A Technique for Measuring Ship's Draught by Ultrasonic Pulse Signal

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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 traditional 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. This technique is useful for measuring draught, being considered the influence of sea surface fluctuation, and for transferring its data briefly to required equipment in integrated bridge system .

1. INTRODUCTION

The draught is important information to the safety navigation and estimation of the loaded cargo quantitatively. As well, it is one of parameters to show ship's dynamic character, 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 condition round 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.

We have been interested in 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 sea surface. Namely, the distance between the sensor and the sea surface can be obtained on the assumption that sound speed in air is constant. If ultrasonic pulse signal that has time resolution is used, the propagation time can be measured by calculating the time difference between transmitted signal and reflected signal to sea surface. In this procedure, the resolution is limited to pulse width, and reflected signals distort from the waveform of transmitted signal, according to transducer and propagation characteristics. 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 be happen to measurement error.

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 required equipment 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 traditional method, this distance is measured by observing draft mark fastened to the stem and sternpost directly. 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 is described with the travel time of sound from the position of transducer to the sea surface as Fig. 1. Namely, the draught is expressed as follows:

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

where H, h_1 represent 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 and t is the time interval taken for one round trip of sound to the sea surface. If the sound velocity in air is assumed as constant, though it varies little by little according to temperature, 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.

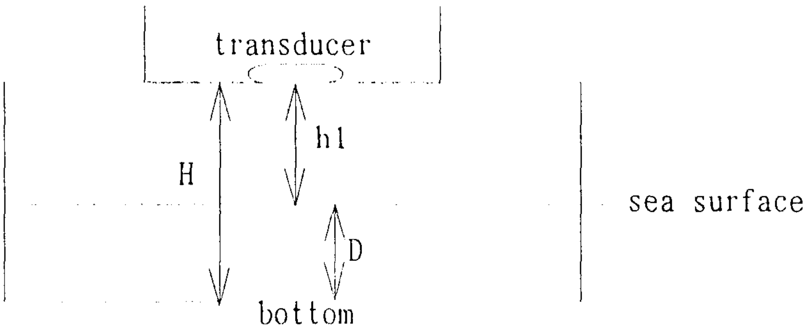

Fig. 1. The remote sensing of draught onboard by ultrasonics.

2.2 Waveforms of Signals

Tone burst pulse was used for measuring the time interval as transmitted signal. Figure 2 shows 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. As Fig.2, the waveform of received signal is different from that of transmitted signal. In determining the time interval between two signals different in waveform, it is difficult to compare transmitted signal with received signal directly because we do not confirm which points correspond each exactly.

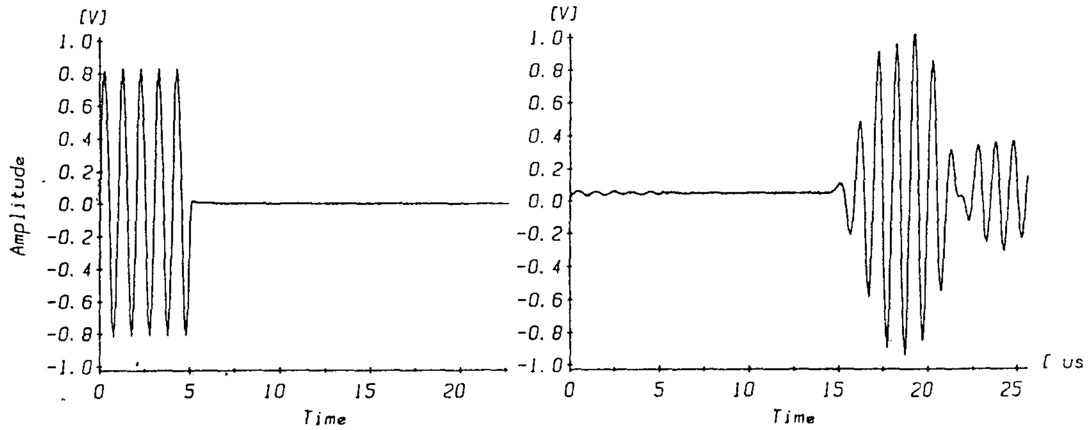

Fig. 2. The waveforms of transmitted and received signal.

2.3 Lateral Resolution and Focusing

When sound is propagated in air from transducer, beam diameter(B_d) is changed according to the frequency(F), the diameter(D_t)of transducer and the

distance(d) off the transducer as Fig.3.
In general , beam pattern described with 3dB is expressed in far zone as Eq.(2)

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

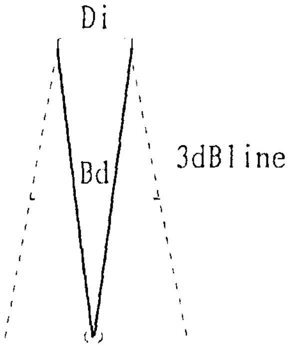

Fig. 3 Beam width described with 3dB.

The beam diameter represents the lateral resolution which is capability for separating two objects located at the lateral direction of sound propagation. Although this resolution is improved by increasing the signal frequency, the propagating distance of sound is shorten in proportion of its frequency.If the beam diameter is extended in the case of draught measurement, measured value will be easily influenced on the sea condition. Hence, the curved transducer is suitable for focusing sound around the sea surface.

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 detail 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 vector 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

$$\begin{aligned} \theta(t) &= \arg\left\{\mathrm{Re}(C(t)) + j\,\mathrm{Im}(C(t))\right\} \\ A(t) &= \sqrt{\mathrm{Re}(C(t))^2 + \mathrm{Im}(C(t))^2} \end{aligned} \tag{3}$$

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 $S_d(t)$

with D.C. component is expressed by

$$S_d(t) = A\cos\omega t + D. \tag{4}$$

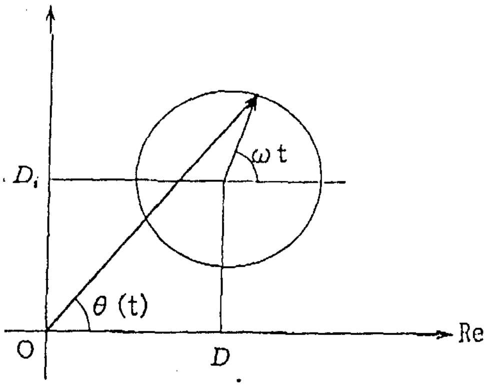

Fig. 4. Fixed vector and rotating vector.

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

$$S_{id}(t) = A\sin\omega t + D_i \tag{5}$$

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

$$R(t) = A\cos\omega t$$
$$I(t) = A\sin\omega t \tag{6}$$

Here, in order to get the above functions, let us observe the signal around time t. So, the signal $S_d(t)$ can be expressed as $S_d(t+\tau)$ which is the signal at the time difference by τ from t. The signal $S_d(t+\tau)$ can be showed as follows:

$$\begin{aligned} S_d(t+\tau) &= A\cos(\omega t + \omega\tau) + D \\ &= A\cos\omega t\cos\omega\tau - A\sin\omega t\sin\omega\tau + D. \end{aligned} \tag{7}$$

It is noted that the real part $A\cos\omega t$ and the imaginary part $A\sin\omega t$ as shown in Eq.(6) are contained in Eq.(7). 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:

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

$$I(t) = 2\int_{-T/2}^{T/2} S_d(t+\tau)\sin\omega\tau\, d\tau = A\sin\omega t \tag{8}$$

The phase θ(t) can be obtained as

$$\theta(t) = \arg(R(t) + jI(t)) = \arg\left\{2\int_{-T/2}^{T/2} S_d(t+\tau)\cos\omega\tau d\tau - j2\int_{-T/2}^{T/2} S_d(t+\tau)\sin\omega\tau d\tau\right\} \tag{9}$$

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 procedures for general function *f(t)*, any complex signal *f(t)* can be defined as

$$f(t) \equiv R(t) + jI(t) \tag{10}$$

where

$$\begin{aligned} R(t) &= 2\int_{-Tc/2}^{Tc/2} f(t+\tau)\cos\omega_c\tau d\tau \\ I(t) &= 2\int_{-Tc/2}^{Tc/2} f(t+\tau)\sin\omega_c\tau d\tau \end{aligned} \tag{11}$$

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

$$\begin{aligned} A(t) &= \sqrt{\mathrm{Re}(C(t))^2 + \mathrm{Im}(C(t))^2} \\ \theta(t) &= \arg\{\mathrm{Re}(C(t)) + j\,\mathrm{Im}(C(t))\} \end{aligned} \tag{12}$$

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

4. Determination of Time Interval

The transmitted and received pulse signals is analyzed into the phase defined in chapter 3. Then, the phase curves of two signals is obtained as Fig.5.

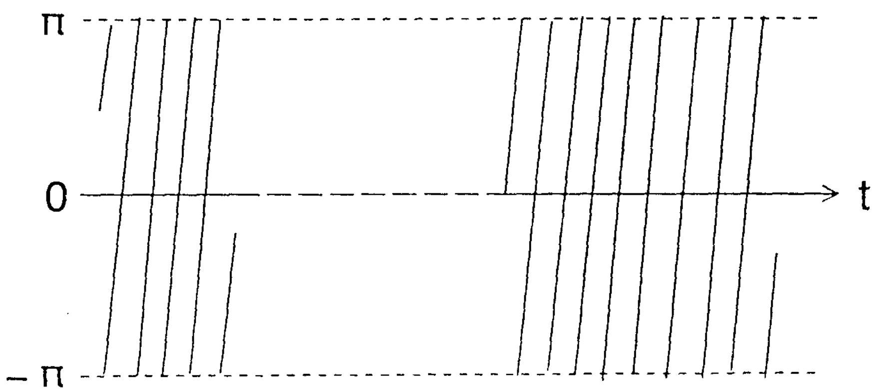

Fig. 5. The phase curves of transmitted and received signals.

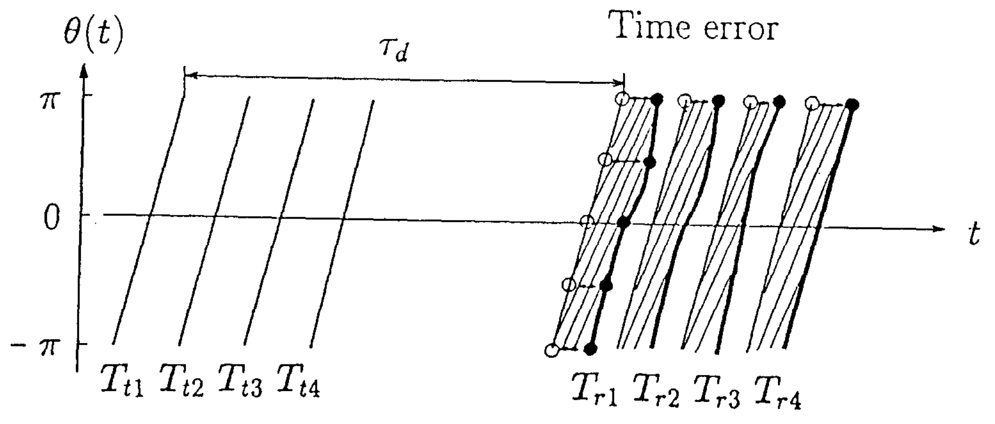

Fig. 6. Determination of time interval on phase curves.

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 estimating by calculating the square time error. On the phase curves of received signal, a place is most similar to the phase curve of transmitted signal is at the time when square 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:

$$E(\tau_d)=\sum_{i=1}^{n}\int_{\phi_1}^{\phi_2}\left\{T_{ri}(\phi)-(T_{ti}(\phi)+\tau_d)^2\right\}d\phi \tag{13}$$

where n is the number of phase segments on phase curve, and $T_{ri},\ T_{ti}$ 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 of $E(\tau_d)$ by least squares method. If the $E(\tau_d)$ is differentiated by τ_d, the derived function is obtained as

$$\frac{dE(\tau_d)}{d\tau_d}=0 \tag{14}$$

The τ_d for the least value $E(\tau_d)$ is calculated from Eq.(14).
In consequence, τ_d can be written by

$$\tau_d=\frac{1}{2(n+1)\pi}\sum_{i=1}^{n}\int_{\phi_1}^{\phi_2}\left(T_{ri}(\phi)-T_{ti}(\phi)\right)d\phi \tag{15}$$

5 . A 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.(15) Figure 7 shows the successive five data sampled at *T/4*. The imaginary part *I(t)* and the real part *R(t)* can be expressed with these sampled data as follows:

$$R(t)=\frac{1}{2}\ R(t)=\frac{1}{2}$$

$$R(t)=\frac{1}{2}\left\{f(t)\cos 0-\frac{f(t-T/2)\cos(-T/2)+f(t+T/2)\cos(T/2)}{2}\right\}$$

$$=\frac{1}{2}\left(c-\frac{a+e}{2}\right)=\frac{c}{2}-\frac{a}{4}-\frac{e}{4} \qquad (16)$$

$$I(t)=\frac{1}{2}\left\{-f(t-T/4)\sin(-T/4)+f(t+T/4)\sin(T/4)\right\}$$

$$=-\frac{b}{2}+\frac{d}{2} \qquad (17)$$

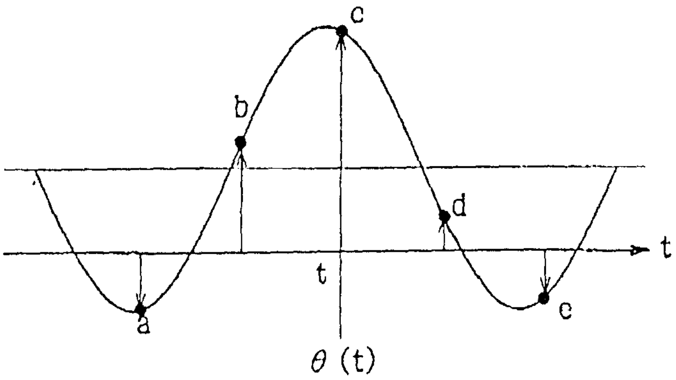

Fig. 7. Practical digital processing.

Thus, θ*(t)* can be determined by the five sampled data as

$$\theta(t)=\arg\left(c-\frac{a+e}{2}+j(d-b)\right) \qquad (18)$$

It can be seen that the phase θ*(t)* can be briefly calculated by the mathematical operations of addition and subtraction instead of correlation in the conventional technique.

5. 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 newly. Secondly, spatial resolution is relatively high. 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 applications such as the measurements of distance and depth and movement speed.

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