본 학회지를 발간하는 데 도움을 주신 한국과학기술단체총연합회에 감사드립니다.

선박의 흘수 측정을 위한 초음파 펄스 신호의 해석기법

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An Analysis Technique of Ultrasonic Pulse Signal for Measuring Ship's Draught

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<목 차>

Abstract

Although ship's draught information onboard is substantial for both the safety of navigation and the estimation of loaded cargoes, its accuracy depends, in conventional surveying method, on the skillfulness of observers and the condition of the sea surface round the vessel. To obtain more accurate information accessibly, measuring instruments with sophisticated sensors such as mechanical, electronic and ultrasonic transducers have been developed. However, they have still limitation in accuracy and in making up a system due to the complexity of processing signal. In this paper, we propose a new technique for analyzing ultrasonic pulse signal, in order to improve the measurement accuracy and simplify a remote sensing system of draught by ultrasonic waves. In this technique, pulse signal is translated into phase curve which is composed of the phase value defined in time domain. Then, the

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time interval between two signals different in waveform, is analytically determined by calculating average time difference on phase curves. Also, analytical procedure can be carried out in real time with the successive five data sampled at *T/4*, for high speed digital processing with computer and A/D converter. This technique is useful for measuring draught under the influence of sea condition and for interfacing its data briefly to the integrated bridge system.

1. Introduction

The draught is important information to the safety navigation and the estimation of the loaded cargo quantitatively. As well, it is one of the parameters to show ship's dynamic characteristics, which is valuable data for enhancing the maneuverability of vessel in integrated navigation system. For these applications, it is necessary to measure draught sensitively and to interface its data with required systems accessibly. In general, its measurement has been carried out by observing the draft mark directly. Thus, its accuracy measured is greatly dependent on personal experience and the sea surface condition round the vessel. As well, continuous measurement is interrupted by foul weather. In recent years, sensors such as mechanical, electronic and ultrasonic transducers have been used in measuring the draught. However, they have still limitation in accuracy and making up a system due to the complexity of processing signal[1-3].

The sound propagation time for the draught can be measured by calculating the time difference between transmitted signal and reflected signal to sea surface by using the time resolution of ultrasonic pulse waves. But, in this procedure, the resolution is limited to pulse width, and reflected signals distort form the waveform of transmitted signal, depend on transducer and propagation characteristics[4-5]. Therefore, it is difficult to compare two signals different in waveform forms, in order to determine ship's draught with high accuracy. In addition, the sea surface fluctuation may cause measurement error.

This paper aims to deal with designing a system for the remote sensing of draught by ultrasonic waves. The basic principle in this method is to measure the propagation time of sound from ultrasonic transducer to seasurface. Namely, the distance between the sensor and the sea surface can be obtained on the assumption that sound speed in air medium is constant, 340 m/sec.

In this paper, we introduce a new technique in which the draught is estimated by analyzing ultrasonic pulse signal into the phase defined in time domain firstly. In this technique, the draught can be determined continuously and analytically by calculating the average time interval at corresponded value on the phase curves of transmitted and received signals, and be interfaced to other equipments accessibly.

2. Measurement Setup

2.1 Remote Measurement of Draught

The draught is the depth of water necessary to float a vessel. At sea, it is regarded as the distance between the vessel bottom and the sea surface. In conventional method, this distance is measured by observing draft marks of the stem and sternpost with eye. Here, let us consider the remote sensing of the draught by using ultrasonic waves. If a transducer is located at the height known from the bottom, the vessel's draught can be described with the travel time of sound from the position of transducer to the sea surface as Fig. 1. Namely, the corresponding expression for the draught is given by

$$D = H - h_1 = H - \frac{c \times t}{2} \qquad (1)$$

where H, h_1 represent the height from the height from the position of transducer to the bottom of vessel and the distance between transducer and the sea surface, respectively, c is the sound velocity in air medium and t is the time interval taken for one round trip of sound to the sea surface.

If the sound velocity in air medium can be assumed as constant, disregarding the influence on the temperature fluctuation, the measuring accuracy of draught(D) depends on how exact the time interval is estimated. In the result, one measures the distance h_l actually for determining ship's draught, on the assumption that sound waves make a straight propagation at a fixed velocity in air medium.

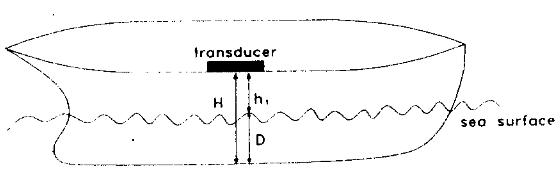
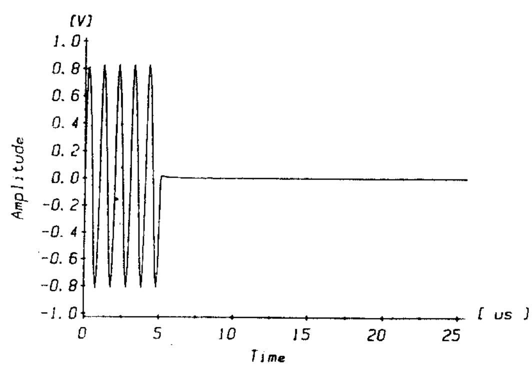


Fig. 1 The remote sensing of draught on board by ultrasonics.

2.2 Weaveforms of Signals

Tone burst pulse which is a part of continuous sinusoidal signal, is often used for measuring distance as transmitted signal since it has time resolution, Figure 2 shows the transmitted signal and received signal when tone burst pulse transmitted in experimental stage. On received wave, some noise and D.C. bias were observed. The initial part of received signal which is small amplitude and low S/N, is thought as the leakage signal of transmitted signal. The waveform of received signal is different from that of signal transmitted as Fig. 2. The distortion of received wave is due to the characteristics(Q) of transducer and multi-propagation in media. Then, in comparing transmitted singal with distorted received signal for determining the time interval or distance, the corresponding points of signals cannot be recognized when signal-waveforms are different each other[6].



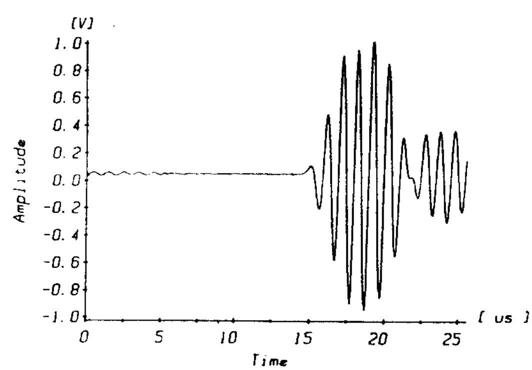


Fig. 2 The waveforms of transmitted and received signals.

2.3. Lateral Resolution and Focusing

When sound wave propagates in air from transducer, it diffuses. So, beam diameter(B_d) described with 3dB, is changed according to the frequency(F), the diameter(D_i) of transducer and the distance(d) off the transducer as Fig. 3.

The beam pattern described with 3 dB is expressed in far field as Eq.(2) [1]

$$B_d(mm) = \frac{3 \times d(mm)}{F(MHz) \times D_i(mm)} \qquad (2)$$

The beam diameter represents the lateral resolution that is capable of separating two objects located at the lateral direction of sound propagation. Although this resolution is improved by increasing the signal frequency, the distance that sound can propagates is shorten in proportion of its frequency. In the case of draught measurement, the spreading of beam causes echoed wave to be propagated through multiple paths. So, the measured value will be greatly influenced by the sea condition. Here, the curved transducer of which focal length is almost equals to the measured distance, is used for focusing sound wave around the sea surface.

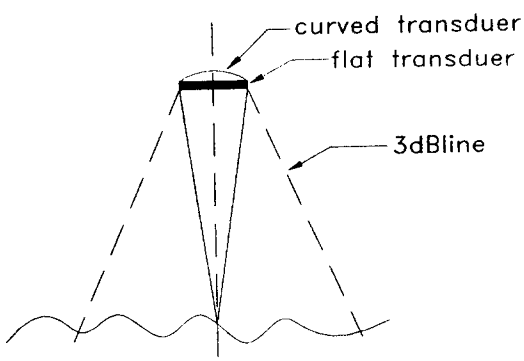


Fig. 3 Sound beam pattern described with 3dB.

2.4 Reflection at air-water interface

A sound wave incident from a medium with a lower sound speed onto an interface separating it from a medium with higher sound speed is reflected. The quantity of reflected wave is related to the acoustic impedance z of medium, written with density ρ and sound speed c as $z = \rho c$. The reflection coefficient R at air-water interface is given by

$$R = \frac{z_w - z_a}{z_w + z_a} \approx 1.0 \qquad (3)$$

where z_w, z_a are acoustic impedance of water and air medium respectively. It is noted that the incident wave is almost reflected at the interface of air water since $\rho_a c_a / \rho_w c_w \cong 0.0003$.

3. Phase Analysis

3.1 Feature of Phase Parameter

The phase is useful for the precise measurement in time, since it is parameter to describe the minute time with a period of sinusoidal signal originally. This feature of phase parameter is introduced into pulse signal in time domain. Complex coordinate has been used for the description of two dimensional vectors instead of real signal. The signal $C(t)$ in complex coordinate has the amplitude $A(t)$ and the phase $\theta(t)$. These can be written by

$$\theta(t) = \arg\{Re(C(t))1 + j\,\mathrm{Im}(C(t))\}$$

$$A(t) = \sqrt{\mathrm{Re}(C(t))^2 + \mathrm{Im}(C(t))^2} \qquad (4)$$

where Re($C(t)$), Im($C(t)$) are the real part and the imaginary part of $C(t)$ respectively.

3.2 Phase Definition of Signal with D.C. Component

In order to define the phase in time domain, first of all, let us consider the relation between the phase and the D.C. component of signal. A signal. A signal $S_d(t)$ with D.C. component is expressed by

$$Sd(t)=A\ \cos\omega t+D_i \qquad (5)$$

Figure 4 shows how D.C. component effects the phase, where the imaginary part $S_{id}(t)$ is assumed as

$$S_{id}(t) = A \sin \omega t+D_i \qquad (6)$$

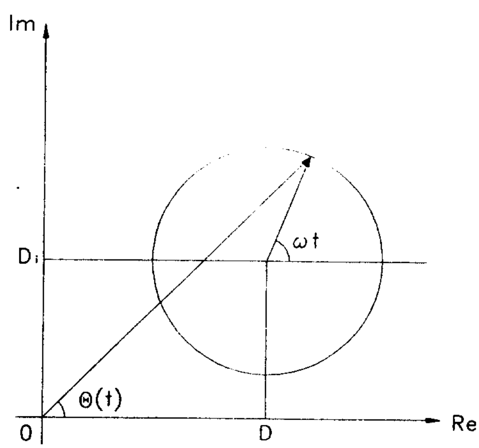


Fig. 4. Fixed vector and rotating vector.

The complex signal is described as the resultant of fixed vector and rotating vector. The phase $\theta(t)$ does not agree with the phase ωt of rotating vector as shown in Fig. 4. The two components for the phase ωt are expected as

$$R(t) = A\cos\omega t$$
$$I(t) = A\sin\omega t \qquad (7)$$

It is noted that the real part, $A\ \cos\omega t$ and the imaginary part, $A\ \sin\omega t$ as shown in Eq.(7) are contained in Eq.(8). The D.C. component D can be eliminated through the integration of the signal Sd(T+ τ) by τ within the period T of the sinusoidal signal. Then, the real part and the imaginary part can be obtained as follows :

$$R(t)=2\int_{-T/2}^{T/2} S_d(t+\tau)\cos\omega\tau d\tau = A\cos\omega t$$

$$I(t)=2\int_{-T/2}^{T/2} S_d(t+\tau)\sin\omega\tau d\tau = A\sin\omega t \quad (9)$$

The phase $\theta(t)$ can be obtained as

$$\theta(t) = \arg(R(t)+jI(t))$$
$$= \arg(2\int_{-T/2}^{T/w} S_d(t+\tau)\cos\omega\tau d\tau$$
$$-2j\int_{-T/2}^{T/2} S_d(t+\tau)\sin\omega\tau d\omega) \quad (10)$$

This phase is independent on D.C. component, and is useful for detecting necessary information in case of D.C. level shift occurred just after the strong pulse signal.

3.3. Generalized Phase in Time Domain

Here, let us apply this procedure for general function $f(t)$, any complex signal $f(t)$ can be defined as [7-9][12]

$$f(t) \equiv R(t)+jI(t) \qquad (11)$$

where

$$R(t)=2\int_{-Tc/2}^{Tc/2} f(t+\tau)\cos\omega_c\tau d\tau$$

$$I(t)=2\int_{-Tc/2}^{Tc/2} f(t+\tau)\sin\omega_c\tau d\tau \qquad (12)$$

where ω_c is center angular frequency and Tc is the period. Then, the amplitude $A(t)$ and the phase $\theta(t)$ are described as

$$A(t)=\sqrt{Re(C(t))^2+\mathrm{Im}(C(t))^2}$$
$$\theta(t)=\arg\{\mathrm{Re}(C(t))+j\mathrm{Im}(C(t))\} \qquad (13)$$

Now, let us call the curve of the phase $\theta(t)$

the phase curve.

4. Determination of Time Interval

4.1 Evaluation of Similarity

The time interval between two phase curves of transmitted and received signals can be defined by using the idea similar to the correlation. Namely, which part of transmitted phase curve is most similar to that of received phase curve?

This similarity can be evaluated by calculating time disparity at each phase. If the phase curve of received signal is the same as that of received signal, phase curve of received signal is completely overlapped with that of received signal by shifting the phase curve of transmitted signal as much as the time interval between two signals. In practice, those curves are not overlapped because they are different in waveform. Here, the similarity of two curves is evaluated by applying the least square method. Precisely, two curves is most similar when the square of time disparity at each phase minimizes.

4.2 Time Interval on Phase Curves

The phase of transmitted and received pulse signals are analyzed as defined in chapter 3. Then, the phase curves of two signals are obtained as Fig. 5[6].
where the time error $e(t)$ represents the time difference at each phase

Here, we describe how to determine the time interval on these phase curves. The similarity of two curves can be estimated by calculating the squared time error. On the phase curves of received signal, a point that is most similar to the phase curve of transmitted signal is at the time when squared time error is the minimum. Figure 6 shows how to calculate the time interval on phase curves. When the phase curve of transmitted signal is shifted as much as τ_d, the summation $E(\tau_d)$ of square time error can be expressed as follows :

$$E(\tau_d) = \sum_{i=1}^{n} \int_{\phi 1}^{\phi 2} \{ T_{ri}(\phi) - (T_{ti}(\phi) + \tau_d)^2 \} d\phi \quad (14)$$

where n is the number of phase segments on phase curve, and T_{ti}, T_{ri} is each time of received signal and transmitted signal at the phase ϕ. It can be thought that a phase curve of received signal is most similar to that of transmitted signal when the summation error $E(\tau_d)$ is the minimum. Then, τ_d is determined so as to be the minimum

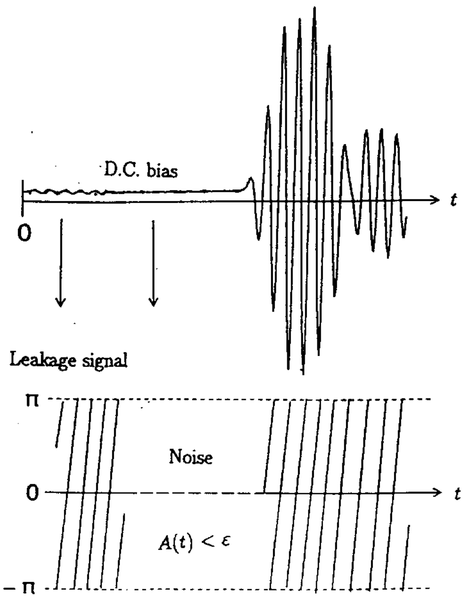


Fig. 5 Phase curves of transmitted and received pulse signal.

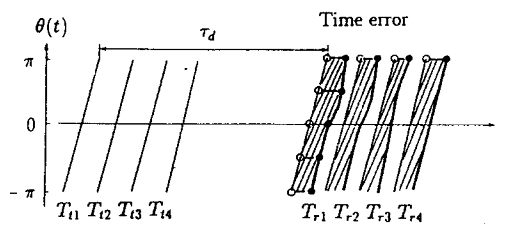


Fig. 6 Determination of time interval on phase curves.

of $E(\tau_d)$ by least square method. If the $E(\tau_d)$ is differentiated by τ_d, the derived function is obtained as

$$\frac{dE(\tau_d)}{d\tau d} = 0 \tag{15}$$

The τ_d for the least value $E(\tau_d)$ is calculated from Eq.(15).

In consequence, τ_d can be written by

$$\tau_d = \frac{1}{2(n+1)\pi} \sum_{i=1}^{n} \int_{\phi 1}^{\phi 2} (T_{ri}(\phi) - T_{ti}(\phi))\, d\phi \tag{16}$$

5. Practical Version For Digital Processing

In recent years, high speed digital processing with computer and A/D converter has been developed rapidly. That allows us to analyze signal digitally in real time. Here, let us derive a practical digital version of Eq.(16). Figure 7 shows the successive five data sampled at $T/4$. The real part $R(t)$ and the imaginary part $I(t)$ can be expressed with these sampled data as follows :

$$\begin{aligned} R(t) &= \frac{1}{2}\left\{ f(t)\cos 0 - \frac{f(t-T/2)\cos(-T/2)}{2} + \frac{f(t+T/2)\cos(T/2)}{2} \right\} \\ &= \frac{1}{2}\left(c - \frac{a+e}{2}\right) = \frac{c}{2} - \frac{a}{4} - \frac{e}{4} \end{aligned} \tag{17}$$

$$\begin{aligned} I(t) &= \frac{1}{2}\{-f(t-T/4)\sin(-T/4) + f(t+T/4)\sin(T/4)\} \\ &= -\frac{b}{2} + \frac{d}{2} \end{aligned} \tag{18}$$

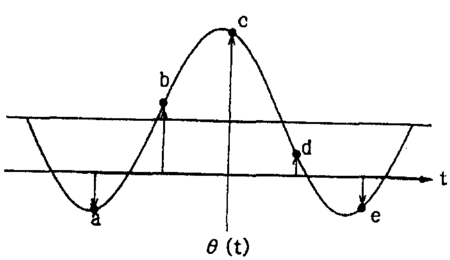


Fig. 7 Practical digital Processing.

Thus, $\theta(t)$ can be determined by the five sampled data as

$$\theta(t) = \arg\left(c - \frac{a+e}{2} + j(d-b) \right) \tag{19}$$

It can be seen that the phase $\theta(t)$ can be briefly calculated by the mathematical operations of addition and subtraction instead of correlation in the conventional technique[10-11].

6. Conclusion

We introduced a new technique for pulse signal analysis, in order to apply for measuring ship's draught by ultrasonic wave sensitively and briefly. This technique has the following features : firstly, the measuring accuracy is independent of D.C. component because signal is analyzed with the phase defined in time domain. Secondly, spatial resolution is higher than that of conventional methods. Thirdly, component around the carrier frequency of pulse signal is reflected sensitively. Moreover the practical digital version enables us to get the phase in real time by digital processing. The technique proposed will be useful for measuring time interval and Doppler frequency in several applicatins such as the measurements of speed, distance and depth.

Acknowledgments

This works has partly been supported by the Society for Enhancing Scientific Research in K.M.U.

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