A study on the determination of Ultrasonic Travel Time by Norm Phase-Time Method

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위상시간법에 의한 초음파전파시간의 결정에 관한 연구

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〈Contents〉

Abstract

In this paper, a new algorithm to measure the ultrasonic travel time is proposed, which is fundamental to estimate distance,depth and volume in several media. Pulse wave has been used to measure travel time of transmitted signal. However, due to the characteristic of transducer and propagation, the received signal is so distorted that it is difficult to measure travel time, which is to be time difference between transmitted and received signals.

In this proposed method, transmitted and received signals are transformed respectively into norm phase newly designed by this paper and displayed on phase-time curve. And travel time is simply determined by the arithmetic numerical mean of time difference at the identical norm phase on the phase-time curves of trasmitted and received signals.

This method has several features: firstly, travel time is calculated analytically with high accuracy by least square error method, secondly, it is useful to compare the difference of signal magnitude for time information, thirdly, noise and discrete errors are relatively small, finally, the measurement accuracy is not influenced by D.C. bias. In particular, this method is useful and applicable to measuring very short distance and sound speed with high accuracy.

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1. INTRODUCTION

Ultrasonic has been used to measure distance,depth and speed in water, which are useful information for the safety of navigation. In recent years, it has extensively applied not only to diagnosis in the medical field but also to sensing the moving targets in traffic system and robot in several industrial fields[1]. In order to extend the ultrasonic application to the industrial field, it is required to measure the inherent parameters accurately in different media.[2),3)] If sound speed were known, the travel time of the sound which is time difference between trasmitted and received signals allows us to measure distance and volume, where mechanical tools do nothing to do with. In case the precision measurement is required, it is necessary to measure travel time with high accuracy.

Several studies for measuring travel time have been developed[4]. They can be classified into continuous and pulse wave methods according to the signal type of used. The former has advantage in estimating relative travel time in homogeneaous media. The latter has that in measuring absolute sound speed without being biased by the effect of multiple reflection. Nonethless, in these method time resolution is limited due to the puls width, and the received signal is distorted by being derived from the characteristic of the transducer and propagation in media. Consequently it is not easy to compare the trasmitted signal with the received one to measure the time difference.

In order to solve this problem, only specific points such as zero cross points on both transmitted signal and received one are used for measuring the travel time. The correlation handling of two signals is carried out, where the time correlation value becomes maximum is regarded as travel time. In zero cross method, measurement accuracy is greatly influenced by the noise component. Therefore, it is only applicable to measure acoustical paremeters of uniform media.

In correlation method, a long computing process is required in taking a correlation between tranmitted and received signals and the measurement accuracy is poor generally because of the gentle slope correction curve. In addition, the magnitute of signal amplitude affects the correltion curve.

Therefore, a new and simple algorithm for measuring travel time is proposed. In this algorithm, firstly, transmitted and received signals are transformed into norm phase newly defined in this paper, and displayed on phase-time curve as phase function[5),6)]. Secondly, the time error beween two signals at identical norm phase is calculated and summed while phase-time curve of transmitted signal is shifted little by little. Thirdly, the shifting time when the least square time error become the minimum is regarded as travel time. In particular, this new method is applicable to measuring travel time of small media and travel time difference in such a case as there is a fluctuation of temperature and pressure of media.

In this paper, we will describe the theretical background of a new algorithm and principle of travel time measurement. Finally, features of this method will be discussed by comparing with those of the conventional ones.

2. THERORECTICAL BACKGROUND

2.1. Phase transformation

Phase has been used as a variable to describe continuous sinusoidal signal[7]. It indicates an identical state at an interval of signal period, and is represented by degree(radian) with the range from 0(0π) to 360(2π). Here, we consider application of phase concept to all signals generally. For this purpose, let's define phase newly as follows.[8),9)]

$$\theta(t) = \arg\left(\int_{-\tau}^{\tau} g(t+\tau)\sin\omega_o\tau d\tau + i\int_{-\tau}^{\tau} g(t+\tau)\cos\omega_o\tau d\tau\right) \quad (1)$$

$$\tau = \frac{\pi}{\omega_o} \quad (2)$$

where, arg shows method to illustrate argument in complex polar coordinate, j means imaginary unit, ω_o is analysis frequency, which determines signal range used for defining phase, namely, τ is $\frac{\pi}{\omega_o}$. The phase defined formerly can be calculated at each time throughout the region of a single cycle of signals, by determing analysis frequency. Though phase $\theta(t)$ depends on signal and analysis frequency, eigen values that has no relation with analysis frequency exits. If these values can be used for certain application, this frequency can be selected freely.

From the above expression, phase value ranges from -180 degree(-π radian) to 180 degree(π radian). In order to discriminate from conventional phase, we will call this phase defined in Eq.(1) norm phase. Any signal can be transformed into norm phase. The process in which signal is changed into norm phase will be called as phase transformation. Figure 1 shows the principle of phase transformation.

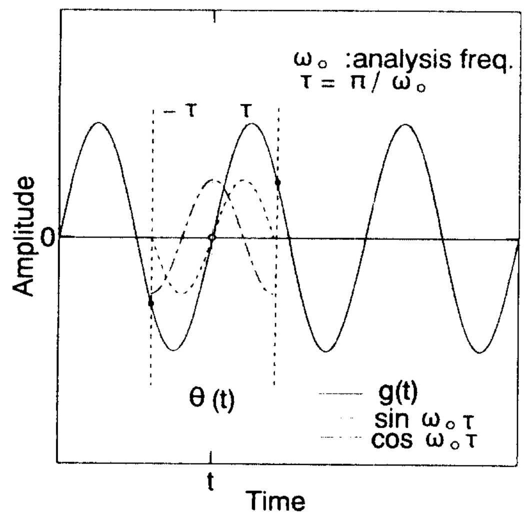

Fig. 1 Signal and Phase transformation.

2.2 Phase-time curve

In general, signal is expressed with amplitude change in time domain with the amplitude on vertical axis and the time on the horizontal axis respectively. The time information of signal such as travel time which is time difference between transmitted and received signals has no relations with magnitude of signal amplitude directly. Since we have interest in measuring travel time, we are to display signal for this purpose. Amplitude value displayed on vertical axis can represent norm phase. The phase-time curve can be shown on the coordinate system with norm phase on vertical axis and time on horizontal axis. Figure 2 shows continuous sinusoidal wave and its phase-time curve, which has some

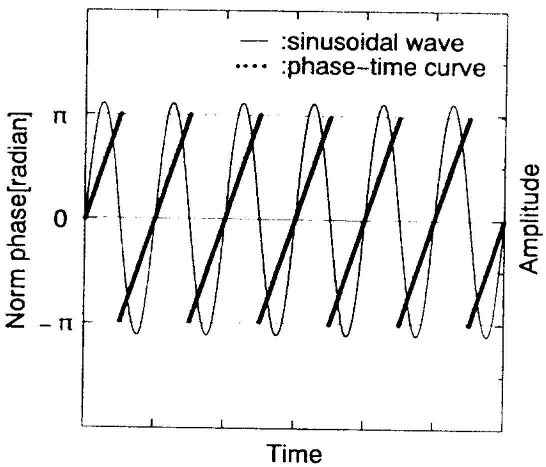

Fig. 2 Continuous sinusoidal wave and its phase-time curve.

features: firstly, it displays time information of signal as signals' fluctuate at the given moment, irrespective of the signal magnitude. Thus, this curve is so useful in comparing with different amplitude signals as to be able to measure travel time. Secondly, it does not suffer from noise since noise components is averaged in phase transformation process. In particular, this illustration is applicable to measuring time information when noise component affect largely on its measuring accuracy. Thirdly, it is not required any process to remove D.C. bias component because its component is compensated automatically.

3. TRANSFORMATION OF SIGNALS

3.1. Tone burst pulse of transmitted signal

Distance can be calculated by measuring travel time which is time difference between transmitted signal and received one, if sound speed were known. In this case, measurment accuracy depends on how the travel time can be measured accurately. Therefore, ultrasonic pulse signal is extensively used to measure travel time in liquid media.

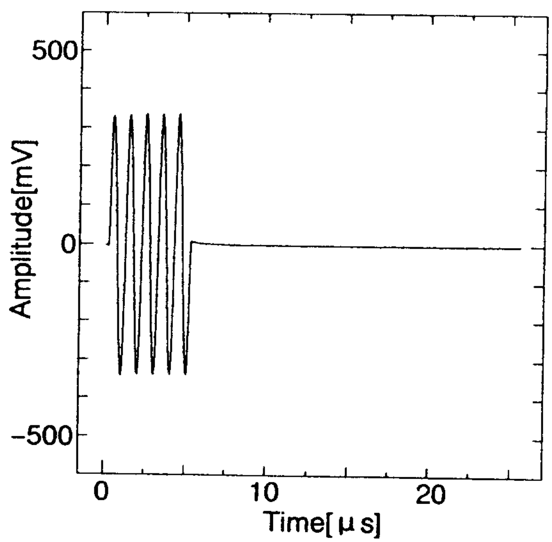

Fig. 3 Tone burst pulse of transmitted signal.

Let's consider tone burst pulse which is a part of continuous sinusoidal signal as transmitted signal. Since this signal can be regarded as truncated continuous sinmusoidal signal, it has intermediate property between impulse and continuous sinusoidal signals. On the base of this signal property, both time and phase conceptions of signals can be made.

3.2. Received signal

Figure 4 shows received signal when tone burst pulse is transmitted, in case transmitted and received signals were triggered by same source. The received singal is distorted from the transmitted one due to the characteristic of the transducer and propagation in media. Hence, it is not easy to measure the time difference by comparing these signals directly. So, the received wave which contains some noise component has to be biased by D.C. bias.

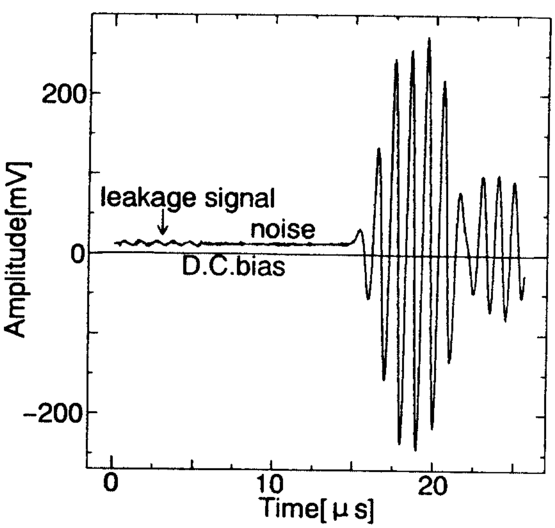

Fig. 4 Distortion of received signal.

3.3. Phase-time curves of transmitted and received signals

Let's transform transmitted and received signals into norm phase-time respectively. First of all, these signals are sampled with certain freqency which is sufficient for required accuracy, and sample datum can be interpolated linearly by using the nearest phase value. We select analysis frequency as the same one as the tone burst pulse which was used as transmitted signal.

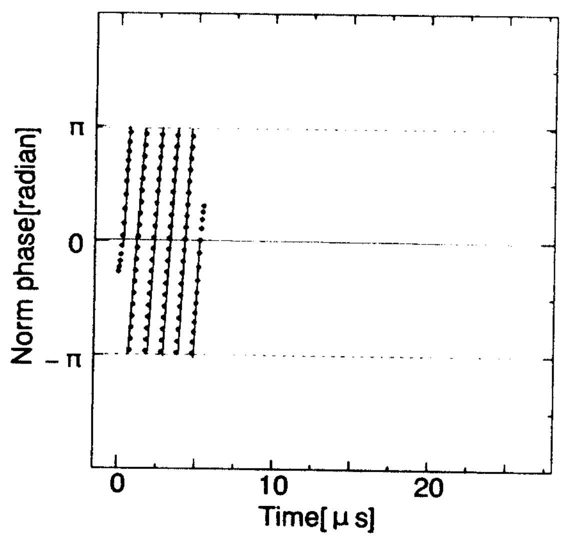

Fig. 5 Phase-time curve of transmitted signal.

Figure 5 shows phase-time curves of tone burst pulse transmitted. Phase-time curve of tone burst pulse is specified into two parts: transient state where phase line is not aligned with the front phase line, nor the rear phase line. And steady state where phase line is aligned with both the front and rear phase lines. Figure 6 shows phase-

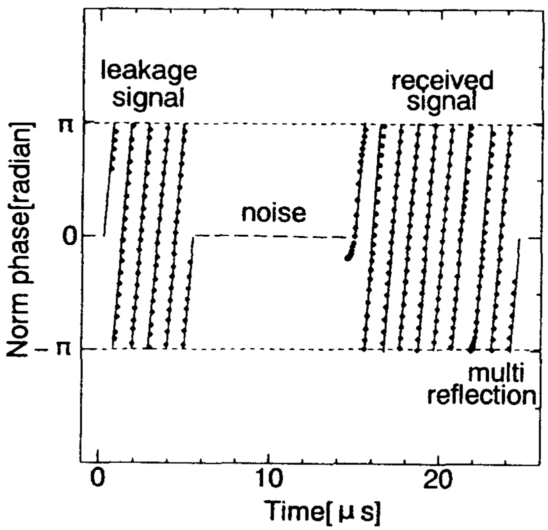

Fig. 6 Phase-time curve of received signal.

time curve of received signal when tone burst pulse be transmitted. On this curve, small amplitude leakage signal was illustrated in the range from $-\pi$ to π . Signals biased by D.C. bias are described on phase-time curve with balance irrespec- tive of its magnitude.

4. DETERMINATION TRAVEL TIME

4.1. Travel time and time difference

Travel time(T_t)of ultrasonic in media can be written by

$$T_t = \Delta t - D_t \quad (3)$$

where Δt is time difference between transmitted signal and received signal, D_t is delay time which is the required in transferring from electrical signal to acoustical signal in transducer. This delay time is invariable in the same measurment system and can be calculated by measuring travel time while travel distance is changing in homogeneous media.

If D_t were known, time difference between transmitted and received signals can be determined. However, it is difficult to define time difference when received signal is distorted, because matching one point on the transmitted sinal to the other on the received one can not be done simply.

Here, to solve this problem, the least square error method is newly designed. Namely, time difference can be calculated by steady state phase line on the phase-time curves of transmitted and received signals. Time difference at identical phase can be written by,

$$T_d = Tr_i(\phi) - Tt_i(\phi) \quad (4)$$

where $Tr_i(\phi)$, $Tt_i(\phi)$ display the time of received signal and transmitted signal at norm phase (ϕ) respectively.

4.2. Time error

If received signal were not distored, phase-time curve of that signal is overlapped with one of transmitted signal when it is shifted as much as time difference between two signals. Here, the time disparity between two signals at identical norm phase on phase-time curves is called time error. Time errors at each phase between two phase-time curves occur due to wave distortion, noise and time shift. Let's calculate summation of time error $E(\tau_d)$ on whole phase-time curve when phase-time curve of transmitted signal be shifted as much as τ_d. The total of time error can be expressed as follows:

$$E(\tau_d) = \int_{-\pi}^{\pi} \sum_{i=0}^{n} \{ Tr_i(\phi) - (Tt_i(\phi) + \tau_d)\} d\phi \quad (5)$$

where n is the number of steady state phase line on phase-time phase curve.

Using least square error method, we consider determining τ_d so as to be the minimum of $E(\tau_d)^2$. Being taken a differential with τ_d, we see that

$$\frac{dE(\tau_d)^2}{d\tau_d} = \sum_{i=0}^{n} \int_{-\pi}^{\pi} \{2\tau_d - 2 (Tr_i(\phi) - Tt_i(\phi))\} d\phi \quad (6)$$

from

$$\frac{dE(\tau_d)^2}{d\tau_d} = 0 \quad (7)$$

In consequence, τ_d is written by

$$\tau_d = \frac{1}{2(n+1)} \pi \sum_{i=0}^{\pi} \int_{-\pi}^{\pi} Tr_i(\phi) d\phi - \frac{1}{2(n+1)\pi} \sum_{i=0}^{n} \int_{-\pi}^{\pi} Tr_i(\phi) d\phi \quad (8)$$

τ_d derived in Eq.(8) is regarded time difference between different signals such as pulse signals transmitted and received. Figure 7 shows calculation of time difference on phase-time curves.

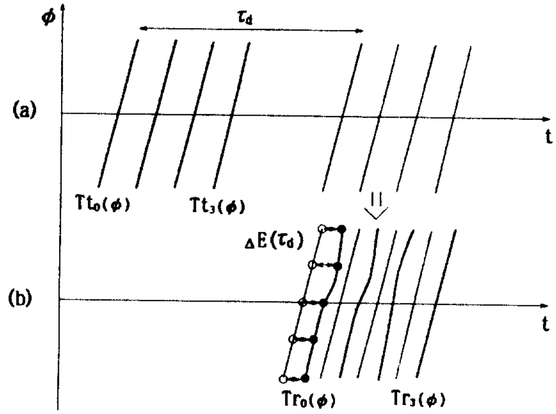

Fig. 7 Calculation of time difference on phase-time curve.

4.3. Average time difference

The above Eq.(8) means that time difference τ_d corresponds to average time error at each identical norm phase when phase-time curve transmitted is not shifted. Transforming signal with norm phase, we can simply measure time difference between different signals by calculating the arithmetic numerical mean of time error at identical norm phase between phase-time curves of transmitted and received signals.

We can obtain several specific points which is discriminated easily on signals from phase transformation. They can be used to measure time difference between two signals, even though zero cross points are used in zero cross method. Therefore, several points can be freely selected to measure travel time in consideration of noise components and accuracy required.

5. RESULT AND DISCUSSIONS

Among several techniques for determining travel time, zero cross method, and correlation method has been well known. In zero cross method, only zero points of signal amplitude are used to measure travel time. In correlation method, correlation handling of both transmitted and received signals is carried out while transmitted signal is shifted, and travel time is regarded as time when correlation value be peak.

In this section, we will discuss and address features of method designed in this paper comparing with two methods described above.

5.1. High accuracy

In correlation method, time difference between transmitted and received signals is regarded as time when correlation value on correlation curve be the maximum. In usual, correlation curve is a gentle slope like Figure 8. So, change rate of correlation

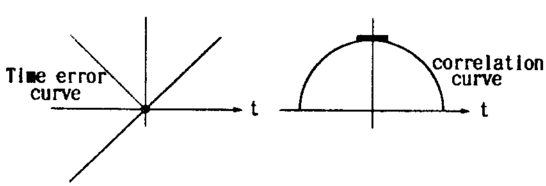

Fig. 8 Comparison of sensibility for determing time between norm phase-time and correlation method.

value versus time is low. Consequently, small error occurs in determining peak value can attribute large error of time difference. In other words, correlation value is low sensitivity to time change, which results in to poor measurement accuracy of time difference.

On the contrary, in our newly designed method, time error conception was introduced and time difference is regarded as time when square error become minimum. Time errors increase linearly with time approximately. So, Travel time is determined with higher accuracy than that in correlation method analytically. Therefore, the method described in this paper is useful for measuring travel time and travel time difference of small media.

5.2. Simple algorithm

For making a correlation curve, we should carry out integral handling repeatedly while transmitted signal is shifting little by little. Thus, long time and large quantity of computer memory is required for this calcultion. In zero cross method, if there is a fluctuation of propagation characteristic in media, it is difficult to calibrate this effect. Thus, this method is not applicable to measuring travel time in inhomogeneous media.

In our new method, travel time is determined by the arithmetic numerical mean of time error at each identical norm phase on whole phase-time curves of transmitted and received signals. As in this method the over-all information of signal is used in measuring travel time, and D.C. bias component of the signal is cancelled automatically, it is applicable to measuring travel time in inhomogeneous media.

5.3. Small noise and discrete errors

As noise component of signal often affects on measurement accuracy, it is essential to reduce its effect. when signal is transformed into norm phase from Eq.(1), noise component of signal is averaged during $2T$. Measurement accuracy in new method is dependent on niose component not more than that in zero cross method and at least not less than that in correlation method.

For mathematical handling, we should make discrete data from continuous signal by sampling, and by using discrete data. Thus, interval value between sample datum should be interpolated. Since phase line on phase-time curve is linear approximately, we can interpolate interval value with small error by taking linear interpolation simply.

6. CONCLUSION

In this paper, we provided new algorithm to measure travel time in pulse wave method. Transmitted and received signals are transformed into norm phase defined for the first time. These signals are illustrated with norm phase on phase-time curve. Travel time is simply determined by calculating average time error at identical norm phase between phase-time curves of transmitted and received signals.

In conclusion, this method has some advantages as follows:

(a) High accuracy
(b) Simple algorithm
(c) Small noise and discrete errors

In particular, this method makes it feasible to measure short distance and travel time difference accurately.

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