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FEASIBILITY STUDY OF AIR-COUPLED ULTRASONIC VERTICAL REFLECTION METHOD USING A SINGLE PROBE

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ABSTRACT

In the conventional nondestructive inspection method using air-coupled ultrasound, the transmission method using two ultrasonic probes is widely used. Although the air-coupled ultrasonic vertical reflection method using a single probe is the simplest inspection mode, it has been considered difficult to realize because of the large mismatch of acoustic impedance between air and object. In this study, we aim to develop an air-coupled ultrasonic vertical reflection method, and to achieve this, we examine the use of chirp signals with various window functions and pulse compression technique. In this study, we verify the effectiveness of using the pulse compression technique and investigate suitable window functions for the air-coupled ultrasonic vertical reflection method. Then, the feasibility of applying the suggested method to a solid object is examined through experiments.

Keywords: Air-coupled ultrasonic, Vertical reflection method, Pulse compression, Window functions

1. INTRODUCTION

Air-coupled ultrasonic nondestructive inspection is an attractive inspection method because it can inspect test objects without contact. By using this method, ultrasonic inspection becomes more easy and convenient method. In the previous reports, air-coupled ultrasonic inspection have mainly introduced as transmission method (FIGURE 1(a)) or pitch-catch method (V transmission method) (FIGURE 1 (b)); both methods use two probes for inspections [1, 2]. On the other hand, vertical reflection method using single probe (FIGURE 1 (c)) has not been achieved, despite that it is the simplest inspection mode and can also estimate the defect depth. 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. Therefore, the aim of this study is to develop an air-coupled ultrasonic vertical reflection method. To achieve this, 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. Then, feasibility of applying the air-coupled ultrasonic vertical reflection inspection to solid objects is examined through experiments for a polymer specimen.

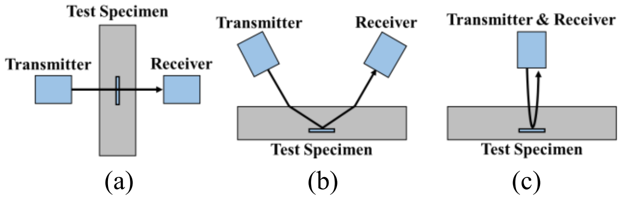

FIGURE 1: CONFIGURATIONS OF AIR-COUPLED ULTRASONIC INSPECTION, (a) TRANSMISSON METHOD, (b) PITCH-CATCH METHOD, and (c) VERTICAL REFLECTION METHOD

2. SIGNAL PROCESSING USING PULSE COMPRESSION TECHNIQUE

Pulse compression is a signal processing method for extracting characteristic signals submerged in noise or unnecessary signals. In this processing, waves detected by the receiver are correlated with a reference signal (a waveform excited from a transmitter is frequently used for the reference signal). The processed waveform $P_c(t)$ is obtained as:

$$P_c(t) = \int_0^{\infty} C_R(t')C_{ref}(t+t')\,dt', \tag{1}$$

where C_R and C_{ref} is a received and a reference signal, and t is the time in the range $0 \le t \le T$. In this study, a chirp wave with a linear frequency modulation 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 $W_{chirp}(t)$ is obtained as [3]:

$$W_{chirp}(t) = \sin\left(2\pi F_i t + \frac{\pi B_w}{T} t^2\right), \tag{2}$$

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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:

$$H(t) = 0.5\left[1 - \cos\left(\frac{2\pi t}{T}\right)\right] \tag{3}$$

$$S(t) = \sin\left(\frac{\pi t}{T}\right) \tag{4}$$

$$B(t) = 0.42 - 0.5\cos\left(\frac{2\pi t}{T}\right) + 0.08\cos\left(\frac{2\pi t}{T}\right) \tag{5}$$

$$C(t) = 0.125\left[3 + 4\cos\left(\frac{2\pi t}{T}\right) + \cos\left(\frac{4\pi t}{T}\right)\right]. \tag{6}$$

3. EXCITED WAVE CONDITION REQUIRED TO REALISE THE VERTICAL REFLECTION METHOD

In order to detect a reflection signals from subsurface defects, the surface reflected wave (S_{surface}) and the defect reflected wave (S_{defect}) must be detected separately. This means there must be a time delay between S_{surface} and S_{defect}. Thus, the minimum time delay (denoted as t_{d}) required to separately detect the S_{defect} was calculated theoretically. In the theoretical calculations, chirp wave with various the conditions were excited, and the pulse compression processing was applied to the excited waves by using the same excited waveform as the reference signal (i.e., autocorrelation processing was applied). B_{w} of the excited chirp was varied from 50 kHz to 1000 kHz; T and F_{i} were 200 µs and 100 kHz, respectively. It is defined that S_{defect} can be detected when the theoretical value of S_{defect} becomes more than twice the amplitude value of the side lobe. The result of t_{d} at each B_{w} obtained by theoretical calculation is shown by the lines in FIGURE 2. From this result, it is estimated that: (1) the t_{d} becomes smaller by increasing B_{w}, and (2) changing the window function affects the value of t_{d} in each B_{w} (t_{d} calculated when using Cos^4 window shows the smallest value in the four window function conditions).

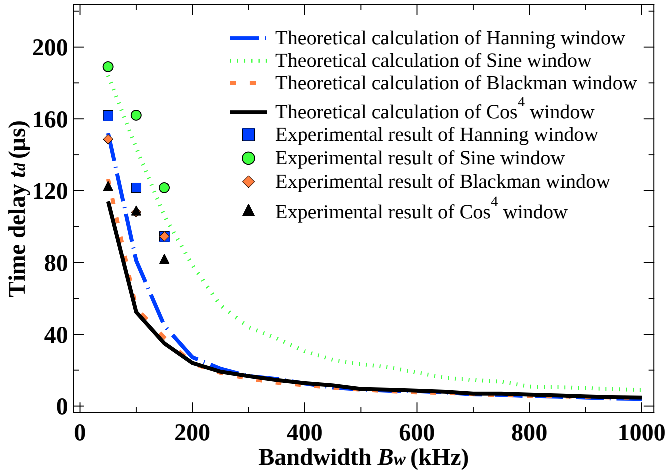

FIGURE 2: MINIMUM t_{d} REQUIRED TO DETECT DEFECT REFLECTED WAVE AS A FUNCTION OF B_{w} OBTAINED FROM EXPERIMENTS (DOTS) AND THEORETICAL CALCUATIONS (LINES).

4. EXPERIMENTAL VERIFICATION

The theoretical calculation results were verified through experiments. In the experiments, 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.

4.1 Experimental setup

A schematic illustration of the experimental setup is shown in FIGURE 3. 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. 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 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).

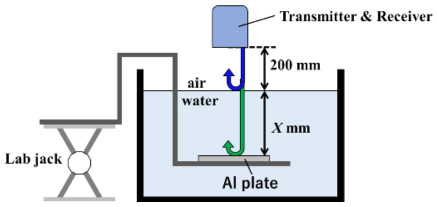

FIGURE 3: SCHEMATIC OF THE EXPERIMENT SETUP.

4.2 Experimental results

FIGURE 4 shows the received waveform obtained when X = 100 mm (B_{w} =100 kHz, Hanning window) before and after applying the pulse compression. In FIGURE 4(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 (FIGURE 4(b)). FIGURE 5 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 FIGURE 5 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 t_{d} was calculated. The t_{d} values obtained from the experiments under each window function condition are plotted in FIGURE 2. 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 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.

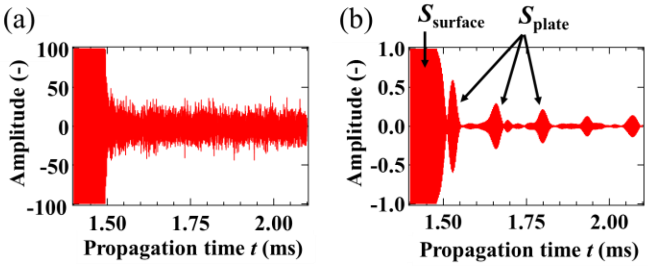

FIGURE 4: EXPERIMENTALLY OBSERVED SIGNALS (a) BEFORE APPLYING PULSE COMPRESSION, AND (b) AFTER APPLYING PULSE COMPRESSION.

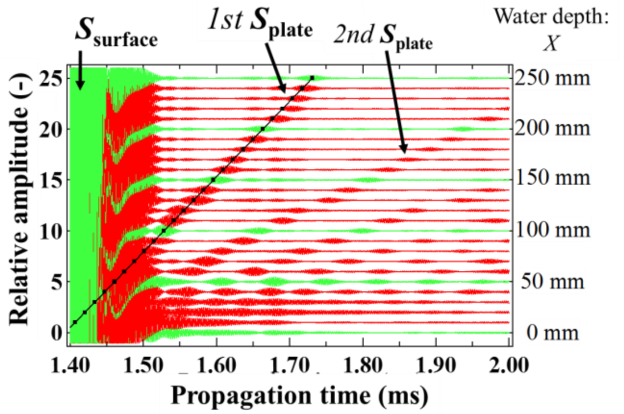

FIGURE 5: EXPERIMENTALLY OBTAINED WAVES AFTER APPLYING PULSE COMPRESSION FOR X = 0 - 250 mm (B_w =100 kHz, Hanning window).

5. DETECTING WAVES AFTER PROPAGATING A SOLID MATERIAL

Based on the obtained results presented in the previous section, detection of the reflection signal observed after its propagation in a solid specimen was examined. FIGURE 7 shows the schematic of the experimental setup. In this experiment, a 90 mm thick polystyrene plate was used as a specimen. A chirp wave using the Cos^4 window (B_w = 150 kHz) was excited and transmitted into the specimen, and the reflected wave from upper and bottom surface of the specimen were observed. FIGURE 8 shows the waves obtained before and after the pulse compression. From FIGURE 8, we can see that the signals reflected from the bottom surface of the specimen (S_{bottom}) are observed in the wave after pulse compression (FIGURE 8 (b)) in addition to the signals from the upper surface ($S_{surface}$). This result suggests that the air-coupled ultrasonic vertical reflection method could be applied to the inspection of solid objects by using the appropriate chirp signal and pulse compression processing.

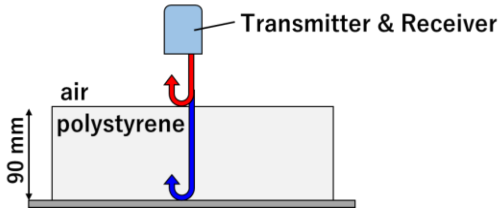

FIGURE 7: SCHEMATIC OF THE EXPERIMENT SETUP.

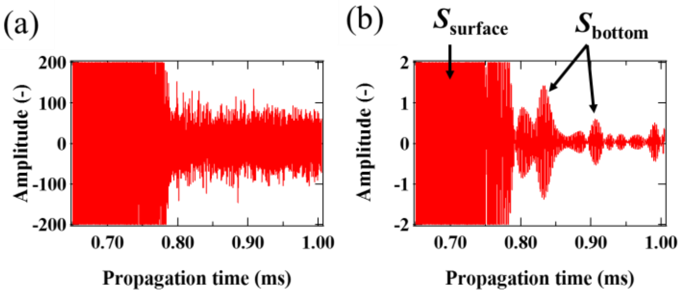

FIGURE 8: EXPERIMENTALLY OBSERVED SIGNALS (a) BEFORE APPLYING PULSE COMPRESSION, AND (b) AFTER APPLYING PULSE COMPRESSION.

6. 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 also investigated. The experimental results suggest that a Cos^4 window is effective in detecting the signals observed after propagating in test objects. Moreover, a reflection wave after its propagation in a polystyrene could be detected by using the Cos^4 window and pulse compression processing. These results show the possibility of realizing the air-coupled ultrasonic vertical reflection inspection. It should be noted that using chirp signals with higher B_w leads to smaller t_d. This means thinner objects or objects with higher wave velocity can be inspected when B_w is higher. However, exciting a broadband wave using conventional air-coupled ultrasonic sensor is not easy. Development of a sensor system that can transmit broadband chirp waves is essential for more practical applications.

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