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Spatial modulation measurement by the SFCW vibro – Doppler measurement system

SFCW 方式加振超音波ドップラ計測システムによる空間変調計測

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1. Introduction

Usually, the cross-range resolution of an ultrasonic(US) wave image is restricted by a point spread function (PSF) of an US wave transducer. Since the bandwidth limitation has lowpass characteristics in a wave-number domain, we cannot obtain the information of a high wave number. So, it is necessary to expand the bandwidth of the wave number region to improve cross range resolution. However, it is difficult to narrower the resolution because the resolution is decided by the aperture of the US wave transducer and frequency. Therefore we paid our attention to a reflection coefficient. If we can shift the wave number spectrum of a reflection coefficient distribution of the ROI, we can obtain the information of a high wave number without expanding the bandwidth of the PSF. Then, the bandwidth can be equivalently expanded by synthesising the shifted spectrum and the usual spectrum.

The shift of the wave number spectrum of the reflection coefficient is accomplished by modulating the sinusoidal spatial variation to the reflection coefficient distribution. We call the procedure as spatial modulation. In this report, we experimentally show that the spatial modulation is accomplished by a vibro-Doppler measurement.

2. Vibro-Doppler measurement

If a vibration by a shear wave is induced to an imaging region, the reflector fluctuates. It cause the change of the propagation path of an US wave. Since the plane vibration wave having the frequency f_v propagate to x direction, surface change $\xi_z(t,x)$ is represented with a wave number k_v of the shear wave as

$$\xi_z(t,x) = \delta\cos(2\pi f_v t - k_v x) \tag{1}$$

where δ is displacement amplitude of the shear wave. Assuming that the ultrasonic wave propagates only to the z-direction with no attenuation for simplicity, complex Doppler signals are obtained by convolution between a PSF $w(x)$ and a product of a reflection coefficient distribution $\dot{\gamma}(x)$ of US wave scatterers and a vibration wave [1]as

$$\dot{g}(t,x) = \int w(x-x')\dot{\gamma}(x')\exp\{-2jk_u\xi_z(t,x')\}dx' \tag{2}$$

where k_u is the wave number of the ultrasonic wave. If $\theta = k_u\delta$ is much smaller than the unity, the following approximation can be applied

$$\exp(j\theta) \cong 1 + j\theta \tag{3}$$

Then, eq. (2) can be approximated as

$$\dot{g}(t,x) \cong \int w(x-x')\dot{\gamma}(x')\{1-2jk_u\xi_z(t,x')\}dx' . \tag{4}$$

By applying Fourier transformation to eq. (4) for time t, we obtain static image and Doppler image at the frequencies $f = 0, \pm f_v$ which are represented by

$$\dot{g}_0(x) = \int w(x-x')\dot{\gamma}(x')dx' \quad \text{and} \tag{5}$$

$$\dot{g}_{\pm f_v}(x) = -j\theta e^{\pm j\varphi}\int w(x-x')\dot{\gamma}(x')\exp(\mp jk_v x')dx' . \tag{6}$$

Here, wave number spectrum in the x direction are obtained.

$$G_0(k_x) = W(k_x)\Gamma(k_x) \quad \text{and} \tag{7}$$

$$G_{\pm f_v}(k_x) = \mp j\theta W(k_x)\Gamma(k_x \pm k_v) . \tag{8}$$

In the static signal as shown in eq. (7), obtained wave number spectrum is limited by low pass characteristics of $W(k_x, k_z)$ in the US wave transducer. It limits the wave number spectrum obtained in the Doppler measurement at the vibration frequency. However, the wave number spectrum obtained by vibro-Doppler measurement can be changed on vibration frequency.

3. SFCW vibro-Doppler system

Figure 1 shows a block diagram of the vibro-Doppler measurement system. In this system, we use a network analyzer which measures the wideband transfer function by sweeping the multiple frequency because of improvement of SNR. The measurement bandwidth is defined as IF bandwidth which is basically narrow such as several hundred Hz. When we apply a vibration wave to the ROI in the vibro-Doppler measurement, the reflected US wave suffers a Doppler shift. Since the vibration frequency is more than 500Hz, the IF bandwidth is set as 100Hz.

In order to obtain Doppler components by narrow band measurement system, the transmitting frequency should be shifted outside the network analyzer. If the transmitting wave is multiplied by a vibration wave at the frequency mixer, sum and difference frequency components appear. But, because the vibration frequency is much smaller than the ultrasonic frequency, it is difficult to cancel the image components by a bandpass filter. So, we use an image cancelling mixer (ICM). In the $+f_v$ vibro Doppler measurement, the ICM pre-shifts the transmitting frequency f to $f - f_v$. And then the reflected US wave separates into three dominant waves having the frequency at $f-2f_v$, $f-f_v$ and f by the Doppler effect. Therefore, the network analyzer can measures only the $+f_v$ Doppler components

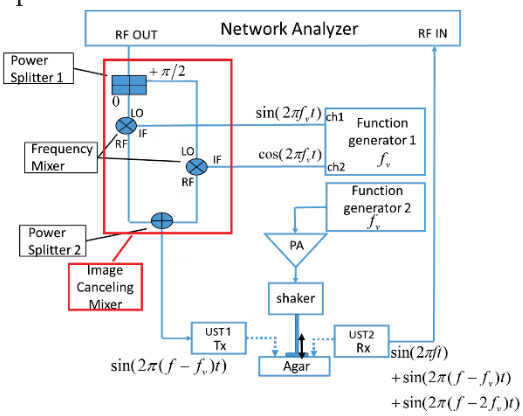

Fig.1 SFCW vibro-Doppler measurement system

5. Measurement result

In order to confirm the spatial modulation, we scan the surface of the agar gel in a water filled tank with and without vibration for vibro Doppler measurement. The distance to the surface is about 10cm below the US transducer. The origin of the x-axis is the position of the vibration source.
For the sensing wave, center frequency of the transmitting US is 5.2 MHz, and frequency Span is 0.5MHz. The IF bandwidth is 15Hz. The frequency of the vibration wave is 500 Hz.

Figure 2 shows an acquired two-dimensional image. The reflection signal from the target surface appears at the depth of 10.75cm in each figure. We show the complex amplitude of the reflected signal at the depth of 10.75cm in **Figure 3.** The static signal changes because the surface is inclined intentionally. The phase change is caused by change of the propagation path. Generally, we can regard the phase change as the change of the complex reflection coefficient of the surface. In the vibro-Doppler signal, much more phase change is observed. The wavenumber spectrum should be shifted by only the wavenumber of the vibration wave due to the spatial modulation effect. The shifted wavenumber is calculated with the vibration frequency of 500 Hz and the velocity of the agar gel of almost 3m/s. The **Figure 4** shows a complex amplitude of the vibro-Doppler signal demodulated by the spatial modulation term. We can observe that the demodulated vibro-Doppler signal agree with the static signal.

6. Conclusion

We examined the spatial modulation of the signal by vibration which was the important matter in the vibro–Doppler measurement method. The signal acquired by vibro-Doppler measurement showed that a spatial modulation is caused by vibro-Doppler measurement.

Acknowledgement

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References

1. T.Miwa and A.Kaneko: USE (2012).p185,186

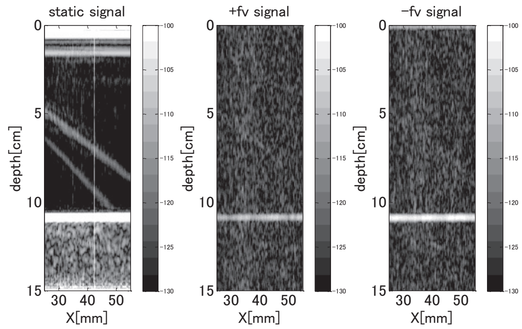

Fig.2 vibro-Doppler imaging results

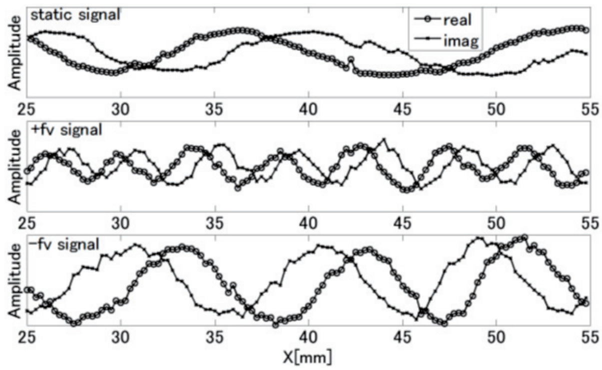

Fig.3 Complex reflection coefficient from surface

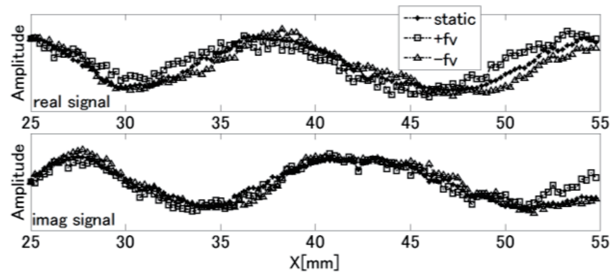

Fig.4 Normalized reflection coefficient after compensation of the spatial modulation.