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Measurement of Elastic Constants by Simultaneously Sensing Longitudinal and Shear Waves as an Overlapped Signal

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Abstract Measurement of elastic constants is crucial for engineering aspects of predicting the behavior of materials under load as well as structural health monitoring of material degradation. Ultrasonic velocity measurement for material properties has been broadly used as a nondestructive evaluation method for material characterization. In particular, pulse-echo method has been extensively utilized as it is not only simple but also effective when only one side of the inspected objects is accessible. However, the conventional technique in this approach measures longitudinal and shear waves individually to obtain their velocities. This produces a set of two data for each measurement. This paper proposes a simultaneous sensing system of longitudinal waves and shear waves for elastic constant measurement. The proposed system senses both these waves simultaneously as a single overlapped signal, which is then analyzed to calculate both the ultrasonic velocities for obtaining elastic constants. Therefore, this system requires just half the number of data to obtain elastic constants compared to the conventional individual measurement. The results of the proposed simultaneous measurement had smaller standard deviations than those in the individual measurement. These results validate that the proposed approach improves the efficiency and reliability of ultrasonic elastic constant measurement by reducing the complexity of the measurement system, its operating procedures, and the number of data.

Keywords: Elastic Constants, Overlapped Signal, Ultrasonic Pulse-Echo Method, Ultrasonic Velocity

1. Introduction

Evaluation of elastic properties or "mechanical properties" is significantly important not only for engineering aspects to predict the behavior of structures under external load or vibration [1-3] but also for structural health monitoring [4-6]. The destructive methods such as tensile failure test have been used to measure the mechanical properties [1-2,7]. However, these require cumbersome test procedures as well as many samples with appropriate orientations [7].

Moreover, they are not suitable for the in-service assessment of structural integrity or the quality control on a manufacturing process. For this, nondestructive evaluation (NDE) methods for the material characterization and the prediction of remaining service life of structures have appeared [8,9,11-13,15].

In various kinds of NDE means such as vibration techniques [16,17] and ultrasonic methods, the velocity measurement of longitudinal and shear waves have been widely used to evaluate the elastic constants of solids such as Poisson's ratio (ν), Young's modulus (E), and shear modulus (G) [9,12,18-20].

Especially, these techniques are effective for the evaluation of local elastic properties of the object being inspected since the velocities of ultrasounds are not dependent on its geometry but relevant to the density (ρ) and the stiffness of the material. What is more important is the correlations between ultrasonic velocities and material damages since the mechanical properties are affected by degradations [18,19]. Thus, the ultrasonic techniques for obtaining elastic

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constants are applicable and practical to monitor the damage evolution of structures in operation.

For the ultrasonic velocity measurement to obtain elastic constants, ultrasonic pulse-echo method has been extensively utilized since it is not only simple but also effective particularly when only one side of the inspected object is accessible [2,3,7,8,13-15,18]. However, the conventional system and commercial equipment using the pulse-echo method measure the velocities of longitudinal and shear waves individually [13]. Thus, either two pulser-receivers or a switching device is necessary, which produces a set of two data for each measurement and leads to the decline in the stability and efficiency of measurement.

In this study, a novel system based on the simultaneous measurement of longitudinal and shear waves as an overlapped signal is proposed to evaluate elastic properties of a material. This proposed approach produces single data for each measurement and thus contributes to improving cost- and time- efficiencies as well as reliability of the measurement system [20]. In Section 2, the backgrounds on ultrasonic measurement of elastic constants are covered first. The conventional approaches using the individual measurement of longitudinal and shear waves are introduced. Then, the novel approach based on the simultaneous measurement of the both waves is proposed, which enables to overcome the limitations and drawbacks the individual measurement have. To verify the reliability and effectiveness of the proposed system compared with the conventional methods, the experiments based on the both techniques are shown in Section 3. In Section 4, the results of elastic constant measurement through the two approaches are compared with each other and the useful tips for signal processing in specific cases are described. Finally, conclusions are drawn in Section 5.

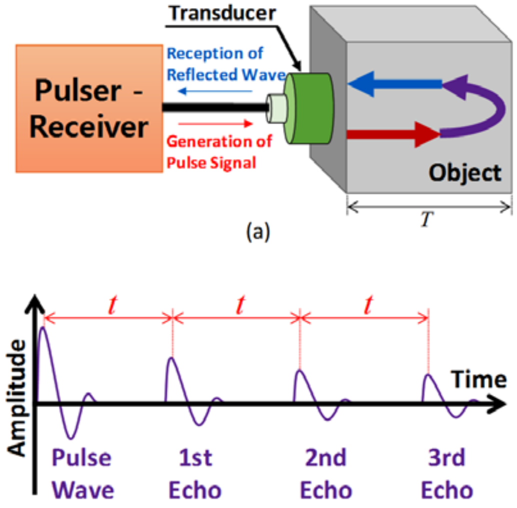

Fig. 1 (a) pulse-echo method and (b) a received pulse-echo signal for the object

2. Backgrounds

2.1. Ultrasonic Measurement of Elastic Constants

Using the ultrasonic nondestructive evaluation methods, elastic constants such as Poisson's ratio (ν), Young's modulus (E), and shear modulus (G) can be determined through calculations based on velocity measurement of longitudinal and shear waves and the density (ρ) [4,7,14,20].

There are various kinds of ways to measure ultrasonic velocity in materials. One of the techniques widely used is the pulse-echo method as shown in Fig. 1. This is especially useful when the thickness (T) of the specimen can be measured or known. The longitudinal wave velocity (c_L) and the shear wave velocity (c_s) can be calculated by the following equations:

$$c_{\mathrm{L}} = \frac{2T}{t_{\mathrm{L}}} \tag{1}$$

$$c_{\mathrm{S}} = \frac{2T}{t_{\mathrm{S}}} \tag{2}$$

where t_L and t_s are the flight times of longitudinal and shear waves, respectively.

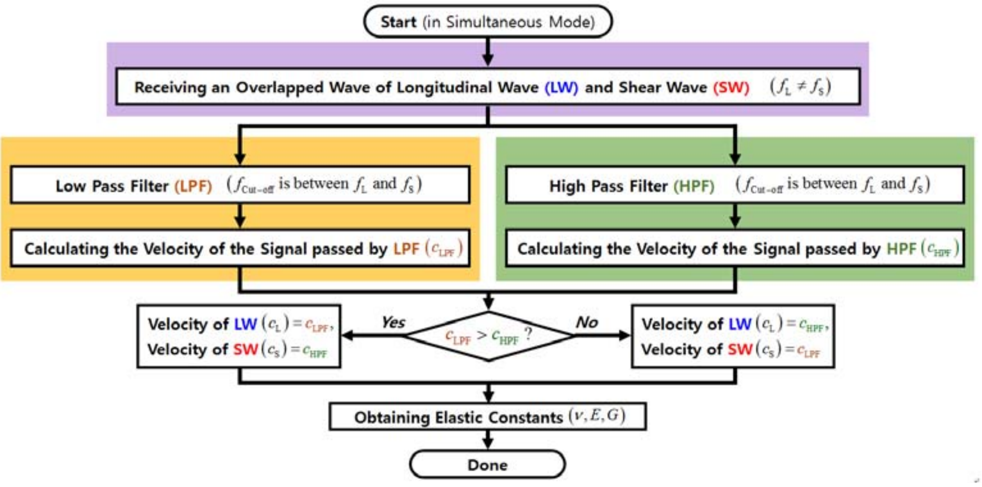

Fig. 2 The simultaneous measurement of longitudinal and shear waves

The elastic constants can be deduced by using the following relations:

$$\nu = \frac{1-2(c_S/c_L)^2}{2-2(c_S/c_L)^2} \tag{3}$$

$$E = \frac{c_L^2\rho(1+\nu)(1-2\nu)}{1-\nu} \tag{4}$$

$$G = c_S^2\rho \tag{5}$$

2.2. Ultrasonic Measurement Systems of Elastic Constants

The measurement systems of longitudinal and shear wave velocities can be classified into two categories in terms of signal acquisition type: individual measurement mode and simultaneous measurement mode. The conventional ultrasonic measurement systems of elastic constants have relied on the former approach. Using a pulser-receiver, the measurement of longitudinal and shear waves are conducted sequentially. Using two pulser-receivers, the waves can be generated and received in parallel. These kinds of individual measurement in any cases produce a set of two data for each measurement: longitudinal and shear wave signals, respectively. The velocities of the longitudinal and shear waves are calculated from each datum, respectively. Putting the velocities into Eqs. (3), (4), and (5), the elastic constants can be obtained.

In this study, a novel system that adopts the simultaneous measurement of longitudinal and shear waves to obtain elastic constants is proposed as shown in Fig. 2. Since the both velocities can be calculated by analyzing the overlapped signal, only single signal is necessary to obtain the mechanical properties. f_L and f_s are the frequencies of longitudinal and shear waves, respectively; $f_{cut-off}$ is the cut-off frequency for the filters used to extract the both wave components from the overlapped signal, c_{LPF} and c_{HPF} are the velocities of the signals passed by the low- and high-pass filters, respectively.

2.3. Proposed System: Simultaneous Measurement of Longitudinal and Shear Waves

There are several ways to generate or receive longitudinal and shear waves at the same time [10,21-22]. However, not all kinds of overlapped signals of the both waves are applicable to obtain elastic constants since it is not always possible to differentiate between the longitudinal and shear wave components from the overlapped signal. In the cases that the frequencies of the both components are different, they can be distinct from each other. Therefore, the key point is making their frequencies different in order to use an overlapped signal of the both waves for elastic constant measurement. Practically, the narrower the frequencies of transducers, the narrower the minimum frequency difference between two waves can be.

If longitudinal and shear waves were generated and received by the longitudinal and shear wave transducers that have resonant frequencies different from each another: f_L and f_s, respectively, elastic constants can be obtained through the proposed system. The cut-off frequency can be determined as the median value between them when each frequency of the longitudinal and shear wave components is known. However, if these frequencies are ambiguous or varying due to certain causes such as frequency dependent attenuation, short-time Fourier transform can be a useful and effective tool to find a proper cut-off frequency.

Although the system based on the contact-method that consists of a pulser-receiver and contact transducers is only introduced in this article, the proposed system is still valid for various kinds of ultrasonic techniques for analyzing the velocities of longitudinal and shear waves. Regardless of contact or non-contact means, there can be various combinations of transmitting and receiving system that have to analyze an overlapped ultrasonic signal. The proposed approach enables them to do it. Although there are several innovative ideas based on simultaneous measurement, this article does not cover them as the introduction of them is beyond the scope of this paper.

2.4. Signal Processing for Accurate Measurement of the Time of Flight

In order to obtain elastic constants precisely from the velocities of longitudinal and shear waves, it is crucial to measure the flight times of these waves accurately [11,14]. For this, in this research, the time of flight was measured according to the following procedures for a pulse-echo signal. First, after taking the absolute values of the signal, the enveloped signal was taken from the positive signal through a low-pass filter. Calculating the lag time intervals of peaks in the autocorrelation function, the flight time can be finally obtained by taking the mean value of them. This procedure is effective for ultrasonic velocity measurement of not only longitudinal waves but also shear waves.

3. Experiments

In order to verify the effectiveness and feasibility of the proposed system for the ultrasonic measurement of elastic constants, two kinds of experiments were conducted in not only the simultaneous measurement of the overlapped signals of longitudinal and shear waves as a novel system but also the individual measurement of the both waves as a conventional system.

The specimen was an Al6061-T6 block (120 × 60 × 40 mm) and the inspection points of the specimen are always same as shown in Fig. 3. According to the tensile test of the aluminum, Young’s modulus (E) is 70.579 GPa as shown in Fig. 4. Its density (ρ) is 2.69 g/cm^3. The ultrasonic pulser-receiver (5072PR, Olympus) to excite and receive an ultrasonic signal, the longitudinal wave transducer (5 MHz, C551-SM, Olympus), and the shear wave transducer (2.25 MHz, V154-RB, Olympus) were used under the same conditions. It should be noted that the main resonant frequency of the transducers must be different to apply the proposed approach. This enables the extraction of the longitudinal and shear waves from the overlapped signal by filtering.

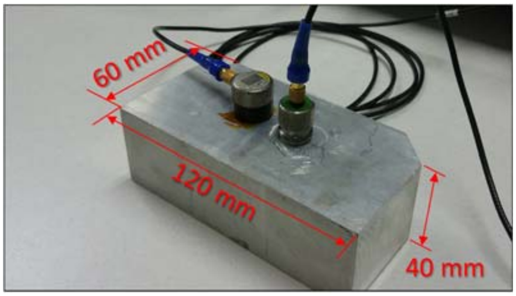

Fig. 3 The specimen and the inspection points that transducers were contacted

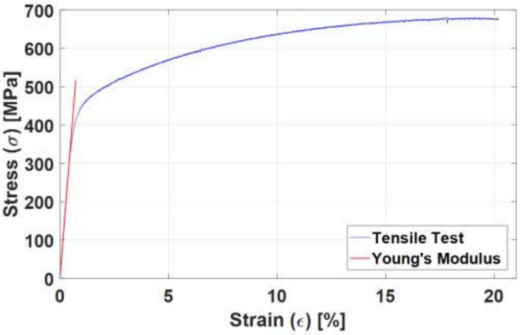

Fig. 4 Strain-stress curve of Al6061-T6

The different condition between the both experiments was the connecting method between the pulser-receiver and the transducers. The pulser-receiver were connected to the transducers one by one in the individual measurement system; whereas, the both transducers were coupled as a line connected to the pulser-receiver in the proposed system. In latter case, the electrical power will be equally distributed for each transducer as the impedances of the transducers are the same.

3.1. Conventional System: Individual Measurement of Longitudinal and Shear Waves

To obtain the reference values of elastic constants through the conventional system, the experiment for the individual measurement of longitudinal and shear waves were designed. In this system, the longitudinal and shear waves were excited and sensed one after another.

Following the signal-processing procedure introduced in Section 2.4 to get the time of flight of the both waves, their absolute values, enveloped signals, and auto-correlation functions were obtained. Calculating mean lag time interval between peaks in the auto-correlation function, the flight times of the longitudinal and shear waves in the specimen were calculated as 12.596 μs and 25.679 μs, respectively. Since the round-trip distance of the both waves was twice of the thickness of 40 mm, the velocities of the longitudinal and shear waves would be 6,365 m/s and 3,118 m/s, respectively. Thus, the elastic constants of the specimen could be obtained by using Eqs. (3), (4), and (5): Poisson's ratio (ν) of 0.3416, Young’s modulus of 70.298 GPa, and shear modulus of 26.200 GPa.

3.2. Proposed System: Simultaneous Measurement of Longitudinal and Shear Waves

To verify the effectiveness of the proposed system for ultrasonic measurement of elastic constants, the experiment for the simultaneous measurement of longitudinal and shear waves were designed as shown in Fig. 5(a). In order to excite and receive longitudinal and shear waves at the same time, the cables linked to the transducers were coupled by a T-junction BNC coupler as shown in Fig. 5(b). This made the system produce only single datum for each measurement: an overlapped signal of longitudinal and shear waves as shown in Fig. 6.

The signals passed by low- and high- pass filters is shown in Fig. 7. The cut-off frequency of the both filters was 3.625 MHz that the median value between the main resonant frequencies of the longitudinal and shear wave transducers: 5 MHz and 2.25 MHz, respectively. Note that the amplitude of each component are slightly lower than those of the individual measurement. This is because combining the two transducers in parallel changed the complex

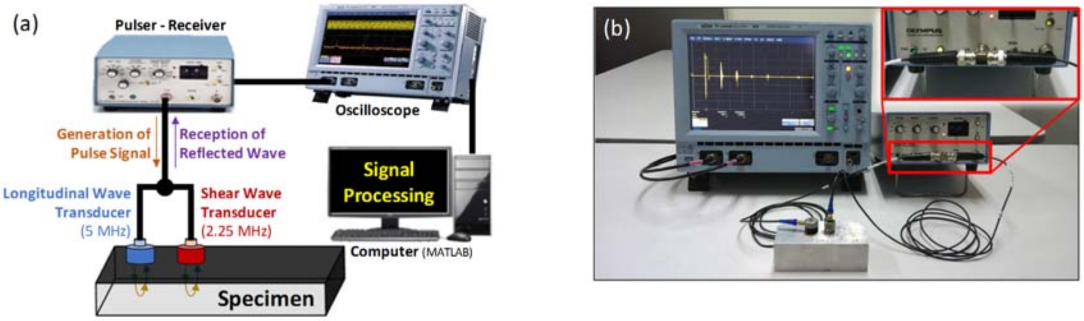

Fig. 5 (a) the experimental scheme for the simultaneous measurement of longitudinal and shear waves and (b) the experimental setup for the proposed system (top right: close-up view of the T-junction BNC coupler)

impendence of the set, which led to lower the applied voltage to the transducers than the case of one transducer. However, the difference is not critical to obtain the elastic moduli by ultrasonic velocity measurement since there are enough echoes to calculate the time of flight in the both wave signals.

The flight time of the filtered signals could be calculated in the same manner used for the experiment through the individual measurement. Following the signal-processing procedure introduced in Section 2.4, their absolute values, enveloped signals, and auto-correlation functions were obtained as shown in Fig. 8. Calculating mean lag time interval between peaks in the auto-correlation function, the flight times of the signals passed by low- and high- pass filters were calculated as 25.651 μs and 12.626 μs, respectively. The longer time of flight between them corresponded to the shear wave and the shorter one is for the longitudinal wave because longitudinal waves are generally faster than shear waves in solids. Since the round-trip distance of the both waves was twice of the thickness of 40 mm, the elastic constants of the specimen could be obtained by using Eqs. (3), (4), and (5): Poisson's ratio (ν) of 0.3401, Young's modulus of 70.375 GPa, and shear modulus of 26.257 GPa.

Although an overlapped signal of longitudinal and shear waves was made through coupling the two transducers by a T-junction coupler to be connected as single cable in this study, there are actually various kinds of means for receiving longitudinal and shear waves simultaneously. The experiment setup introduced as a proposed simultaneous measurement system in this article is one of them.

4. Results and Discussions

The experiments were conducted five times each for the individual measurement of longitudinal and shear waves and the simultaneous measurement of the overlapped signals of the both waves. The wave velocities and elastic constants obtained are illustrated in Table 1 and 2 according to the measurement method. The differences of the obtained elastic moduli between the individual and simultaneous measurement are less than 0.11 GPa, which supports that the proposed simultaneous measurement system is reliable compared with the conventional individual-measurement method. In addition, the standard deviations of the results in the simultaneous measurement are smaller than those in the individual measurement. This indicates that our proposed system without switching transducers is more stable than the other system including the switching function. This results show that the stability and repeatability of the measurement system can be improved as well as

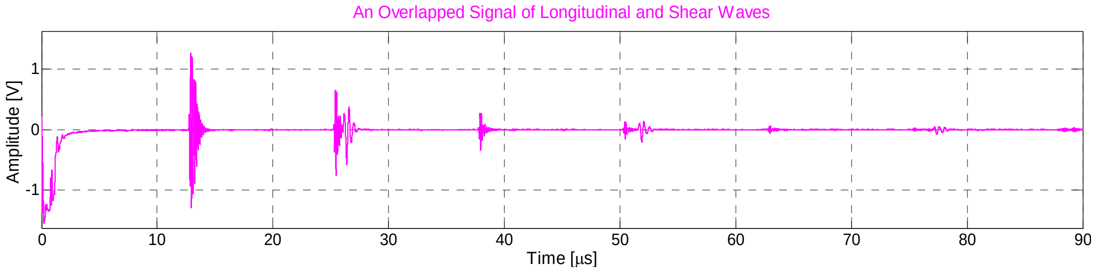

Fig. 6 An overlapped signal of longitudinal and shear waves sensed at once

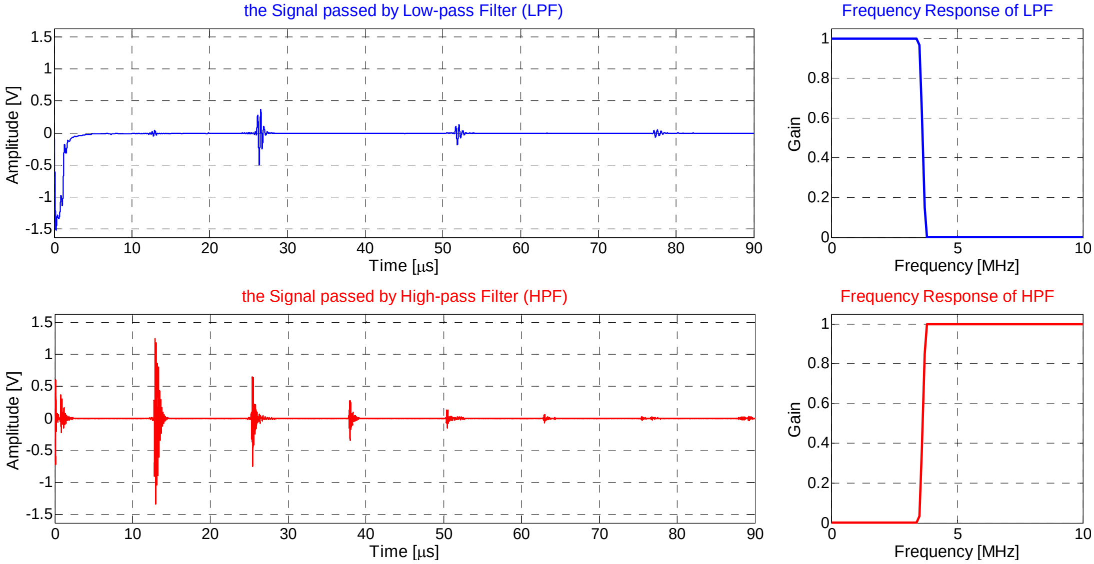

Fig. 7 The signals passed by the low- and high- pass filters ($(f_{Cut-off} = 3.625[MHz])$)

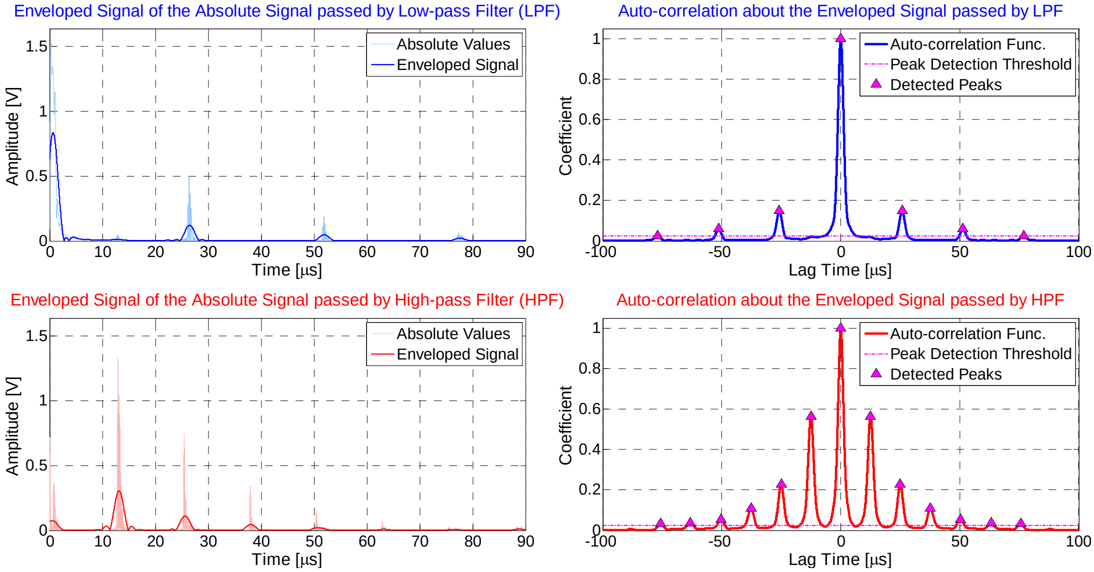

Fig. 8 Absolute values, enveloped signals, and auto-correlation functions of the filtered signals

Table 1 Wave velocities and elastic constants obtained by the individual measurement (T: 40 mm)

Test	Wave Velocity [m/s]		Elastic Constant		
	Longitudinal	Shear	Poisson's Ratio	Young's Modulus [GPa]	Shear Modulus [GPa]
1st	6320	3114	0.3397	69.88	26.08
2nd	6322	3117	0.3393	70.02	26.14
3rd	6343	3115	0.3410	70.02	26.11
4th	6365	3118	0.3421	70.20	26.15
5th	6368	3116	0.3427	70.12	26.11
Mean	6344	3116	0.3410	70.05	26.12
Standard Deviation	18.73	1.372	0.0012	0.0969	0.0230

Table 2 Wave velocities and elastic constants obtained by the simultaneous measurement (T: 40 mm)

Test	Wave Velocity [m/s]		Elastic Constant		
	Longitudinal	Shear	Poisson's Ratio	Young's Modulus [GPa]	Shear Modulus [GPa]
1st	6332	3118	0.3400	70.09	26.15
2nd	6325	3119	0.3393	70.10	26.17
3rd	6348	3119	0.3409	70.18	26.17
4th	6369	3118	0.3423	70.22	26.16
5th	6362	3119	0.3419	70.22	26.16
Mean	6347	3119	0.3409	70.16	26.16
Standard Deviation	15.36	0.3806	0.0010	0.0512	0.0064

Table 3 Wave velocities and elastic constants obtained by the individual measurement (T: 60 mm)

Test	Wave Velocity [m/s]		Elastic Constant		
	Longitudinal	Shear	Poisson's Ratio	Young's Modulus [GPa]	Shear Modulus [GPa]
1st	6428	3125	0.3452	70.69	26.28
2nd	6426	3118	0.3460	70.40	26.15
3rd	6424	3096	0.3487	69.54	25.78
4th	6421	3127	0.3446	70.72	26.30
5th	6423	3100	0.3481	69.72	25.83
Mean	6424	3113	0.3465	70.21	26.07
Standard Deviation	2.13	11.670	0.0015	0.4497	0.1953

Table 4 Wave velocities and elastic constants obtained by the simultaneous measurement (T: 60 mm)

Test	Wave Velocity [m/s]		Elastic Constant		
	Longitudinal	Shear	Poisson's Ratio	Young's Modulus [GPa]	Shear Modulus [GPa]
1st	6435	3124	0.3458	70.68	26.26
2nd	6427	3117	0.3462	70.37	26.14
3rd	6428	3096	0.3490	69.55	25.78
4th	6431	3113	0.3470	70.23	26.07
5th	6422	3101	0.3480	69.73	25.87
Mean	6429	3110	0.3472	70.11	26.02
Standard Deviation	3.84	9.6279	0.0011	0.3784	0.1611

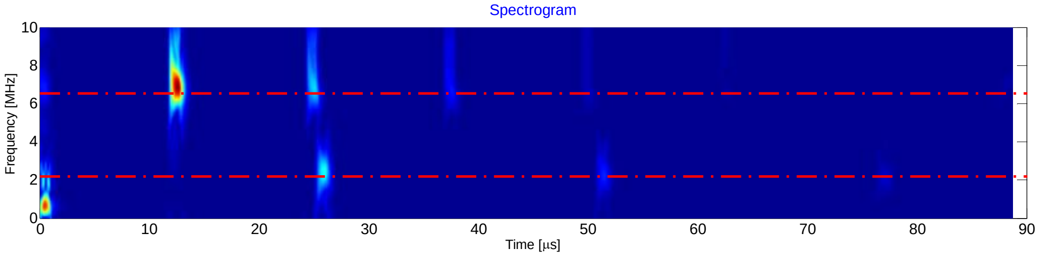

Fig. 9 Spectrogram via short-time Fourier transform of an overlapped signal

the cost- and time- efficiencies can be enhanced by reducing the number of devices that are required.

In order to verify the influence of the geometric dimensions to the result, the same experiment was additionally carried out in another direction with the propagation distance of 60 mm. As illustrated in Table 3 and 4, the results correspond to the preceding case of 40 mm propagation distance and the differences of the obtained elastic moduli between the individual and simultaneous measurement are less than 0.1 GPa. Although there is slight variation in the elastic moduli with respect to the thickness of the specimen, it is not significant enough to be considered meaningful compared with the standard deviations. These supports that the geometry does not affect this technique for isotropic materials. Furthermore, the standard deviations of the results in the simultaneous measurement are likewise smaller than those in the individual measurement. We think that this was because we excited and received the ultrasounds at the same time as well as used the same pulse signal for the both transducers. On the other hand, in the individual measurement, time difference between those measurement is inevitable. Besides, the pulse signals for each measurement cannot be the same with one another. Although the differences can be regarded as trivial, the errors caused by them can be slightly alleviated via the proposed approach.

According to the geometry of the object being inspected, it can happen that the longitudinal and shear waves arrive at the similar time so they seem to be less distinguishable. The proposed method is particularly advantages for these cases. Although the waves were overlapped in the time domain as shown in Fig. 6, they were separated in frequency domain as shown in Fig. 7. This shows that the filters in this manner enable to extract each wave component from the overlapped signal.

Fortunately, the cut-off frequency could be determined easily in this experiment since the main resonant frequencies of the used transducers were already known. However, the real frequencies of the longitudinal and shear waves may not be known from case to case. In this case, using the short-time Fourier transform is effective to determine a proper cut-off frequency for low- and high- pass filters as shown in Fig. 9. In this example, there are two distinguishable frequency components that have different peak repetition interval around 2 and 6 MHz, respectively; thus, a certain frequency between them can be chosen as the cut-off frequency such as the median frequency, 4 MHz.

5. Conclusions

In order to improve the efficiency and reliability of conventional systems using individual velocity measurement of longitudinal and shear waves to obtain elastic constants, a simultaneous sensing system of the both waves as an overlapped signal is proposed in this study. The main concept of the proposed technique is to sense the both waves as single overlapped signal after making their frequencies different from each other. This approach enables to extract longitudinal and shear components from the single datum by using low- and high-pass filters, respectively. While the conventional systems measure the both waves individually and analyze these two signals one after another or in parallel to obtain elastic constants, the proposed system measures an overlapped signal of the both waves at the same time and analyzes the signal to get the same results.

To verify the reliability and effectiveness of the proposed system, two kinds of experiments were conducted. They corresponded to a typical application of conventional methods and the proposed approach, respectively. As the conventional system, the longitudinal and shear waves were generated and received individually by switching the link between a pulser-receiver and the both wave transducers. In the experiment for the proposed system, the cables connected to the both transducers were coupled as single cable linked to the pulser-receiver.

According to the results, between the individual and simultaneous systems, the maximum difference of elastic constants obtained is less than 0.11 GPa, which supports that the proposed system is reliable. In addition, the simultaneous measurement showed smaller standard deviations than those in the individual measurement, which indicates that the proposed system without switching the transducers is more stable than the system with doing it. Moreover, since the proposed system produces half the number of data to obtain elastic constants compared with the conventional system, using the proposed approach is more efficient than the individual measurement case.

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