海洋安全學會誌 第2卷 第1號, pp. 1~10, 1996. 1.

論 文

A Basic Study on the Measurement of Velocity Distribution of Underwater Targets

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수중 물체의 속도 분포 측정에 관한 기초 연구

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〈Contents〉

Abstract

초음파는 액체 및 고체의 매질 속에서도 그 전달 특성이 우수하여 수중 물체의 감지, 지질조사, 자원탐사 뿐만 아니라, 의학 분야에서도 널리 사용되고 있다. 물체유동정보 측정방식에는 연속파를 이용한 도플러식과 펄스 신호를 이용한 도플러식이 개발되어 있다. 펄스 도플러는 거리 분해능이 좋으므로 깊이에 따른 속도 정보를 쉽게 얻을 수 있는 장점이 있으나, 수신되는 도플러 신호가 탐촉자의 특성과 매질 속에서의 전파특성 등에 의하여 송신된 신호와 파형이 다르고 복잡한 주파수 특성을 가지므로 연속파에서와 같이 도플러 주파수를 직접 측정하기 곤란하다. 도플러 주파수를 검출하기 위하여 여러 방법이 개발되어 있으나, 측정거리와 측정속도의 제약과 더불어, 실시간(real time) 처리에 의한 분포적 측정이 어려운 실정이다.

본 연구에서는 시간 영역에서 국소 데이터를 이용하여 펄스 신호의 위상을 정의하고 실시간에서 펄스 신

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호를 위상으로 변환하는 신호 처리법을 제안하였다. 또한 이 신호 처리법을 응용하여 측정 범위의 위상 곡선에서 위상 차를 계산함으로써 평균 가속도와 유동속도정보를 분포적으로 얻을 수 있는 새로운 펄스 도플러 기법을 제안하였으며, 모델 신호를 만들어 제안된 방법의 유용성을 검토하였다.

1. INTRODUCTION

The ultrasound has been widely applied to both the detection of targets submerged in liquid and solid media and to the estimation of the velocity of underwater moving objects, the volume blood flow in medical field, and flow dynamics. In particular, ultrasonic pulse signal has been extensively used in measuring dynamic parameters of objects because it has time resolution[1][2].

The feasibility of measuring the flow velocity of scatterer based on the Doppler effect in ultrasonic waves has become well known. With respect to Doppler technique, there are two kinds: continuous wave Doppler and pulsed wave Doppler. The pulsed Doppler is capable of providing flow information at any depth on the sound beam, which is widely used at the present time. However, when pulse signal is propagated in media, received signal do not correspond with transmitted signal because of the characteristics of transducer and propagation in media. So it is difficult to estimate Doppler frequency shift directly, in order to measure the flow velocity of scatterer. Despite the significant progress in several studies made in pulsed Doppler technique, there remains a fundamental limitation not only on the maximum range at which the system will operate and on the maximum velocity that the system will sense, but also on real time sense and measuring accuracy[3][4][5].

The paper aims to propose a technique of detecting Doppler shift in time domain, in order to estimate the velocity distribution in concerned depth on real time. In this technique, first of all, pulsed Doppler signal is analyzed with the phase defined in time domain. The velocity distribution of objects is determined by calculating the phase difference on velocity response curve obtained in phase analysis of signal[6][7]. We describe a way of local phase extraction in time domain and compare with conventional methods. Finally, by using this phase curve, the technique for the measurement of velocity distribution on real time is introduced.

2. LOCAL PHASE EXTRACTION IN TIME DOMAIN

2.1 Theoretical Background

The phase is useful information for the instantaneous evaluation of signal since it is a parameter to describe the minute time within a period of sinusoidal signal. In particular, if the phase of pulse signal can be extracted in time domain as in the case of sinusoidal signal, the parameter can be applied to the measurement of the velocity and its distribution of moving targets in pulsed Doppler system.

The complex coordinate has been extensively used for the description of vector. A sinusoidal signal $f(t)$ within a period can be expressed with amplitude $A(t)$ and phase $\theta(t)$ in complex coordinate. The phase $\theta(t)$ can be derived by[8]

$$\theta(t) = \arg(Re(f(t)) + jIm(f(t))) \qquad (1)$$

where $Re(f(t)), Im(f(t))$ are real part and imaginary part in complex signal respectively. Imaginary part associated with real signal $f(t)$ is required in order to extract the phase $\theta(t)$. Here, it is necessary to get phase $\theta(t)$ by using the short interval signal adjacent to t for the purpose of instantaneous evaluation of transient signal. So we consider a method to transform complex signal with local data. First of all, let us consider how to extract phase $\theta(t)$ of sinusoidal signal for understanding the basic idea of phase extraction. This signal can be represented by

$$s(t) = A\sin\omega t \qquad (2)$$

Then, $s(t+\tau)$ is described as

$$\begin{aligned} s(t+\tau) &= A\sin(\omega t+\omega\tau) \\ &= A\sin\omega t\cos\omega\tau + A\cos\omega t\sin\omega\tau \qquad (3) \\ &= A\sin\theta(t)\cos\omega\tau + A\cos\theta(t)\sin\omega\tau \end{aligned}$$

where $\theta(t)$ is the phase function within a period. If τ is set to the period T of sinusoidal signal, the phase $\theta(t)$ at the time t can be calculated as follows:

$$\begin{aligned} \theta(t) = \ & \arg\Big(\int_{\frac{-T}{2}}^{\frac{T}{2}} s(t+\tau)\sin\omega\tau d\tau \\ & + j\int_{\frac{-T}{2}}^{\frac{T}{2}} s(t+\tau)\cos\omega\tau d\tau\Big) \end{aligned} \qquad (4)$$

This equation shows that the phase $\theta(t)$ can be extracted with the local data from $t-\tau$ to $t+\tau$ On referring to the equation of the phase extraction, we can extend the phase concept from sinusoidal signal to general signal by determining the range of local data.

2.2 The Phase Extraction with Local Data

The phase is originally defined for describing continuous sinusoidal signal together with amplitude. We consider the phase $\theta(t)$ of any signal $f(t)$ which is not sinusoidal signal. In the first place, in order to generalize the phase, the range of local data is determined by using the periodic characteristics of signal. Namely, the periodicity T_b of signal is detected on its auto correlation. Let us define the phase function of $f(t)$ in time domain as:[9][10]

$$\begin{aligned} \theta(t) = \ & \arg\Big(\int_{\frac{-T_b}{2}}^{\frac{T_b}{2}} f(t+\tau)\sin\omega\tau d\tau \\ & + j\int_{\frac{-T_b}{2}}^{\frac{T_b}{2}} f(t+\tau)\cos\omega\tau d\tau\Big) \end{aligned} \qquad (5)$$

The phase $\theta(t)$ can be calculated with local data as the function of time and applied to the analysis of signal in real time. This parameter is useful for analyzing transient signal in order to estimate moving speed and its distribution in ultrasonic pulsed Doppler system. In the way of phase extraction proposed, both real part and imaginary part in analytic complex signal have to transform, while only imaginary part is transformed in other time domain techniques.

2.3 The Influence of Data Width

In order to examine the influence of data range on phase, a sine wave $s(t)$ was analyzed into the phase extracted in Eq.(5). Figure 1 shows phase curves by setting the width of local data($-T/2\sim T/2$). The phase curves are deviated from the phase of sinusoidal signal modulated with 2π. However, eigenvalues, which is independent on the data range used in phase extraction, exist when the modulated phase become specific value such as $0, \pi/2, 3\pi/2$.

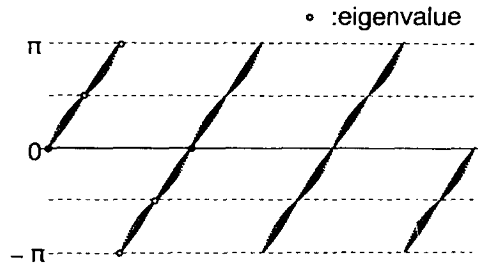

Fig. 1 The relations between phase curve and data width.

2.4 The Influence of Amplitude

The influence of amplitude on phase curve was evaluated here. Figure 2 shows the phase curves in the case that amplitude varies at fixed rate, when the signal frequency and the width of data used in phase extraction keep a constant. It can be seen that the phase curve of signal is independent on the magnitude of amplitude but dependent on the change rate of amplitude.

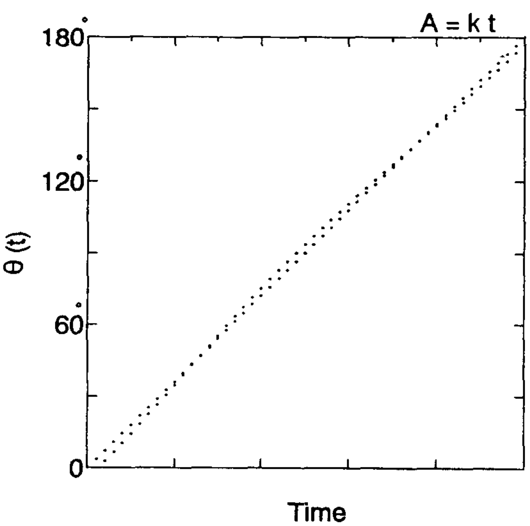

Fig. 2 The relations between phase curve and amplitude.

3. CONVENTIONAL METHODS

In this section, we summarize the theory and process of the time domain techniques which is adopted to get analytic complex signal for the calculation of instantaneous phase and envelope, in order to be compared with the method proposed formerly[11][12].

3.1 Complex Demodulation

Time domain technique which yield a description of a real signal in terms of its instantaneous phase and envelope have been developed. Complex Demodulation is one of techniques to properly extract envelope and phase functions. In order to compose the analytic complex signal in this technique, the imaginary part associated with the real signal is obtained by demodulating about given frequency and employing a low pass filter, denoted symbolically as follows:

$$z(t) = x(t)e^{-j\omega t} \text{ (demodulation)} \quad (6)$$

$$\Psi(t) = H[\ z(t)] \text{ (low-pass filter)} \quad (7)$$

$$y(t) = \Psi(t)e^{j\omega t} \text{ (remodulation)} \quad (8)$$

where H[] denotes transfer function of ideal low-pass filter. For example, these processes are equivalent to eliminating $e^{j\omega t}$ from Eq.(9).

$$x(t) = \cos\omega t = \frac{e^{j\omega t} + e^{-j\omega t}}{2} \quad (9)$$

The analytic signal $x_+(t)$ associated with $x(t)$ can be expressed by

$$x_+(t) = (\cos\omega t + j\sin\omega t) \quad (10)$$

The envelope and phase function of $x(t)$ can be subsequently obtained from the magnitude and argument of $x_+(t)$. In this technique, the signal must be of a bandpass type in order to extract phase function because it is impossible to separate exactly the positive and the negative parts of frequency spectrum by means of a physically realizable lowpass filter. In addition, the information of signal during long time interval is required by using the filter.

3.2 Hilbert Transformation

Hilbert transformation has been widely used in order to obtain the analytic complex signal associated with the real signal, and consequently its envelope and phase functions. The analytic signal $x_+(t)$ can be expressed in terms of the signal $x(t)$ and its Hilbert transform as follows:

$$x_+(t) = x(t) - jx_1(t) \tag{11}$$

where $x_1(t)$ is defined by

$$x_1(t) = -\frac{1}{\pi} \oint_{-\infty}^{+\infty} \frac{x(y)}{t-y}\, dy \tag{12}$$

The notation $\oint$ indicates the Cauchy principal value of the integral. If $x(t) = \cos\omega t$, $x_1(t)$ can be written by

$$x_1(t) = \cos\omega t \int_{-\infty}^{\infty} \frac{\cos z}{z}\, dz + \sin\omega t \int_{-\infty}^{\infty} \frac{\sin z}{z}\, dz \tag{13}$$

The envelope and phase function can be obtained when the Hilbert transform of the real signal $x(t)$ is known. In this technique, the information of signal during long time interval is required to obtain imaginary part of the analytic complex signal in Hilbert transform, too. The envelope and phase function of any signal has various values according to the selection of Cauchy principal value.

3.3 In-Phase and in-Quadrature Filtering

This technique extracts the analytic signal associated with the item component $x_{HL}(t)$ of a real signal $x(t)$ relative to the frequency interval (x_L, x_H). It is thus equivalent to Complex Demodulation when the cutoff frequency of lowpass filter is made equal to $(x_H - x_L)/2$, or to Hilbert transformation when the signal $x(t)$ has been previously bandpass-filtered between x_L and x_H. Namely, the signal $x(t)$ is filtered with filters having transform functions:

$$H[f] = \begin{cases} 1 & x_L \le |f| \le x_H \\ 0 & \text{otherwise} \end{cases} \quad \text{(In-Phase Filter)} \tag{14}$$

$$H_1[f] = \begin{cases} +j & x_L \le |f| \le x_H \\ -j & -x_L \le |f| \le -x_H \\ 0 & \text{otherwise} \end{cases} \quad \text{(In-Quadrature Filter)} \tag{15}$$

The real part and imaginary part of the analytic signal associated with $x(t)$ are outputs of In-Phase Filter and In Quadrature Filter respectively.

4. EXAMPLES OF SIGNAL ANALYSIS

4.1 Linear-amplified Signal

The model signals $f_1(t), f_2(t)$ are analyzed into the local phase proposed in this paper, of which amplitudes have relations as follows:

$$A_2(t) \equiv a_0 A_1(t) \tag{16}$$

Figure 3 shows the phase curves of simulated pulse signals in the case that

$$f_1(t)=\frac{1}{\sqrt{2}}\exp(-\frac{t^2}{2})\cos 2\pi f t \qquad (17)$$

Here, it can be seen that phase functions $\theta(t)$ is the same without depending on the magnitude a_0 of amplitude. The similar pulse signals are often received when ultrasonic pulse signal is multi-reflected to any object.

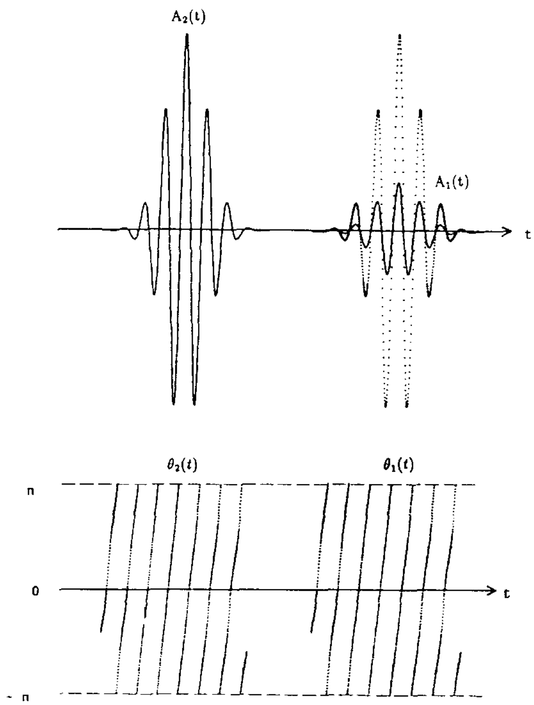

Fig. 3 The phase curve of linear-amplified signal.

4.2 Nonlinear-amplified Signal

Generally, the ultrasonic echo of surrounding media is much stronger than that of interested media in measuring Doppler frequency in order to measure flow speed and its distribution, and it is often amplified asymmetrically. Then the concerned echo signal is superposed with D.C. component. Figure 4 shows the simulated signal which contains characteristics superposed with D.C. component. The proposed technique generates phase curves in Fig. 4. Here, it is noted that the phase curve is almost detected without the effect of D.C. component.

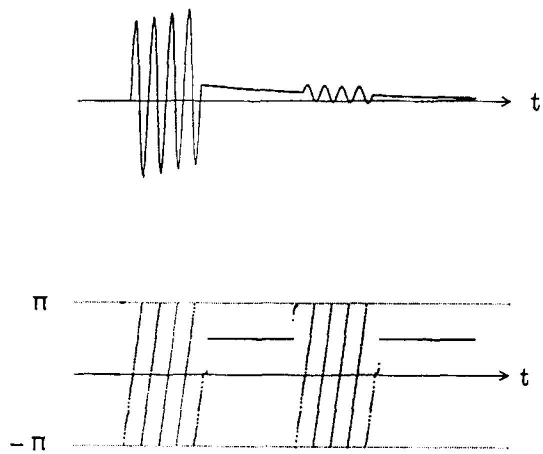

Fig. 4 The phase curve of nonlinear-amplified signal.

4.3 Chirp Signal

The chirp signal of which frequency varies with time is common in various field of science and engineering. In particular, the similar echo signal is received when reflected objects move in ultrasonic pulsed Doppler technique. For mathematical simplification, the model signal is designed to represented a real chirp signal, expressed by

$$f_c(t)=A\sin(\omega t+\gamma\frac{t^2}{2}) \qquad (18)$$

The simulated signal and its phase curve are shown up in Fig. 5. This phase curve enables us to estimate the Doppler velocity by successive responses.

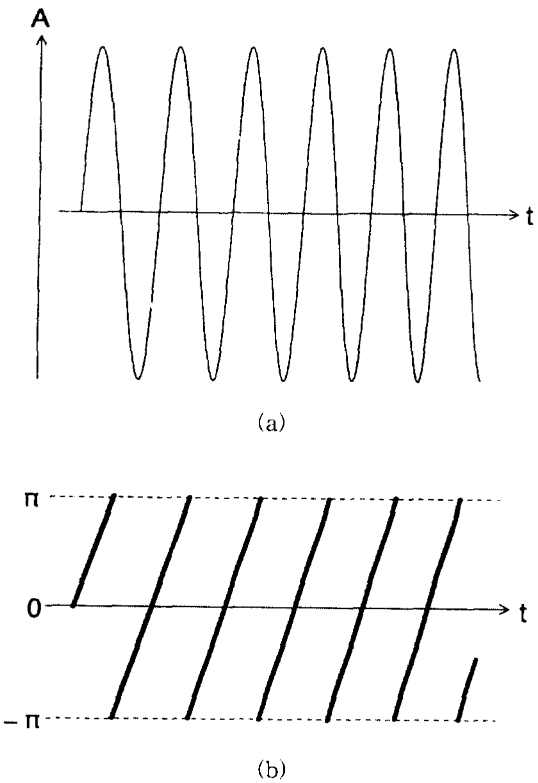

Fig. 5 The chirp signal(a) and it's phase curve(b)

5. MEASUREMENT OF VELOCITY DISTRIBUTION

5.1 Pulsed Doppler Technique

In the meantime the feasibility of measuring a liquid flow and velocity of underwater moving targets using the Doppler effect in ultrasonic waves has become well known. With respect to the method of the measurement of flow and velocity, there are two kinds, continuous wave Doppler and pulse wave Doppler, or the so-called pulsed Doppler. Since the pulsed Doppler is capable of providing flow information of targets at any depth on the sound beam axis simultaneously with B-mode and M-mode images. Figure 6 shows the model of pulsed Doppler technique. At intervals of time T , pulse waves are transmitted two times to multi-scatters, which move at the speed of $v(l)$, two Doppler signals obtained in Fig. 6. The speed of $v(l)$ is formulated as follows:[13]

$$v(l) = \frac{f_d(l)}{2f}c \tag{19}$$

where f_d is Doppler frequency, c is the speed of wave. Here, to measure the speed $v(l_1)$ of scatter at the depth $l_1(=c \cdot t)$, the Doppler frequency must be extracted. Several techniques have been proposed for detecting it. They have disadvantage that flow information with a narrow range of sampling site on the beam axis is obtained. So it is difficult to measure flow information of multi-scatters entirely when they move at distributional velocity. Now, we estimate the velocity- distribution of multi-scatters by using the phase defined in Eq. 5 as

$$v(l) \equiv \frac{\Delta\theta(l)}{2f}c \tag{20}$$

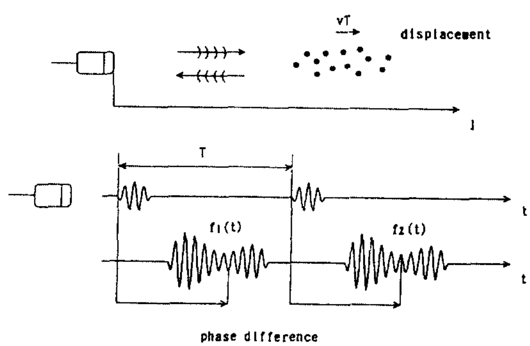

Fig. 6 The model of pulsed Doppler technique.

5.2 Velocity Response Curve

To evaluate the feasibility in appling the proposed method for phase extraction, to estimation of scatterer-velocity, we design the model signal to represent pulsed Doppler signal, which is reflected pulse signal to moving objects. Figure 7 shows the pulse signal of which frequency is changed as the function of time. Within a period, the change rate of frequency can be described as

$$\Delta f(l) \equiv \Delta\theta(l) \qquad (21)$$

where distance(or depth) l equals to $c \times t$. If we have interests to measure the velocity of scatters according to their depth, the phase difference $\Delta\theta(l)$ at the depth between Doppler signals, received at a constant interval, is required. Here, let the designed method for phase extraction in time domain be applied so that the phase at the depth should detect in real time efficiently.

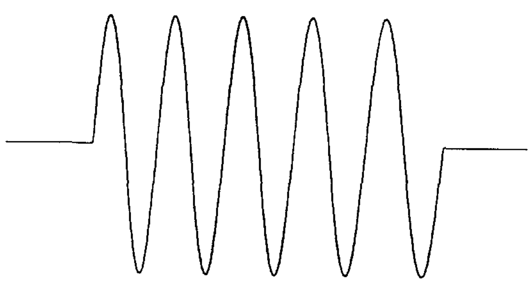

Fig. 7 The simulated Doppler signal.

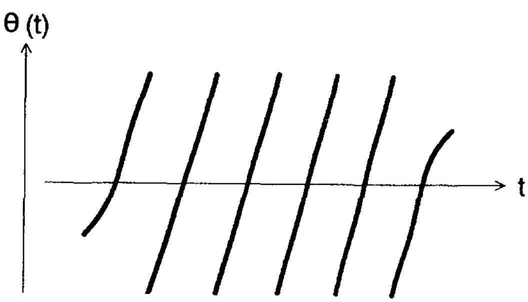

Fig. 8 The phase curve of simulated signal.

Figure 8 represents the curve of local phase extracted as the function of time. This phase curve will be adapted to rapid and continuous instrumentation of moving speed of multi-scatters in concerned depth.

5.3 Estimation of Velocity Distribution

Let us consider the local phase to be adopted in estimating the velocity distribution. In general, the underwater scatterer, for example a group of fishes, moves with a velocity distribution according to the depth of water.

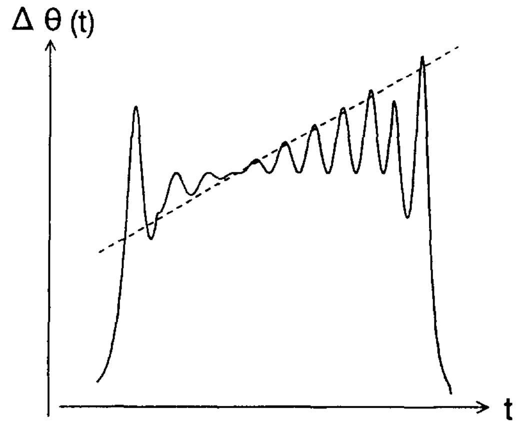

Fig. 9 The velocity response curve and average accelerated velocity.

The measurement of velocity distribution would be useful for a resource development and geological survey, as well fishery since it enables us to provide several information on their dynamic state. Figure 9 shows the velocity response curve for model signal presented in Fig. 7. Here, the model signal represents Doppler signal reflected to object, of which speed accelerated little by little. From Eq. 20, we are able to estimate the velocity of object as the function of depth, by calculating the phase difference $\Delta\theta(l)$. In addition, the average accelerated velocity, which is necessary for measuring a moving distance of object exactly, can be determined. The dotted line in Fig. 9, shows the response for an average accelerated velocity.

6. CONCLUSIONS

We presented a local phase method in order to extract phase in time domain with the local range of data. Being compared with conventional methods, the way of phase extraction proposed in this paper has feature as follows: (1) the phase obtained is independent of D.C. component, (2) the spacial resolution is relatively high (3) the used range of data is narrow, (4) the phase is extracted on almost real time. In the second place, through the local phase method, we proposed a new pulsed Doppler technique in order to estimate the velocity distribution of moving targets on real time. The results obtained for simulated Doppler signals with the proposed technique are in good agreement with the velocity information of signal. As well, this technique provide average accelerated velocity for the determination of the displacement of targets.

It can be thought that the pulsed Doppler technique proposed in this paper, will be applied to the measurement of the velocity distribution of multi-scatterer, on the results obtained about simulated signals. In the future, we will plan to analyze a real Doppler signal obtained from the transducer, and discuss the measured accuracy of the flow velocity.

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