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Improvement of cross range resolution in B-mode image by US Doppler measurement with forced vibration

加振ドップラー計測による B モード画像のクロスレンジ分解能向上

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1. Introduction

Cross range resolution in a B-mode image depends on aperture of an ultrasonic(US) wave transducer. Generally, it is required to use the wider aperture and higher frequency in order to improve the cross range resolution. However, it is technically difficult to focus US beams with wide aperture in high frequency. We propose a novel improvement method of the cross range resolution, which is achieved without any modification of the US wave transducer by uing an US doppler measurement of US wave scatterers vibrated by a plane shear wave.

2. Doppler measurement of vibrated scatterers

When a plane shear wave propagates to x-axis in a region of interest (ROI), US wave scatterers vibrate at the vibration frequency f_v. Then, the z-component of the shear wave displacement $\xi(t,\boldsymbol{p})$ at $\boldsymbol{p}=(x,z)$ is represented with wave number k_v of the shear wave and initial phase φ as

$$\xi(t,x)=\delta\sin(2\pi f_v t-k_v x+\varphi) \tag{1}$$

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

$$\dot{g}(t,\boldsymbol{p})=\iint w(\boldsymbol{p}-\boldsymbol{p}')\dot{\gamma}(\boldsymbol{p}')\exp\{-2jk\xi(t,x')\}dx'dz'\,. \tag{2}$$

where k is the wave number of the ultrasonic wave. If $\theta=k\delta$ 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

$$\dot{g}(t,\boldsymbol{p})\cong\iint w(\boldsymbol{p}-\boldsymbol{p}')\dot{\gamma}(\boldsymbol{p}')\{1-2jk\xi(t,x')\}dx'dz'\,. \tag{4}$$

By applying Fourier transformation to eq. (4) for time *t*, we obtain Fourier spectrum as

$$\dot{g}_f(\boldsymbol{p})\cong\int_0^T\dot{g}(t,\boldsymbol{p})\exp(-j2\pi ft)dt \tag{5}$$

where T should be integral multiplication of 1/*f*. The Fourier components $\dot{g}_f(\boldsymbol{p})$ at the frequencies $f=0,\pm f_v$ are represented by

$$\dot{g}_0(\boldsymbol{p})=\iint w(\boldsymbol{p}-\boldsymbol{p}')\dot{\gamma}(\boldsymbol{p}')dx'dz' \quad \text{and} \tag{6}$$

$$\dot{g}_{\pm f_v}(\boldsymbol{p})=\mp\theta e^{\pm j\varphi}\iint w(\boldsymbol{p}-\boldsymbol{p}')\dot{\gamma}(\boldsymbol{p}')\exp(\mp jk_v x')dx'dz'\,. \tag{7}$$

Here, a wave number spectrum is obtained by applying two-dimensional Fourier transformation to eq. (6) and (7) for *x* and *z* as

$$G_0(k_x,k_z)=W(k_x,k_z)\Gamma(k_x,k_z) \quad \text{and} \tag{8}$$

$$G_{\pm f_v}(k_x,k_z)=\mp\theta e^{\pm j\varphi}W(k_x,k_z)\Gamma(k_x\pm k_v,k_z)\,. \tag{9}$$

In the static signal as shown in eq.(8), 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 of $G_{\pm f_v}(k_x,k_z)$ obtained in the Doppler measurement at the vibration frequency. However, it is noted that we can select the extracted wave number region by considering the vibration frequency f_v and the shear wave velocity of the ROI

3. Improvement of cross range resolution

We can shift the obtained wave number spectrum $G_{\pm f_v}(k_x,k_z)$ back by $\pm k_v$. In order to expand the bandwidth of the static spectrum, we synthesize the shifted spectrum with the considering appropriate amplitude θ as follows:

$$G_0(k_x,k_z)+\frac{G_{+f_v}(k_x-k_v,k_z)}{-\theta e^{j\varphi}}+\frac{G_{-f_v}(k_x+k_v,k_z)}{\theta e^{-j\varphi}} =\Gamma(k_x,k_z)W_{synth}(k_x,k_z)\quad. \tag{10}$$

Since $W_{synth}(k_x,k_z)$ is written as

$$W_{synth}(k_x,k_z)=W(k_x,k_z)+W(k_x+k_v,k_z) +W(k_x-k_v,k_z)\quad, \tag{11}$$

the bandwidth of the synthesized image expands. If we can adjust the appropriate vibration frequency by considering the spectrum of the PSF, it is expected that the bandwidth of $W_{synth}(k_x,k_z)$ becomes almost 3 times wider than the original one $W(k_x,k_z)$ as shown in **Figure 1**.

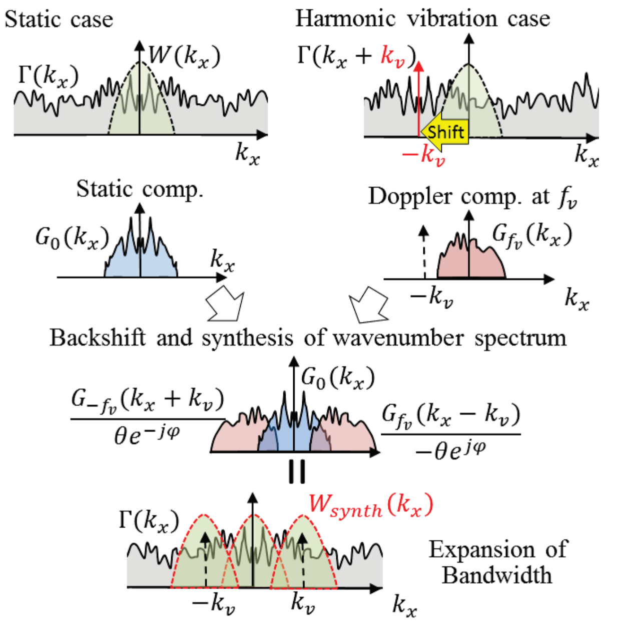


Fig.1 Concept of bandwidth expansion

4. Simulation condition

To validate the expansion of the wavenumber bandwidth, numerical simulations are carried out as a 2D problem. The center frequency of the transmitting US pulse is 5 MHz. The burst length is 4. The velocity and attenuation constant of the US wave are assumed to be 1500 m/s and 1 dB/MHz/cm, respectively. For simplicity, we assume that the directivity of a US transducer depends on only the x-direction as follows:

$$D(x) = \begin{cases} \cos(\pi x / 2r_T) & if \quad |x| \le r_T \\ 0 & otherwize \end{cases} \qquad (12)$$

where r_T is the transducer radius. This simulation uses r_T of 2.5 mm. An impulse response from a US scatterer is numerically generated in 1 GHz sampling. Then, a received RF signal is calculated by accumulating the impulse responses from all the US wave scatterers. The IQ signal after quadrature detection is obtained with a baseband bandwidth of 1.5 MHz. The pulse is repeated with the period of 0.1 ms for 8 ms for Doppler analysis. A 2D cross-sectional Doppler image is obtained with every 0.1 mm and 75 μm in x- and z-directions, respectively.

Assumed targets are two adjacent point reflectors with the separation of 1.25 mm. Moreover, numerous point scatterers are regarded as clutter sources, which are randomly aligned with the averaged separation of a quarter wavelength of the US wave. The reflection coefficient having normal distribution is 1/30 times smaller than the target amplitude.

In order to vibrate the targets, a plane shear wave propagating to x-axis is assumed. The vibration amplitude is 5 μm which corresponds to $\theta \cong 0.1$. Because a reflection of the shear wave should sometimes significant in the realistic condition, we assume a reflected wave having the reflection coefficient of 0.3.

5. Simulation result

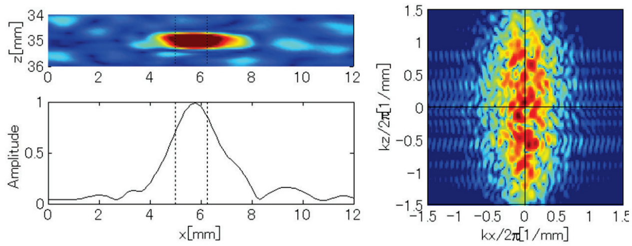
Figure 2(a) shows the wavenumber spectrum of the static target image. The horizontal bandwidth of PSF is about 0.4 [1/mm] which corresponds to eq.(12). Figure 2(b) shows the static image of the two targets. Since the horizontal size of the PSF is larger than the target separation, the two target are not separated. **Figure 3**(a) shows the synthesized wave number spectrum $W_{synth}(k_x, k_z)$ when the vibration frequency and the shear wave velocity are 500 kHz and 1m/s, respectively. We can observe that the bandwidth significantly expands. Figure 3(b) shows the synthesized image. We can clearly observe two target responses with the separation of 1.25mm due to improvement of the resolution.

6. Conclusion

We propose an improvement method of the cross range resolution of the US image by using Doppler measurement with a forced vibration. The validity of this proposed method is demonstrated by a numerical simulation even if we take the reflection of the shear wave into consideration.

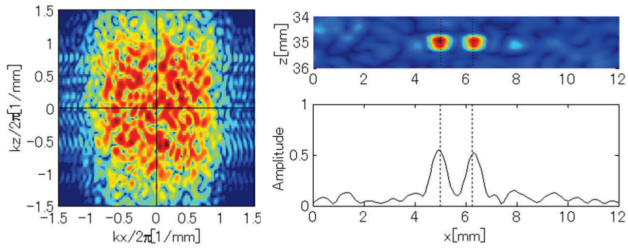
References

1. T. Miwa, R. K. Parajuli, R. Tomizawa, and Y. Yamakoshi: Jpn. J. Appl. Phys. **50**(2011) 07HF07.



(a) B-mode image and x-profile (b) Spectrum

Fig.2 Conventional static signal (r_T :2.5 mm, Target position : 5mm, 6.25mm,)



(a) Synthesized spectrum (b) Synthesized image

Fig.3 After bandwidth expansion by using vibration frequency of 500 Hz (Existence of the reflection of the shear wave, Reflection coefficient : 0.3)