanning window $H(t)$, Sine window $S(t)$, Blackman window $B(t)$, and Cos^4 window $C(t)$. The window functions are expressed as follows:

$$H(t) = 0.5\left[1 - \cos\left(\frac{2\pi t}{T}\right)\right] \qquad (2)$$

$$S(t) = \sin\left(\frac{\pi t}{T}\right) \qquad (3)$$

$$B(t) = 0.42 - 0.5\cos\left(\frac{2\pi t}{T}\right) + 0.08\cos\left(\frac{2\pi t}{T}\right) \qquad (4)$$

$$C(t) = 0.125\left[3 + 4\cos\left(\frac{2\pi t}{T}\right) + \cos\left(\frac{4\pi t}{T}\right)\right]. \qquad (5)$$

The windowed chirp waves are shown in Fig. 1.

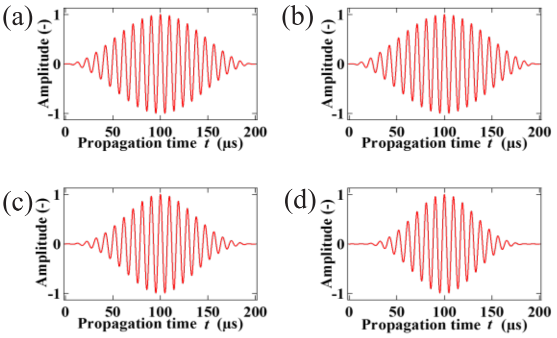

Fig. 1 Chirp waves with (a) Hanning window, (b) Sine window, (c) Blackman window, and (d) Cos^4 window.

3. Experiments

3.1 Experimental method

A schematic illustration of the experimental setup is shown in Fig. 2. An air-coupled ultrasonic sensor (0.4k14×20N-TX, Japan Probe Co., Ltd.) with a center frequency of 400 kHz was used as the transmitter and receiver of chirp waves. In this experiment, water was used as the test object because of its low sound velocity and small attenuation; it is considered that the detection of signals received after transmission through water is relatively easy. An aluminum plate was placed in the water as a reflector, and the propagation distance in the water (X) was varied by adjusting the distance between the aluminum plate and water surface. The experiments were carried out by varying X from 0 to 250 mm. The

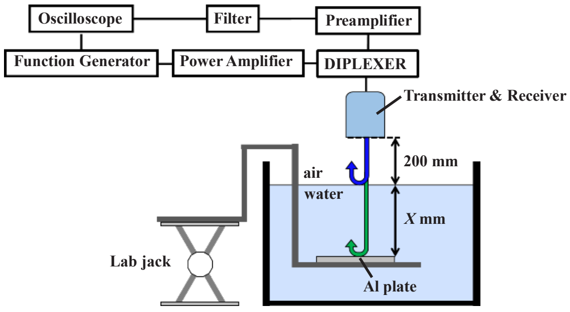

Fig. 2 Schematic of the experiment. setup.

transmitted waves were windowed chirp waves. The T value of the chirp waves was 200 µs, and B_w was varied as 50, 100, and 150 kHz (F_i for each B_w condition was 370, 350, and 300 kHz, respectively).

3.2 Experimental results

Figure 3 shows the received waveform obtained under the condition where $X = 100$ mm (B_w =100 kHz, Hanning window) before and after applying the pulse compression. In Fig. 3(a), although the signal reflected from the water surface (S_surface) can be observed, the signal reflected from the aluminum plate in the water (S_plate) cannot be observed. In contrast, S_plate and its multiple reflected signals can be observed clearly after pulse compression was applied (Fig. 3(b)). Fig. 4 shows the experimental results obtained after applying pulse compression for $X = 0$–250 mm when the chirp wave with the Hanning window ($B_w = 100$ kHz) was transmitted. It is observed in Fig. 4 that the first S_plate approaches S_surafce as X decreases, and it cannot be detected when $X \leq 80$ mm. From this result, the minimum time delay between S_surface and S_plate required to detect the first S_plate (defined as t_d) was calculated. The t_d values obtained from the experiments under each window function condition are plotted in Fig. 5, where the results of the theoretical calculations simulating the experimental condition are also presented as solid lines. It is found from the results that t_d decreases with increasing B_w, and that the Cos^4 window is the most effective for detecting S_plate with small t_d (although the experimental result is slightly different from the theoretical calculation, the tendency of the value according to the change in the window function is consistent). When a chirp wave with a higher B_w was used, the pulse width of S_surafce after pulse compression decreased. Furthermore, by applying a window function to the chirp wave, side lobes appeared in the wave after applying pulse compression is suppressed. These effects should lead to the results in Fig. 5. These results suggest that using chirp waves with higher B_w values accompanied by the Cos^4 window is an effective way for detecting S_plate with small t_d values. This means that the inspection of objects with smaller thicknesses or higher wave velocities becomes possible by using chirp waves with higher B_w values and using the Cos^4 window.

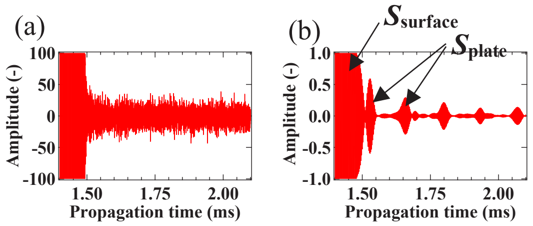

Fig. 3 Experimentally observed signal (a) before applying pulse compression, and (b) after applying pulse compression.

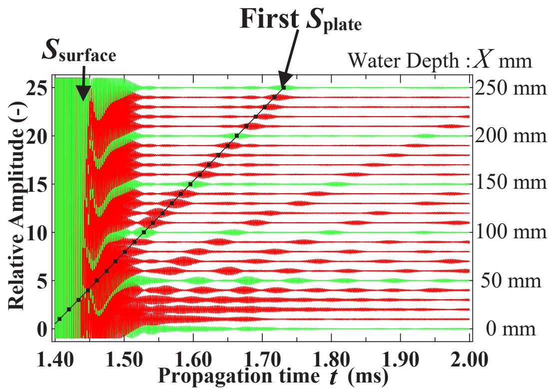

Fig. 4 Experimentally obtained waves after applying pulse compression for $X = 0$ - 250 mm (B_w =100 kHz, Hanning window).

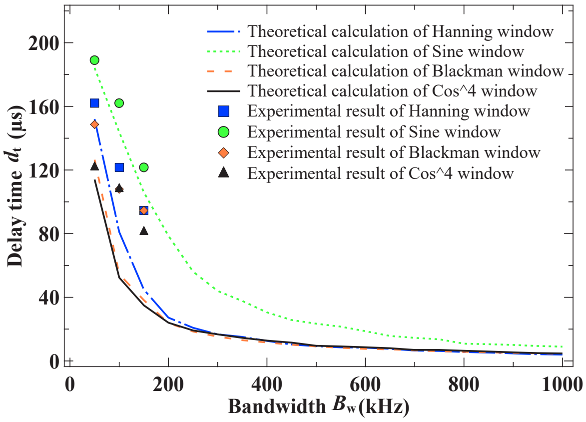

Fig. 5 Minimum time delay t_d required to detect S_plate as a function of B_w obtained from experiments (dots) and theoretical calculations (solid lines).

4. Conclusion

In this study, the feasibility of the air-coupled ultrasonic vertical reflection method using the pulse compression technique was examined, and suitable window functions for the inspection were investigated. The experimental results suggest that a Cos^4 window is effective to detect signals observed after propagating in test objects. In addition, a chirp signal with a relatively high B_w is required for inspection. However, it should be noted that exciting a broadband wave using only one air-coupled ultrasonic sensor is not easy. Thus, the development of a sensor system that can transmit broadband chirp waves is required for the practical use of the air-coupled ultrasonic vertical reflection method.

Acknowledgements

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